Huadong Guo
Michael F. Goodchild
Alessandro Annoni *Editors*

Manual of Digital Earth

International Society for Digital Earth

Springer Open

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Editors
Huadong Guo
Institute of Remote Sensing
and Digital Earth
Chinese Academy of Sciences
Beijing, China

Michael F. Goodchild
Department of Geography
University of California
Santa Barbara, CA, USA

Alessandro Annoni
Joint Research Centre
European Commission
Ispra, Varese, Italy

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Preface

In October 2015, the 10th Executive Committee Meeting of the International Society for Digital Earth (ISDE) was held in Halifax, Canada where I was elected as the third president of ISDE. I put forward a work plan for my tenure that included a proposal to publish a manual that would address questions regarding the relevance of Digital Earth, its future, and its potential to support scientific development and societal needs. The Executive Committee approved the proposal, and now, after 4 years and a culmination of efforts from numerous contributors, it is my great pleasure to present this manuscript, *Manual of Digital Earth*, for publication and release. The 1st International Symposium on Digital Earth was held in Beijing on November 1999, marking the humble beginnings of ISDE's Symposia 1 year after Mr. Al Gore famously put forward the concept of Digital Earth. Now, after two decades, it is a privilege for me to oversee preparations for the 11th International Symposium on Digital Earth in Florence, Italy, on September 2019.

Over the years, ISDE has successfully hosted 10 International Symposia on Digital Earth and 7 Digital Earth Summits in 11 countries. ISDE and its journals *International Journal of Digital Earth* and *Big Earth Data* launched in 2008 and 2017, have gained international recognition in academic circles. ISDE has become a participating member of the Group on Earth Observations and an affiliate member of the International Science Council since 2009 and 2017, respectively. This has been possible in large part due to its success in organizing intellectual events that appealed to the interests of researchers and scientists in the realm of Digital Earth. ISDE has also established a series of national committees and chapters that address Digital Earth issues. All of these recognitions and achievements have helped to provide the foundation for Digital Earth by developing numerous data platforms and research institutions, and by supporting academic meetings, papers, and monographs that have not only benefited our society but improved our understanding of the world and its Earth shaping processes. With great honor, I have the opportunity to personally experience all the milestone events of Digital Earth during the past two decades. As a witness, organizer and participant, I have been a part of Digital Earth and it has become a part of my life.

Presently, it is necessary for us to gain a profound understanding and make an in-depth analysis of the expanding scope of the concept of Digital Earth and the rapid advancements in Digital Earth technologies, as well as the impacts of Digital Earth on interdisciplinary science and social progress. As an evolving discipline, we need to answer the following questions: (1) What is the basic theory of Digital Earth? (2) What are the key technologies? and (3) What are its main applications? In terms of its content, we need to understand: (1) What are its core characteristics; (2) What is the difference between Digital Earth and geospatial technology? and (3) How does Digital Earth—a frontier interdisciplinary field of Earth science, information science, and space science—promote disciplinary integration and data sharing? To answer these questions, a focused monograph is necessary and relevant.

The manual has been designed to be simple yet academic in nature and professional in design. The information in the manual is forward-looking and will prove to be instrumental in developing the future concepts for Digital Earth. It presents a systematic analysis of the theories, methods, and technical systems of Digital Earth. It also presents a summary of the key achievements to date and predicts the likely direction and probable future developments within the discipline. Broadly, the manual includes information on the following: (1) theories on Digital Earth, the contents of Digital Earth science, and Digital Earth frameworks and platforms; (2) Digital Earth system technologies, including data acquisition, management, processing, mining, visualization, virtual reality, network computing, spatial data facilities, and information service technologies; (3) applications in climate change, natural hazards, digital cities, digital heritage, and global sustainable development goals of the United Nations; (4) regional applications of Digital Earth, especially in regions and countries such as Europe, Australia, China, and Russia; and (5) Digital Earth Education and Ethics and the outlook for the future development of Digital Earth.

Science and technology are continually involved in the process of development and innovation. Digital Earth is becoming even more relevant as the world is undergoing a profound digital revolution. The three frameworks of the United Nations, including Sustainable Development Goals, Climate Change, and Disaster Risk Reduction, along with the rise in digital economies have created more of a need for Digital Earth. The increasing volume of data amassed through Earth system science and geo-information science are prompting experts to investigate and experiment with highly automated and intelligent systems in order to extract information from enormous datasets and to drive future innovative research that will greatly benefit from developments in Digital Earth technologies and systems. Frontier technologies such as Internet of Things, big data, artificial intelligence, blockchain, and 5G are creating opportunities for the next stage of Digital Earth. Digital Earth could help bridge the information gap for the general public by integrating data and information from multiple sources including those from space, social networks, and economic data. By developing intelligent models and data-intensive computing algorithms, Digital Earth can generate useful information and scientific knowledge supporting social service functions as well as drive scientific discoveries.

This manual has only been possible by the support from ISDE, and it is sponsored by programs in the Chinese Academy of Sciences (CAS), "Research on the Development Strategy of the New Generation of Digital Earth" and "Research on the Development Strategy of Digital Earth Discipline" provided support from the CAS Academic Divisions. The CAS Strategic Priority Research Program supported the manual through "Big Earth Data Science Engineering Project (CASEarth)".

Over 100 authors and editors from 18 countries contributed to this manual, and I would like to thank them for their hard work. Special thanks go to my co-editors, Dr. Michael F. Goodchild, and Dr. Alessandro Annoni, who reviewed the manual's numerous contributions, the ISDE Council Members for their support, and Dr. Changlin Wang for his tremendous effort. Particularly, I would like to thank Dr. Zhen Liu for the work she has done over the past 2 years organizing all aspects of this publication, which would have been impossible without her efforts. Taking this opportunity, I would also like to express my appreciation to everybody who has contributed to Digital Earth. I sincerely wish Digital Earth continued success and strongly support its vigorous development.

Beijing, China | Huadong Guo
June 2019 | President, International Society for Digital Earth

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List of Editors

Editors-in-Chief

Huadong Guo, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, China
Michael F. Goodchild, Department of Geography, University of California, Santa Barbara, USA
Alessandro Annoni, Joint Research Centre, European Commission

Managing Editors

Zhen Liu, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, China
Changlin Wang, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, China

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About the Editors-in-Chief

Huadong Guo is a Professor of the Chinese Academy of Sciences (CAS) Institute of Remote Sensing and Digital Earth (RADI), an Academician of CAS, a Foreign Member of Russian Academy of Sciences, a Foreign Member of Finnish Society of Sciences and Letters, and a Fellow of TWAS. He presently serves as President of the International Society for Digital Earth (ISDE), Member of UN 10-Member Group to support the Technology Facilitation Mechanism for SDGs, Director of the International Center on Space Technologies for Natural and Cultural Heritage under the Auspices of UNESCO, Science Committee Member of the Integrated Research on Disaster Risk (IRDR) Program of ISC and UNDRR, Chair of the Digital Belt and Road Program (DBAR), Chairman of the International Committee on Remote Sensing of Environment, and Editor-in-Chief of the *International Journal of Digital Earth* and the journal of *Big Earth Data* published by Taylor & Francis. He served as President of ICSU Committee on Data for Science and Technology (CODATA, 2010–2014) and Secretary General of ISDE (2006–2014). He specializes in remote sensing, radar for Earth observation and Digital Earth science. He is the Principal Investigator of Moon-based Earth Observation Project of National Natural Science Foundation of China and the Chief Scientist of the Big Earth Data Science Engineering Project of CAS. He has published more than 400 papers and 17 books, and is the principal awardee of 16 domestic and international prizes.

Michael F. Goodchild is Emeritus Professor of Geography at the University of California, Santa Barbara. He is also Distinguished Chair Professor at the Hong Kong Polytechnic University and Research Professor at Arizona State University, and holds many other affiliate, adjunct, and honorary positions at universities around the world. Until his retirement in June 2012, he was Jack and Laura Dangermond Professor of Geography, and Director of UCSB's Center for Spatial Studies. He received his BA degree from Cambridge University in Physics in 1965 and his Ph.D. in geography from McMaster University in 1969, and has received five honorary doctorates. He was elected member of the National Academy of Sciences and Foreign Member of the Royal Society of Canada in 2002, member of the American Academy of Arts and Sciences in 2006, and Foreign Member of the Royal Society and Corresponding Fellow of the British Academy in 2010; and in 2007, he received the Prix Vautrin Lud. He was editor of *Geographical Analysis* between 1987 and 1990 and editor of the Methods, Models, and Geographic Information Sciences section of the *Annals of the Association of American Geographers* from 2000 to 2006. He serves on the editorial boards of 10 other journals and book series, and has published over 15 books and 500 articles. He was Chair of the National Research Council's Mapping Science Committee from 1997 to 1999, and of the Advisory Committee on Social, Behavioral, and Economic Sciences of the National Science Foundation from 2008 to 2010. His research interests center on geographic information science, spatial analysis, and uncertainty in geographic data.

Alessandro Annoni is working in European Commission's Joint Research Centre since 1997. He has been the Head of the Spatial Data Infrastructure and the Digital Earth Units working on Information Infrastructures, advancing research on multidisciplinary-interoperability and ensuring the Technical Coordination of the INSPIRE Directive 2007/2/EC that lays down rules for the establishment of the European Spatial Data Infrastructure. Since 2016 is the Head of the Digital Economy Unit targeting the impact of Digital Transformation on economy and society and in charge of the European Artificial Intelligence Observatory (AI Watch). Alessandro graduated in Physics from the University of Milan. Before joining the European Commission, he worked for 20 years in the private sector and managed companies dealing with Digital Earth technologies. Alessandro has 40 years working experience in several domains (forestry, agriculture, oceanology, nature protection, … and more recently on digital economy) dealing with Spatial Planning, Spatial Analysis, Environmental Modelling, Spatial Data Infrastructures, Geo-Information, GIS technologies, Artificial Intelligence, Remote Sensing, Image Processing, System Design, and Software Development. He has participated in several European projects relevant for Geo-Information and Digital Technologies and is author, co-author, and editor of more than 100 papers and books. Since 2006, Alessandro served as co-chair of the Architecture and Data Committee of the Group on Earth Observations (GEO). He co-chaired the GEO Infrastructure Implementation Board and he is now member of the GEO Programme Board. He is a visionary member and Vice President of the International Society for Digital Earth (ISDE). Alessandro has been awarded the 2013 Ian McHarg Medal of the European Geosciences Union reserved for distinguished research in Information Technology applied to Earth and space sciences. In 2016, he received the Digital Earth Science and Technology Contribution Award from the International Society for Digital Earth for outstanding contribution to advancing the development of Digital Earth.

Chapter 1
Understanding Digital Earth

Zhen Liu, Tim Foresman, John van Genderen and Lizhe Wang

Abstract In the two decades since the debut of the Digital Earth (DE) vision, a concerted international effort has engaged in nurturing the development of a technology framework and harnessing applications to preserve the planet and sustain human societies. Evolutionary threads can be traced to key historic and multidisciplinary foundations, which were presciently articulated and represented at the first International Symposium on Digital Earth hosted by the Chinese Academy of Sciences in 1999. Pioneering groups in government, industry, and academia have cultivated this fertile futuristic conceptual model with technological incubation and exploratory applications. An array of space-age developments in computers, the internet and communications, Earth observation satellites, and spatially oriented applications sparked an innovative discipline. The *Beijing Declaration on Digital Earth* is recognized for its role in promulgating the series of International Symposia on Digital Earth to promote understanding of the impacts of DE technology and applications on behalf of humankind. Combinations of industrial, academic, and government organizations have rapidly advanced the technological components necessary for implementing the DE vision. Commercial leaders such as Google have accelerated the influence of DE for large segments of society. Challenges remain regarding requisite collaboration on international standards to optimize and accelerate DE implementation scenarios. This chapter provides an overview of the DE initiative and basic framework, the global response to DE, the evolution of DE, its relationship to key global science initiatives, and the response to global challenges.

Z. Liu (✉)
Secretariat of International Society for Digital Earth, Beijing, China

Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China
e-mail: liuzhen@radi.ac.cn

T. Foresman
International Center for Remote Sensing Education/Earth Party, Elkridge, MD, USA

J. van Genderen
Department of Earth Observation Science, University Twente, Enschede, The Netherlands

L. Wang
School of Computer Science, China University of Geosciences, Wuhan, China

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1.1 The Digital Earth Initiative

Three years after a human first stepped on the moon's surface, the space and information age launched with the Landsat series of Earth observation satellites. Beginning in 1972, Landsat data kick started the big-data epoch by capturing imagery of the whole Earth's surface every two weeks. From these space-age origins, a multitude of technologies have developed to address data storage, preprocessing, classification, interpretation, analysis, integration with computational models, and visualization in digital image processing workflows. Digital image processing has spread across science, medical, computer, gaming, and entertainment fields, creating multitudes of new industries. With the booming development of Earth observation, considered the first wave of big data, massive amounts of digital data about the Earth's surface and near-surface have been collected from an ever-growing constellation of various satellites and sensors. Increased information technology capacity, following Moore's Law, has fostered disruptive changes regarding applications of Earth system data within the scientific community, relevant industries, and by consumer citizens. 'Digital' refers to more than the electronic format of the data in bits and bytes or the automated workflow used to manage the data. The Digital Era encompasses the much wider and greater societal and technological transformations facing humans. "Digital Earth is the inevitable outcome of the space era in the history of information society development" (Chen 2004). Digital Earth captures this phenomenal extension to harness the 'digital' world in which we live.

The concept of Digital Earth, first coined in Al Gore's book entitled "*Earth in the Balance*" (Gore 1992), was further developed in a speech written for Gore at the opening of the California Science Center in 1998. In this speech, Digital Earth was described as a multiresolution and three-dimensional visual representation of Earth that would help humankind take advantage of geo-referenced information on physical and social environments, linked to an interconnected web of digital libraries (Gore 1999). The concept of Digital Earth was further explained as the use of "digital technologies to model Earth systems, including cultural and social aspects represented by human societies living on the planet. The model is a multidimensional, multiscale, multitemporal, and multilayered information system. Digital Earth is envisaged as a common platform to support national and international cooperation for global sustainable development, and a newly developing point of economic growth and social well-being" (International Society for Digital Earth 2012).

Digital Earth theories and relevant technologies have flourished across a range of disciplines and applications worldwide (Chen 1999; Goodchild 1999, 2008; Foresman 2008; Guo et al. 2009; Annoni et al. 2011; Craglia et al. 2012; Goodchild et al. 2012). This momentous turn in the histories of cartography, meteorology, and geography was made feasible by the confluence of enabling information technologies in computational science, mass storage, satellite imagery, broadband networks, interoperability, metadata, and unprecedented 'virtual reality' technologies. Powered by advances in semiconductor devices networked to telecoms, navigation, and Earth observation satellites, a new era of spatially enabled technologies transformed and fused multiple disciplines in the 21st century. As a system of interconnected systems, Digital Earth should be fully empowered with multiple sources of geospatial information, a 3D representation platform of the Earth, and a user interface, and act as the framework that combines these domains. As stated in the *Beijing Declaration on Digital Earth*, "Digital Earth is an integral part of other advanced technologies including: Earth observation, geo-information systems, global positioning systems, communication networks, sensor webs, electromagnetic identifiers, virtual reality, grid computation, etc." (International Society for Digital Earth 2009).

In addition to being a global strategic contributor to scientific and technological developments, Digital Earth was regarded as an approach for "addressing the social, economic, cultural, institutional, scientific, educational, and technical challenges, allows humankind to visualize the Earth, and all places within it, to access information about it and to understand and influence the social, economic and environmental issues that affect their lives in their neighborhoods, their nations and the planet Earth" (International Society for Digital Earth 1999). It is "a catalyst in finding solutions to international scientific and societal issues" (International Society for Digital Earth 2009). Contemporary local and global issues can be characterized as complex and interrelated. Solutions to challenging problems remain elusive under conventional governance. In this dynamic environment, better methods for organizing vast data and managing human affairs are sought at all organizational levels. While not a panacea, Digital Earth has been regarded as the most effective approach, organizing metaphor, or model, to turn raw and disaggregated data into understandable, visualized information to gain knowledge about the Earth and human influence (Goodchild et al. 2012). Consequently, it can aid in the sustainable development of all countries and regions (Chen 2004). Thus, Digital Earth plays "a strategic and sustainable role in addressing such challenges to human society as natural resource depletion, food and water insecurity, energy shortages, environmental degradation, natural disasters response, population explosion, and, in particular, global climate change" (International Society for Digital Earth 2009).

1.2 Basic Framework of Digital Earth

Digital Earth is described as a virtual globe constructed of massive, multiresolution, multitemporal, multityped Earth observation data and socioeconomic data combined with relevant analysis algorithms and models (Goodchild 2013; Grossner et al. 2008). From a scientific point of view, the basic implication of Digital Earth includes two aspects. First, Digital Earth represents a huge data and information system that aggregates and presents data and information related to the Earth. In addition, Digital Earth is a virtual Earth system that can perform reconfigurable system simulations and decision support for complex geoscience processes and socioeconomic phenomena (Guo et al. 2014).

1.2.1 Basic Scientific Problems

The basic scientific problems concerning Digital Earth comprise three aspects:

(1) How to construct Digital Earth provided that we have massive, multiresolution, multitemporal, multitype Earth observation data and socioeconomic data? And how to organize, map, and compute these data to generate the data ecosystem—a harmonious, multidimensional, multiscale, multitemporal, and multilayered information system for Digital Earth?
(2) How to discover knowledge in Digital Earth? Assuming a data ecosystem has been built well, the next task is to compute, analyze, and mine the data for knowledge discovery to understand the Earth system using physical models (e.g., climate change models, Earth system models) or artificial intelligence algorithms (machine learning, data mining, deep learning, etc.).
(3) How to operate and utilize Digital Earth? As various of types of Digital Earth exist, coordinating and operating multiple subsystems of a Digital Earth platform to deliver flexible, efficient and user-friendly service for Digital Earth users and applications is a basic scientific problem.

1.2.2 Theoretical and Methodological Framework

To target the aforementioned scientific problems, we need a theoretical and methodological framework for Digital Earth:

(1) The theory and methodology of Digital Earth construction and implementation

This task is to generate the data and computer systems to produce a basic platform and infrastructure for a Digital Earth. The related theories and methods include remote sensing, geography, cartography, Earth information science, database theory, cloud computing, information networks, software engineering, and information theory.

(2) The theory and methodology of Digital Earth knowledge discovery

This task is to comprise implementation of the change from data to knowledge to understand the Earth system, for example, how Earth has changed, what the next change is and how human activities affect the Earth system. The related theories and methods include information theory, artificial intelligence, data mining, and Earth system science.

(3) The theory and methodology of Digital Earth operation and utilization

This task is to comprise management of the Digital Earth system and a whole and delivery of services to users and applications. The related theories and methods includes software engineering, cloud computing, Earth Information science, visualization, and information networking.

1.3 Global Response to Digital Earth

Responding to the vision for Digital Earth, the US government established a NASA-led Interagency Digital Earth Working Group in 1999 (Foresman 2008). Although this working group lost momentum and government support after 2001, its influence remained, with many stakeholders maintaining keen interest in pursuing this initiative.

1.3.1 International Society for Digital Earth

In 1999, the first International Symposium on Digital Earth to promote Digital Earth as a global initiative was held in Beijing, China, sponsored by the Chinese government and hosted by the Chinese Academy of Sciences. More than one thousand scientists, engineers, educators and governors from nearly 40 countries worldwide attended. The attendees approved a milestone document for the movement, the *1999 Beijing Declaration on Digital Earth*. This symposium laid the foundation for the development of Digital Earth at the global scale, and kicked off the worldwide responses to the Digital Earth initiative.

During the symposium, an International Steering Committee of the International Symposium on Digital Earth was established to organize subsequent symposia in the coming years. In 2006, the International Society for Digital Earth (ISDE) was formally established with the secretariat hosted by the Chinese Academy of Sciences. The ISDE is a nonprofit international scientific organization that principally coordinates and promotes academic exchange, education, science and technology innovation, and international collaboration towards Digital Earth.

Following the 1999 symposium, a symposium has been held every two years at different locations around the world. In addition, since 2006, Digital Earth summits have been added to the biannual symposia schedule to focus on specific academic themes that have been identified as important. After 20 years of development, ten symposia and seven summits have been hosted in 11 different countries. The upcoming symposium will be held in Italy in 2019 and the summit will take place in Russia in 2020.

Important to the professional standing of the ISDE is the addition of an international peer-reviewed academic journal, the *International Journal of Digital Earth*

(IJDE). The highly rated journal is published jointly by the ISDE and the Taylor & Francis Group. Inaugurated in March 2008, the IJDE was accepted for coverage by the Science Citation Index. Expanded in August 2009, the journal had an impact factor of 2.746 in 2018, ranking 13th out of 30 remote sensing journals, and has been included in 12 large international citation databases.

The Digital Earth initiative fits within many global organizations' missions through sharing knowledge and ideas about Digital Earth and seeking global benefits using Digital Earth technology. In 2009, the ISDE joined the Group on Earth Observations (GEO), the world's largest intergovernmental organization on using geospatial data. The ISDE also has established partnerships with the Committee on Data for Science and Technology (CODATA), the International Eurasian Academy of Sciences, the Global Spatial Data Infrastructure Association, and the African Association of Remote Sensing of the Environment. In 2017, the ISDE was recognized as a member of the International Council for Science (ICSU, now is the International Science Council). In August 2019, ISDE becomes a member of the United Nations Committee of Experts on Global Geospatial Information Management—Geospatial Societies (UN-GGIM GS). The ISDE is now widely recognized globally as a leadership organization in geospatial information science research.

1.3.2 Group on Earth Observations' Membership

In 2005, delegations from nearly 60 countries endorsed a ten-year Implementation Plan for the 2005–2015 Global Earth Observation System of Systems (GEOSS) and further established the intergovernmental Group on Earth Observations (GEO) to implement the plan. The ISDE's membership in the GEO guarantees organizational and scientific harmonization with all major international communities.

One of the GEO's missions is to implement GEOSS to "better integrate observing systems and share data by connecting existing infrastructures using common standards" (https://www.earthobservations.org/geo_community.php). "GEOSS is a set of coordinated, independent Earth observation, information and processing systems that interact and provide access to diverse information for a broad range of users in both public and private sectors. GEOSS links these systems to strengthen the monitoring of the state of the Earth. It facilitates the sharing of environmental data and information collected from the large array of observing systems contributed by countries and organizations within GEO. Further, GEOSS ensures that these data are accessible, of identified quality and provenance, and interoperable to support the development of tools and the delivery of information services. Thus, GEOSS increases our understanding of Earth processes and enhances predictive capabilities that underpin sound decision making: it provides access to data, information and knowledge to a wide variety of users" (https://www.earthobservations.org/geoss.php). GEOSS currently contains more than 400 million open data resources from more than 150 national and regional providers such as NASA and ESA, international organizations such as the World Meteorological Organization (WMO), and groups in the commercial sector such as Digital Globe (now Maxar) (https://www.earthobservations.org/geo_community.php).

1.3.3 The Australian Geoscience Data Cube

The Australian Geoscience Data Cube (AGDC) aims to realize the full potential of Earth observation data holdings by addressing the big data challenges of volume, velocity, and variety that otherwise limit the usefulness of Earth observation data. The AGDC is a collaborative initiative of Geoscience Australia, the National Computational Infrastructure (NCI), and the Australian Commonwealth Scientific Industrial Research Organisation (CSIRO). The AGDC was developed over several years as researchers sought to maximize the impact of Land surface image archives from Australia's first participation in the Landsat program in 1979. There have been several iterations, and AGDC version 2 is a major advance on previous work. The foundation and core components of the AGDC are (1) data preparation, including geometric and radiometric corrections to Earth observation data to produce standardized surface reflectance measurements that support time-series analysis, and collection management systems that track the provenance of each data cube product and formalize reprocessing decisions; (2) the software environment used to manage and interact with the data; and (3) the supporting high-performance computing environment provided by the Australian National Computational Infrastructure (NCI) (Lewis et al. 2017).

A growing number of examples demonstrate that the data cube approach allows for analysts to extract rich new information from Earth observation time series, including through new methods that draw on the full spatial and temporal coverage of the Earth observation archives, such as extracting the intertidal extent and topography of the Australian coastline from a 28-year time series of Landsat observations. Sagar et al. outlined an automated methodology to model the intertidal extent and topography of the Australian coastline that leverages a full time series of Landsat observations from 1987 to 2015 managed in the Australian Geoscience Data Cube (AGDC) (Sagar et al. 2017). The Australian Government established a program to improve access to flood information across Australia. As part of this, a project was undertaken to map the extent of surface water across Australia using the multidecadal archive of Landsat satellite imagery. The "initial scoping of the full processing time required for the analysis indicated that one analysis of the entire Landsat archive for surface water was over four years. The analysis as conducted on the AGDC was completed in under 8 h, making it feasible to review and improve the algorithms, and repeat the analyses many times, where previously such an analysis was essentially not feasible" (Mueller et al. 2016).

The AGDC vision is of a 'Digital Earth' (Craglia et al. 2012) composed of observations of the Earth's oceans, surface and subsurface taken through space and time and stored in a high-performance computing environment. A fully developed AGDC would allow for governments, scientists and the public to monitor, analyze and project the state of the Earth and will realize the full value of large Earth observation datasets by allowing for rapid and repeatable continental-scale analyses of Earth properties through space and time. To enable easy uptake of the AGDC and facilitate future cooperative development, the AGDC code is developed under an open source Apache License, version 2.0. This open source approach is enabling other organizations including the Committee on Earth Observing Satellites (CEOS) to explore the use of similar data cubes in developing countries (Lewis et al. 2017). It creates the potential for expansion of the AGDC concept into a network of data cubes operating on large geoscientific and geospatial datasets, colocated in suitable HPC-HPD facilities, to address global and national challenges.

1.3.4 CASEarth Data Bank

The Earth observation community has entered into the era of big data. The CASEarth Data Bank, part of the Project on Big Earth Data Science Engineering (Guo 2018), provides big Earth data infrastructure that focuses on Earth observation data.

With new computing infrastructures, technologies and data architectures, the CASEarth DataBank system aims to meet the data management and analysis challenges that arise from the huge increase in satellite Earth observation data. The CASEarth DataBank system is designed to increase the value and impact of Ready to Use (RTU) products by providing an open and freely accessible exploitation architecture to broaden their applications for societal benefit (Guo 2018).

The CASEarth DataBank system is an intelligent data service platform that provides RTU products from multisource spatial data, especially satellite remote sensing data, and big Earth data analysis methods and high-performance computing infrastructure.

The CASEarth Databank consists of three main parts:

(1) Standardized long time-series RTU products from Earth observation data including (1) Chinese satellite data: ZY, GF, HJ, CBERS, FY, HY, and CASEarth satellites, with spatial resolutions from one km to submeter; (2) Landsat data received by the China Remote Sensing Satellite Ground Station since 1986, with 12 RTU products including digital orthophoto maps, regional image maps, top of atmosphere reflectance, land surface reflectance, top of atmosphere brightness temperature, land surface temperature, normalized difference vegetation index, ratio vegetation index, global environment monitoring index, normalized burnt ratio, normalized difference water index, and pixel quality attribute; and (3) other big Earth data sources: DEM, vector, and social data (He et al. 2015, 2018a, b). These RTU products provide consistent, standardized, multidecadal image data for robust land cover change detection and monitoring across the Earth sciences.

(2) The Software Environment. For the data engine, a databox was developed for time series data management and global tiling. For the CASEarth Data Bank system, a global subdivision grid was designed to effectively manage, organize and use long-term sequential RTU data and facilitate the integration and application analysis of multisource and multiscale geospatial information. The global subdivision grid was designed for RTU data based on the national standard of China (GB/T 12409-2009) (Guo 2018).
The computation engine consists of time series data analysis, computational modeling and data integration, middleware and tool modeling, data-intensive computing technologies, data-driven innovation, advanced manufacturing and productivity. It provides basic data analysis algorithms, a distributed parallel computing mechanism, and intelligent analysis solutions for big Earth data.
The visualization engine aids in data visualization in a pictorial or graphical format. With rich, interactive visuals such as graphs and charts, it is easy to discover insights hidden in the data due to the way the human brain processes information. It enables decision makers to see analytics presented visually. A visualization engine is being developed to better understand the data in the CASEarth Databank.

(3) Infrastructure and services. It provides a high-performance computing environment and services with 50P storage and 2PF computing capability. The infrastructures and systems of datafication for big Earth data include storage, management, computing, optimizing cloudification, architectural features, stateless processing, microservices, containers, open software and inherent orchestration.

1.4 Evolution of Digital Earth

Fundamental changes in society have occurred since the Digital Earth concept was proposed 20 years ago. Along with these social changes, technology advances have been incrementally achieved, resulting in the evolution of Digital Earth.

1.4.1 Visionary Incubation of Digital Earth

Based on command and control technologies, there are several virtual globe platforms, or geobrowsers, with associated visualization applications. Among them, the three major categories are location-based commercial platforms, science platforms based on Earth system sciences, and public platforms oriented towards regional sustainable development and decision support (Guo et al. 2017).

In 2001, based on a 3D Earth geographic teaching software 'Atlas 2000' by Microsoft, an original prototype of the Earth system was developed, which integrated large-scale remote sensing imagery and key point datasets into a global 3D model.

Following that, ESRI launched ArcGIS Explorer, and Google Earth was launched in 2005. These early geobrowsers were supported by geospatial tessellation engines operated within desktop computers using 3D technology. When integrated, these Digital Earth systems allowed for querying, measurement, analysis, and location services based on massive geospatial data (Grossner and Clarke 2007). Since then, a number of virtual globes have been produced, including WorldWind, Skyline Globe, GeoGlobe, and Bing Maps 3D. Keysers (2015) provides comparative descriptions of 23 virtual globes, demonstrating the early breadth of Digital Earth technology. This implies that the technology of virtual globes is not yet completely mature.

In addition, many other countries' governments and institutes have produced Digital Earth platforms for specific research purposes. The Chinese Academy of Sciences started research on a Digital Earth Prototype System in 1999 and released the Digital Earth Science Platform (DESP/CAS) in 2010 (Guo et al. 2009). The Jet Propulsion Laboratory created Eyes on the Earth to visualize in situ data from a number of NASA's Earth orbiting spacecraft (NASA 2009). The Australian government explored Blue Link and Glass Earth to observe and simulate the ocean and explore the top kilometer of the Australian continent's surface and its geological processes. A consortium of Japanese institutes developed the Earth Simulator to support environmental change research (Yokokawa 2002).

In 2011, a group of experts from the International Society for Digital Earth gathered at the "Digital Earth Vision to 2020" workshop in Beijing to discuss the developing trends of Digital Earth. This workshop discussed the achievements of Al Gore's first generation of the Digital Earth vision. Goodchild et al. (2012) indicated that the existing generation of Digital Earth (or Virtual Globes) represented great progress in Gore's vision. In Gore's vision, 3D representation of the Earth tops the list in realization of Digital Earth. 3D technology is derived from computer and 3D graphic technologies supported by the film and video game industries and is involved in the representation of the Earth, hence the name Digital Earth. Digital Earth is regarded as a "disruptive approach to the methods of geospatial analysis and visualization currently employed within the field of GIS that uses a virtual (3D) representation of the globe" and as a spatial reference model to visualize, retrieve, and analyze geospatial data at different levels (Mahdavi-Amiri et al. 2015). Data (including imagery, elevation data, vector data, 3D geometric data, and statistical data) are mostly assigned to discretized and hierarchical cells of the Earth, which is a structure known as Discrete Global Grid Systems (DGGSs) that serves as the backbone of the Digital Earth system (Goodchild 2000; Sahr et al. 2003). The first generation of these systems could also be extended and adapted to different user requirements, i.e., displaying the oceanography, atmosphere, or geomorphology of the surface and near-surface of the Earth. However, some aspects fall short of Gore's vision, such as the exploration of historical and future scenarios of the Earth, as well as limitations in the storage, retrieval, and sharing of the huge amount of collected information related to the Earth, and in visualization of the Earth (Goodchild et al. 2012).

1.4.2 Digital Earth in Support of Data-Intensive Knowledge Discovery

With the tremendous growth of the geospatial data collected from satellite-based and ground-based sensors, a fourth paradigm of science was required to characterize data-intensive knowledge discovery. High-performance computing capacity, international collaboration, and data-intensive analysis using high-end visualization have been developed to deal with the multisource data management hurdles. New awareness of the challenges Digital Earth could face has attracted attention to theoretical and scientific innovations in data-intensive geoscience knowledge discovery methods, massive data convergence and service models, and data-intensive geoscience computing and knowledge discovery (Goodchild 2013).

Various types of observation data represent essential foundations for the development of Digital Earth. Massive amounts of geospatial data including satellite-borne data are being processed, exploited and combined with other massive data sources, and delivered in near-real time to users in highly integrated information products. In the context of the widespread use of massive geospatial data, Digital Earth prototypes, popularly represented by Google Earth, began to use the internet to provide the world with high-resolution digital rendering services beginning in 2005. Google's game-changing Earth tessellation engine enabled the public to realize free and convenient access to conduct geo-spatial inquiry and mapping operations on Earth-related data using their personal computers (Goodchild 2013). The challenges inherent in intensive data provide Digital Earth an opportunity to play a significant role in scientific knowledge discovery.

1.4.3 Digital Earth with Multisource Data

As a complex system, Digital Earth increasingly embraces massive multi-resolution, multitemporal and multitype Earth observation data and socioeconomic data as well as relevant analysis algorithms and models (Guo 2012; Grossner et al. 2008). Data acquisition, organization, analysis and application all reflect the importance and necessity of effectively handling massive volumes of scientific data. With the rapid development of internet, mobile 5G network, and Web 2.0 technologies, significant improvements occurred in the collection of multisource spatial data. The availability of data providers is increasing as digital citizens are no longer limited to government agencies or professional companies. Ordinary civilian users can participate in and cooperate with others to maintain and update geographic information data. The idea that everyone can serve as a data collection sensor has become a reality. Goodchild (2007) termed this new geographical era neogeography. New sources of data from both citizen science and smartphone activity enable the public to become mass providers of data. Concepts that embrace this new public data collection, such as volunteered geographic information (VGI) (Goodchild 2007), crowdsourcing geospatial data (Giles 2006; Howe 2006; Heipke 2010), and generalized geographic information (Lu and Zhang 2014), have been highlighted. Although the concepts vary, all of them emphasize the transformation of geospatial data acquisition. The bottlenecks in acquisition due to reliance on traditional, professional or government mapping have been uncorked using diversified and increasingly accurate active or passive data provided by the public.

The aforementioned "Digital Earth Vision to 2020" workshop led to two scientific papers: *Next-Generation Digital Earth* published in the *Proceedings of the National Academy of Sciences of the United States of America (PNAS)* (Goodchild et al. 2012) and *Digital Earth 2020: Towards the Vision for the Next Decade* published in the *International Journal of Digital Earth (IJDE)* (Craglia et al. 2012). Goodchild et al. (2012) proposed that inevitable new developments in internet communications and API services, multidimensional representation, and Earth observation visualization technologies would accelerate fulfillment of the Digital Earth concept and expand the potential of Digital Earth for all stakeholders. The next generation of Digital Earth is not projected to be a single system and will likely be multiple interconnected infrastructures based on professional standards for open access and horizontal participation across multiple technological platforms. Client-friendly and customized platforms will drive the growth of different audiences. One metaphor proposed Digital Earth as a digital nervous system for the globe, actively informing users about events happening on or near the Earth's surface by connecting to sensor networks and situation-aware systems (Foresman 2010). de Longueville et al. (2010) believed that Digital Earth is a powerful metaphor for accessing the multiscale 3D representation of the globe but, due to its non-self-aware feature, the inclusion of temporal and voluntary dimensions would be more helpful in a description of the real world. Craglia et al. (2012) articulated the main policy, scientific and societal drivers for the development of Digital Earth. These papers help illustrate the multifaceted nature of next-generation Digital Earth. The growth of Digital Earth is predicated in part on emphasizing its usefulness to the public. Continued development and evolution of internet bandwidth and improved visualization techniques can be expected to maintain the growth of Digital Earth applications. Equally important for public applications are social developments and the widespread adoption of social networks, which serve as key ways to communicate and turn citizens into force multipliers as providers of information.

1.4.4 Digital Earth in Big Data Era

Entering the big data era, national and regional governments responded by releasing relevant strategies accordingly. For example, in 2011 the European Commission announced a statement on "Open Data: An Engine for Innovation, Growth and Transparent Governance". In 2012, the United States released the "Big Data Research and Development Initiative" to enhance the capability of knowledge discovery through big data (http://www.whitehouse.gov/sites/default/files/microsites/

ostp/big_data_fact_sheet_final_1.pdf). Australia published "The Australian Public Service Big Data Strategy" in 2013. Subsequently, the Chinese government began emphasizing big data as one of the strategic resources of social development in 2013 and issued the "The Action Plan for Promoting Big Data Development" in 2015, including a proposal for "Developing Science Big Data". In 2012, the UN Global Pulse published "Big Data for Development: Opportunities and Challenges" to promote the significant role of big data in responding to climate changes. The International Council for Science (joined in 2017 with the International Social Science Council to form the International Sciences Council) published their "Strategic Plan 2012–2017", which emphasized the importance of data management in new knowledge discovery.

Big data has created a new computational perspective in the use of continuously collected data from various sources to explore trends in large volumes of data and to better understand world dynamics. Such advances bring great opportunities for Digital Earth to play its visionary role in integrating the massive amount of multidimensional, multitemporal, and multiresolution geospatial data as well as socioeconomic data in a framework for comprehensive analysis and application systems about the Earth.

Digital Earth has evolved into a new connotation of 'big Earth data'. Big Earth data incorporates the litany of powerful tools requisite to understanding and explaining the Earth system and to investigating sustainable global development. It focuses on the synthesis and systematic observation of Earth, as well as data-intensive methods for studying Earth system models with the goal of increasing knowledge discovery. Big Earth data can be expected to promote the Digital Earth vision by connecting multiple satellites and geographical information centers that rely on national spatial infrastructures and high-speed internet to complete the acquisition, transmission, storage, processing, analysis, and distribution of spatial data.

1.5 Relationship with Other Initiatives

1.5.1 Geospatial Information Infrastructures

The United States pioneered the development and implementation of the National Spatial Data Infrastructure (NSDI) in the 1990s. Clearly defined, the NSDI is the sum of the technologies, policies, standards, human resources, and related activities necessary to collect, process, publish, use, maintain, and manage geospatial data from all levels of government, private and nonprofit organizations, and academic communities. The NSDI makes existing and accurate geospatial data more accessible, greatly facilitates the collection, sharing, distribution and utilization of geospatial data, and has played an active role in economic growth, environmental quality and protection, and social progress in the United States.

The NSDI model has been accepted and adopted to fit the needs of many other countries that have implemented their own spatial data infrastructure plans. The federal government of Canada implemented the GeoConnections program in 1999, a national program of partnerships involving the federal government, provincial (district) governments, municipal and local governments, research institutes, universities, and private companies. The main role of GeoConnections is to establish the Canadian Geospatial Data Infrastructure (CGDI) and enable online access to Canadian geospatial databases and services. The CGDI is the sum of the policies, technologies, standards, access systems and protocols necessary to coordinate all geospatial databases in Canada and make them available on the internet. For more than a decade, the implementation of GeoConnections has enabled online access to Canadian geospatial databases and services, and effectively coordinated partnerships, investments and developments between federal, provincial, local government, private and academic communities.

In 2007, the Infrastructure for Spatial Information in Europe (INSPIRE) Directive came into force (https://inspire.ec.europa.eu/about-inspire/563). This directive established a web-based infrastructure to make more visible, shareable and usable environmental and geospatial information necessary to support European environmental policies that affect the environment such as transport, agriculture, and marine policy. INSPIRE is decentralized, i.e., the infrastructure builds on those set up and maintained by the 28 EU member states. It does not require the collection of new data and develops the technical, and organizational arrangements to achieve interoperability among the infrastructures in the member states and among the 34 data themes falling in the scope of the directive. INSPIRE will take more than 12 years to implement, from 2007 when the directive was adopted to 2019–20 and beyond. As this process takes place, it is important to consider the technological and policy developments that will shape the future data infrastructures so that the investments of today are open to the developments of tomorrow.

1.5.2 Earth Observation Program

Earth observation has been become a major part of many countries' environmental and defense programs since the final decades of the last century. Nations were influenced by the Planetary Mission of NASA's Earth Observation Program. The program was developed for the scientific research of the Earth systems. Its goals were to collect sufficient data on the Earth's systems to enable whole planetary assessments and conduct comprehensive research on the Earth. NASA's program consists of three parts: the scientific plan, Earth observation platforms, and data information systems.

A new generation of space-Earth observation continues and has been extended to incorporate observations of the land, atmosphere, ocean, ecosystem processes, water and energy cycles, and solid Earth.

The Global Monitoring for Environment and Security (GMES) program was jointly established by the European Space Agency (ESA) and the European Commission in 2003. The ESA created a series of next-generation Earth observation missions, including the Copernicus program. To meet the operational needs of the Copernicus program, the ESA developed the Sentinel program to replace older Earth observation missions. Each Sentinel mission is based on a paired satellite model to provide datasets for Copernicus Services and focuses on different aspects of Earth observation, including atmospheric, oceanic, and land monitoring.

Earth observations have expanded rapidly around the globe, as demonstrated by the fact that the GEO now has more than 100 member nations. Bringing Earth observation down to Earth with an ever-increasing number of Earth observation satellites with increasing spatial, temporal and spectral resolutions represents a critical data input to the Digital Earth concept.

1.5.3 National/Regional Digital Earth Programs

Dozens of countries such as Australia, China, Japan, Singapore, South Africa, and the European Commission have generated their own Digital Earth-related programs. There has been important progress in these efforts, such as Digital Earth Australia established by the Australia federal government in 2017, the Geoscience Australia Data Cube (supported by the Commonwealth Scientific and Industrial Research Organization, the National Computational Infrastructure, and the National Collaborative Research Infrastructure Strategy of Australia), Digital China promoted by the Chinese government, the Key Laboratory of Digital Earth Sciences established by the Chinese Academy of Sciences, and the IDEAS (International Digital Earth Applied Science Research Center) at Chubu University in Japan, as well as those at several universities with Digital Earth departments or laboratories (e.g., Austria and Malaysia). Some of these are described in detail in Part III of this manual.

1.6 Digital Earth in Response to Global Challenges

Correlated with and a derivative of many sciences dealing with the surface and near-surface of the Earth, Digital Earth was envisioned as an initiative for harnessing the Earth's data and information resources. With powerful tools to quantitatively describe a science-based representation of the planet, Digital Earth could serve as a tool to map, monitor, measure, and forecast natural and human activities. The prowess of the Digital Earth technology was envisioned as requisite to assist nations, organizations, and individual citizens in addressing the problems humans are facing in the 21st century. These challenges for all nations, such as climate change, natural disasters, and sustainable development, require the comprehensive scope and analytical capacity of Digital Earth technology.

1.6.1 Response to Climate Change

Since the middle of the 20th century, large-scale, high-intensity human activities and the rapid growth of the population and social economy have compounded global change problems such as global warming, air pollution, water pollution, land degradation, rapacious resource exploitation, and biodiversity decline. Global change threatens national security and all aspects of our lives, including economic and social development conditions from social, economic, living, and health perspectives. Sustainable development is now recognized as the most serious challenge facing human society.

The United Nations, in partnership with various intergovernmental coalitions, has organized and implemented a series of environmental research programs on global or regional scales, such as the World Climate Programme (WCP), the Man and the Biosphere Programme (MAB), and the International Biosphere Programme (IBP). Within the International Geosphere Biosphere Programme (IGBP), each country is challenged to address the natural resource and environmental issues caused by global change as a primary means to achieve sustainable approaches for socioeconomic development.

Global change is recognized as a significant threat to sustainable development worldwide. To address these multidisciplinary issues at a global scale, global change research faces the unpredicted challenge of obtaining copious data from the interacting subsystems of the Earth for analytical modeling and generating management decisions (Chen 1999; Shupeng and van Genderen 2008). Thus, it is important that Digital Earth facilitates the collection of data from various elements of the Earth system through monitoring the progress of global change in large-scale, long-term sequences, and aids in data processing, analysis, and simulation.

The Paris Agreement, which was negotiated by representatives of 196 countries, was endorsed at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) in LeBourget, France on 12 December 2015. The Paris Agreement's long-term goal is to "strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above preindustrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius." The agreement states the need to "strengthen the ability of countries to deal with the impacts of climate change" as well as reduce the risks and effects of climate change (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement). Under this agreement, starting in the year 2020, a litany of financial policies and new technology frameworks will be put into action to support the realization of greenhouse gas emission mitigation, adaptation, and finance. Increasingly, scientists are documenting that the impacts of temperature increases in the polar regions indicate that our collective actions may be too little, too late.

Big Earth data should provide a wide range of long-term sequences and multiple spatiotemporal scales to cover all of Earth's systems including the atmosphere, cryosphere, hydrosphere, lithosphere, and biosphere. To stock Digital Earth with big

Earth data requires the only known science approach, which is to amass a space-air-ground integrated Earth observation system and a global near-real time, all-weather Earth data acquisition network. Through continuous and long-term monitoring of the Earth system, scientists can use advanced geospatial processing technologies to simulate and analyze Earth's dynamic surface processes and reveal spatiotemporal change mechanisms. Stakeholders will need to formulate scientific strategies and take progressive actions to respond to global change for sustainable development at varying local and regional scales. In this sense, big Earth data provides strong support to the Digital Earth vision, which will hopefully strengthen new approaches to global change research.

1.6.2 Response to the UN SDGs

In September 2015, the United Nations General Assembly adopted "Transforming our World: The 2030 Agenda for Sustainable Development" (United Nations 2015). This international milestone provides a blueprint for action for all countries and stakeholders. This agenda defines 17 Sustainable Development Goals (SDGs) and 169 targets and creates a global indicator framework until 2030. The 2030 Agenda for Sustainable Development provides a new insight into the global actions and transformative policies necessary to guide our collective pursuit of sustainable development.

Achieving sustainable development presents all countries with a set of significant development challenges. These challenges are inherently embedded with spatial-temporal complexities, that is, they are almost entirely geographic in nature. Many of the structural issues impacting sustainable development goals can be analyzed, modeled, and mapped using Earth observation data, which can provide the integrative and quantitative framework necessary for global collaboration, consensus and evidence-based decision making.

Digital Earth is closely interrelated with the global sustainable development challenges and processes, as evidenced through national Earth observation agencies' efforts to connect and integrate big Earth data into the application of many social and environmental programs. Earth observation data provide a substantial contribution to the achievements of the SDGs in support of decision making by monitoring impacts and results, improving the standardization of national statistics, addressing cross-cutting themes such as climate and energy, and facilitating countries' approaches to working across different development sectors (Anderson et al. 2017).

At the United Nations World Geospatial Information Congress (UNWGIC) held in Deqing, Zhejiang Province in China from 19 to 21 November 2018, attention was paid to strengthening national geospatial information management and systems and national implementation of the 2030 Agenda for Sustainable Development (https://www.unwgic2018.org/). It has become important to the science and governance communities to understand, analyze and discover knowledge from huge geospatial data resources. This must be accomplished in a collaborative way among nations to effectively address local, regional, and global challenges and to share big Earth data worldwide as prerequisites to meet the requirements of sustainable development.

Effective transfer of all relevant technologies and Earth-related data represents an important challenge (Scott and Rajabifard 2017). However, under the Digital Earth framework, there are immense opportunities for digital transformation and sharing of resources. Achieving sustainable development will entail significant advances in overcoming political and technical bottlenecks to smooth the digital divide. Internet-based infrastructure with advancing 5G communication shows promise for expanding Digital Earth technologies to all nations.

1.6.3 Response to Disaster Mitigation

Addressing natural and human-caused disasters remains the highest priority of all nations. Climate change experts are in agreement that global warming will increase the frequency and intensity of storms and disruptive weather patterns. Therefore, application of the Digital Earth framework and technology for disaster response and mitigation is of paramount importance.

Recently, the Sendai Framework for Disaster Risk Reduction 2015–2030 (Sendai Framework) was adopted by the UN member states in March 2015 at the World Conference on Disaster Risk Reduction held in Sendai, Japan, and endorsed by the full UN General Assembly in June 2015. This 15-year development framework agenda contains seven targets and four priorities for action. The United Nations International Strategy for Disaster Reduction (UNISDR) has been tasked with supporting the implementation, follow-up and review of the Sendai Framework. The framework's central aim is to "reduce disaster risk… and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries" with the efforts of local governments, the private sector and other stakeholders within a voluntary, nonbinding agreement (https://www.unisdr.org/we/coordinate/sendai-framework).

Notably, disaster-related applications have been prominent since the inception of the Digital Earth community. Chen's (2004) comprehensive review of Digital Earth science in China includes examples of research on flood, coastal, river, and other disasters. The International Society for Digital Earth has sponsored or cosponsored many disaster-oriented workshops and symposia. Importantly, the collaboration with UNISDR, GEO and CODATA and other international associations has been anchored by the common commitment to collaboration and focus on applications for disaster response. Chapter 15 addresses these applications.

1.7 Conclusions/Structure of the Manual

In this manual, the Digital Earth vision has been introduced in the first chapter. Part I has eleven chapters about various Digital Earth technologies; Part II has seven chapters describing the role of Digital Earth in multidomain applications; and Part III contains four chapters showing how the Digital Earth concept has developed from Al Gore's original vision to its current implementation as employed around the world through four regional/national chapters of the International Society for Digital Earth. Part IV considers Digital Earth education and ethics. The concluding chapter of this Manual of Digital Earth describes some of the key challenges and future trends for the development of Digital Earth over the coming years.

Digital Earth is an evolving concept that is strongly influenced by the evolution of technology and the availability of new data. In a couple of years, the Earth will be revisited several times a day by the new generation of satellites, and real-time observation will no longer be a chimera. As we look to the future, it is unlikely that a unified vision of Digital Earth will capture all the perspectives of all stakeholders. A one-size-fits-all Digital Earth would not be appropriate for all nations and cultures. The current social and technological trends expressed in the literature prescribe a robust and comprehensive list of likely characteristics for an updated version for Digital Earth, which closely follows the original vision. There will be a series of connected perspectives of Digital Earth based on varying priorities and applications of the same framework data sources operating with different user-specified functionalities. In the future, the concept and vision of Digital Earth will evolve with the development of science and technology.

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Zhen Liu received her Ph.D. degree in Cartography and Geographical Information System from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. She is now the Executive Director of the secretariat of the International Society for Digital Earth and the Managing Editor of the *International Journal of Digital Earth*.

John van Genderen is a Professor from the ITC, who has been involved in Digital Earth since the first ISDE Symposium in Beijing in 1999. His main research is in Remote Sensing Image Fusion, and in transfer of technology to Less Developed countries. He has carried out EO projects in some 140 countries.

Lizhe Wang is a "ChuTian" Chair Professor at School of Computer Science, China University of Geosciences (CUG). Prof. Wang received B.E. & M.E. from Tsinghua University and Doctor of Eng. from University Karlsruhe (Magna Cum Laude), Germany. His main research interests include remote sensing image processing and spatial data processing.

Part I
Digital Earth Technologies

Chapter 2
Digital Earth Platforms

Troy Alderson, Matthew Purss, Xiaoping Du, Ali Mahdavi-Amiri and Faramarz Samavati

Abstract In this chapter, we provide a thorough discussion on Digital Earth with particular focus on Discrete Global Grid Systems (DGGS), which are a standardized representation of the Earth. We describe the necessary components of a DGGS, such as the underlying 2D representation, indexing system, projection, and cell types. We also discuss a selection of well-known public and commercial DGGSs followed by current DGGS standards.

Keywords Discrete Global Grid · OGC Standard · Digital Earth

2.1 Introduction

Digital Earth is a framework for geospatial data management. In this model, data are assigned to locations on a 3D model of the Earth and analyzed at multiple resolutions, each representing data at a specific level of detail. To locate and retrieve data sets associated with the Earth, mechanisms are needed for data representation, region addressing, and the assignment and retrieval of data for a region of interest. Digital Earth provides a reference model that can handle all of these queries.

T. Alderson · F. Samavati
Department of Computer Science, University of Calgary, Calgary, Canada
e-mail: tfalders@ucalgary.ca

F. Samavati
e-mail: samavati@ucalgary.ca

M. Purss
Geoscience Australia, Canberra, Australia

X. Du
Key Laboratory of Digital Earth, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China

A. Mahdavi-Amiri (✉)
Department of Computing Science, Simon Fraser University, Burnaby, Canada
e-mail: amahdavi@sfu.ca

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Two main approaches have arisen for the creation of a Digital Earth: Discrete Global Grid Systems (or DGGSs for short), and datacubes. In a DGGS, the surface of the Earth is discretized into a set of highly regular spherical/ellipsoidal cells. These cells are then addressed using a data structure or indexing mechanism that is used to assign and retrieve data. Datacubes are n-dimensional arrays that store geospatial data, ordered according to various attribute/coordinate axes, which can be spatial or non-spatial in nature.

In this chapter, we focus particularly on Discrete Global Grid Systems, which have global scope, more readily support interoperability than datacubes, are generally compatible with conventional datacube approaches, and can be used to provide the back-end support for a datacube implementation (Purss et al. 2019). The following section discusses DGGS as well as its components and their characteristics in detail.

2.2 Discrete Global Grid Systems

The traditional approach to discretizing the Earth is to use a latitude/longitude coordinate system on a sphere (Cozzi and Ring 2011), in which the 2D domain (or planar map of the Earth) is partitioned into a grid of cells by discretizing the 2D latitude/longitude domain. These cells may be further subdivided to increase the resolution and mapped to the sphere through the use of spherical coordinate equations and/or an appropriate spatial projection. The resulting spherical cells are primarily quadrilateral, though singularities and triangular cells appear at the poles, and the areas of the cells vary according to the latitude.

In order to better represent the Earth with more uniform cell structures, a polyhedron with the same topology as the sphere can be used. With an initial discretization of the Earth into planar cells (typically produced by considering the planar faces of an approximating polyhedron), the initial cells may then be refined to an arbitrary resolution and mapped from planar cells to spherical cells via some projection method (see Fig. 2.1). Given a regular refinement, a multiresolution hierarchy between cells (in which each cell has a coarser resolution parent and a number of finer resolution

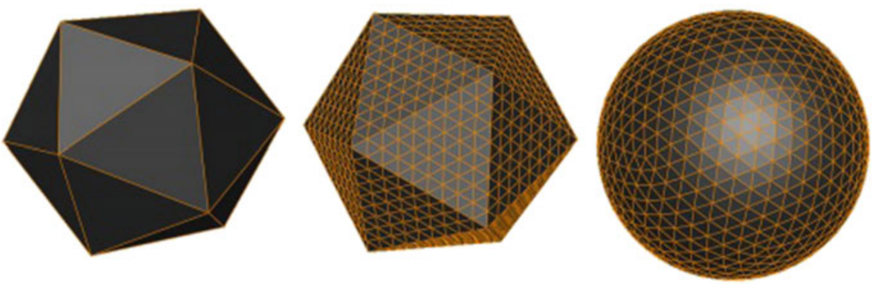

Fig. 2.1 An initial polyhedron that has been refined and projected onto the sphere

children) with a semiregular cell structure can be systematically defined. To query and render cells, they are then typically addressed via an indexing mechanism.

DGGSs are defined in terms of several different components. The main components of a DGGS include the initial planar or piecewise domain, cell type, projection, indexing, and refinement. In the following, we discuss each of these components in more detail in the context of DGGS construction.

2.2.1 Initial Domain

The simplest domain for a DGGS is a 2D map of the Earth, of which latitude/longitude grids are the standard. As these tend to exhibit large distortions across the globe and singularities at the poles, complicating queries and data analysis, a spherical polyhedron can instead be used for the initial domain of a DGGS. Such DGGSs are also known as Geodesic DGGSs (Sahr et al. 2003).

The most common choices for an initial polyhedron are the platonic solids—the tetrahedron, cube, octahedron, dodecahedron, and icosahedron—in addition to the truncated icosahedron. Each of these polyhedra offers distinct benefits. For instance, the octahedron defines a simple and symmetric domain, and can be unfolded into a very simple quadrilateral domain. Cubes are made of quadrilateral facets that are appropriate for the generation of quadrilateral cells. In comparison to other polyhedra, the icosahedron and truncated icosahedron undergo less angular distortion when processed through an equal area projection (Snyder 1992).

2.2.2 Cell Type

There are three main cell types that are used in a DGGS: hexagonal, triangular, and quadrilateral. If the initial domain is a polyhedron, other extraordinary cell types may be present, such as pentagons in a truncated icosahedron. However, the number of extraordinary cells is fixed no matter the resolution. Each of the three main cell types presents some advantages over the others that ought to be considered when selecting the base cell of a DGGS. For instance, quadrilateral cells are congruent, compatible with Cartesian coordinate systems, easy to index, and compatible with standard rendering libraries. Triangular cells are planar, easy to use, compatible with standard rendering techniques and libraries, and congruent. Hexagonal cells are the best for sampling, with the smallest quantization error, and they have uniform adjacency. Depending on the initial domain of a DGGS and the application that the DGGS was designed for, any of these types of cells can be employed as the DGGS cell type.

2.2.3 Refinement

Refinements are used to produce finer cells from an initial set of coarse cells. In a DGGS, they can be used to construct cells at multiple resolutions on the sphere by refining the faces of a polyhedron. Refinements are in part characterized by a ratio known as the aperture, or factor, of the refinement. This ratio relates the number of coarse cells to the number of fine cells at the next resolution, and several different apertures have been employed in DGGSs. After applying a refinement, the resulting fine cells may be assigned to a coarse *parent* cell as *children* of that cell, producing a hierarchical structure that is useful for many grid and spatial processing operations. Traversing from a parent cell to its children or from a child to its parent is known as hierarchical traversal.

In addition to the factor of refinement, other aspects play an important role in characterizing a refinement, such as congruency and alignment. In a congruent refinement, a coarse cell encompasses precisely the same area as a union of finer cells at the next resolution (see Fig. 2.2). For example, the 1-to-4 quadrilateral refinement shown in Fig. 2.2a is congruent while the 1-to-3 hexagonal refinement shown in Fig. 2.3b is not. Assigning a set of fine cells to serve as the children of a coarse cell is trivial in congruent refinements, as children are uniquely covered by a single parent cell and, therefore, the handling of hierarchical traversal queries is simplified. In contrast,

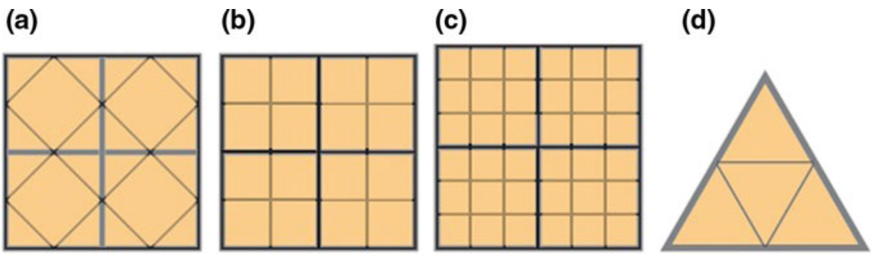

Fig. 2.2 (**a**) A center-aligned 1-to-2 refinement that is not congruent. (**b**) A vertex-aligned and congruent 1-to-4 refinement. (**c**) A center-aligned and congruent 1-to-9 refinement. (**d**) A center-aligned and congruent 1-to-4 refinement for triangles. The boundaries of coarser cells are highlighted using thicker lines

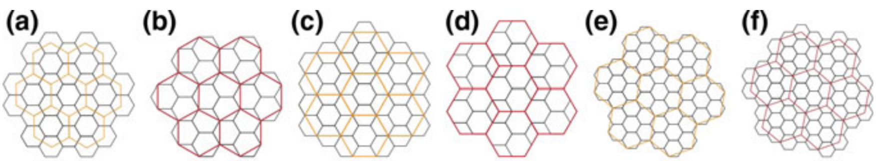

Fig. 2.3 (**a**) Center-aligned and (**b**) vertex-aligned 1-to-3 refinements. (**c**) Center-aligned and (**d**) vertex-aligned 1-to-4 refinements. (**e**) Center-aligned and (**f**) vertex-aligned 1-to-7 refinements. Note that each of these refinements is incongruent

incongruent refinements create ambiguity in the assignment of a child to a coarse cell, since there may exist several potential parents for a fine cell (Fig. 2.3).

If, after applying a refinement, every coarse cell shares its centroid with a fine cell, then that refinement is called center-aligned. Any DGGSs that employ such refinements are likewise called center-aligned. If such a property does not hold for the refinement, then it is usually vertex-aligned, meaning that the parent and child cells share a vertex (Fig. 2.2).

Various types of refinements exist for quadrilateral, triangular, and hexagonal DGGS cells. However, whereas many different refinements have been employed in DGGSs based on quadrilateral and hexagonal cells, DGGSs represented using triangular cells generally use 1-to-4 refinements (see Fig. 2.2d). Quadrilateral refinements can be congruent whilst hexagonal refinements never are (see Fig. 2.3). Consequently, parent-child relationships must always be explicitly defined in a hexagonal DGGS. However, once defined, this becomes a static feature of the DGGS infrastructure, allowing for consistent hierarchical traversal of the grid system, and incongruent refinements still exhibit characteristics that can be useful in a DGGS. Hexagonal 1-to-3 refinement has the lowest aperture of all hexagonal refinements; while hexagonal 1-to-4 refinement produces rotation-free lattices at all levels of resolution (simplifying hierarchical analysis in contrast to other refinements). Of the refinements shown in Fig. 2.3, fine cells in the 1-to-7 refinement cover the hexagonal coarse shape better than other refinements, and therefore more closely resemble congruency and provide a simpler hierarchical relationship between the cells. As a result, there is growing interest in this type of refinement (Middleton and Sivaswamy 2005).

2.2.4 Projection

Projections have traditionally been used to create maps of the Earth. Various forms of projection can be used to flatten the Earth (usually treated as spherical), and these can be categorized into different types, such as conformal, gnomonic, or equal area (Grafarend et al. 2014). When a spherical projection is used, some unavoidable distortions appear that one may try to reduce. In the following, we discuss several spherical projections in more detail.

2.2.4.1 Traditional Cartography

In traditional cartography, a spherical projection is a transformation from a point on the Earth (a sphere) to a point on a 2D map. Such a projection can be represented as a function: $P' = F^{-1}(P)$, where P lies on the sphere, and P' lies on the 2D map (see Fig. 2.4). The simplest method that can be used to create a 2D map from a spherical representation of the Earth is to use spherical coordinates $((\theta, \varphi))$. Doing so involves cutting the Earth (e.g. along a meridian) and unfolding it to form a 2D square, with θ (the longitude) and φ (the latitude) serving as the two main axes of

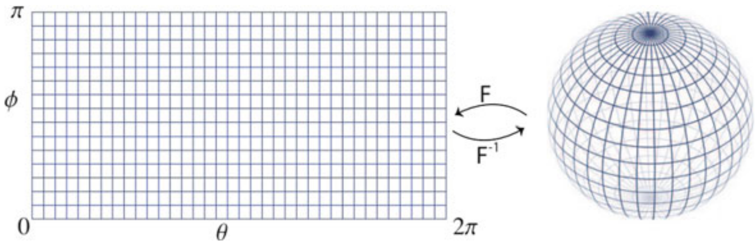

Fig. 2.4 2D domain and its corresponding sphere

the 2D domain. This 2D domain and its corresponding sphere are related through the following equations:

$$F(\theta, \varphi) = \begin{pmatrix} Rcos(\theta)\sin(\varphi) \\ Rsin(\theta)\sin(\varphi) \\ Rcos(\theta) \end{pmatrix}$$

$$F^{-1}(x, y, z) = \begin{pmatrix} \theta \\ \varphi \end{pmatrix} = \begin{pmatrix} tan^{-1}\left(\frac{y}{x}\right) \\ cos^{-1}\left(\frac{z}{R}\right) \end{pmatrix}$$

where R is the radius of the sphere: $R = \sqrt{x^2 + y^2 + z^2}$.

As can be observed from Fig. 2.4, perfect squares on the 2D domain are mapped to distorted quadrilateral or even triangular cells (at the poles) on the sphere. In order to reduce different distortions, it is possible to define alternative mappings, which can be equal-area, conformal (angle-preserving), or possibly stretch-preserving. Since the purpose of a DGGS is to use planar or piece-wise planar (i.e. polyhedral) domains to sample the spherical surface of the Earth, the use of an equal-area projection (in which data values sampled from the Earth occupy similar areas in the DGGS) is often desired (White et al. 1992). Here, we describe some of the most commonly used equal-area projections. There are several traditional options, such as the projections proposed by Lambert (cylindrical and azimuthal), Mollweide, and Werner (see Fig. 2.5) (Snyder 1992).

Among these projections, the Lambert azimuthal equal-area projection is particularly interesting, since it serves as the base projection for a number of equal-area polyhedral projections. In this projection, a point P on the sphere S is projected to a point P' on the 2D domain (2D map). To find P', a plane ρ which is tangent to S at another point C is used. Then, P' is the intersection of ρ with a circle that has its origin at C, passes through P, and is perpendicular to ρ (see Fig. 2.6). Note that the antipode of C (i.e. the point diametrically opposite C) is excluded from the projection as its intersecting circle is not unique. In addition, C is projected to itself along a circle of radius 0. This projection and its inverse can be explicitly described using simple mappings:

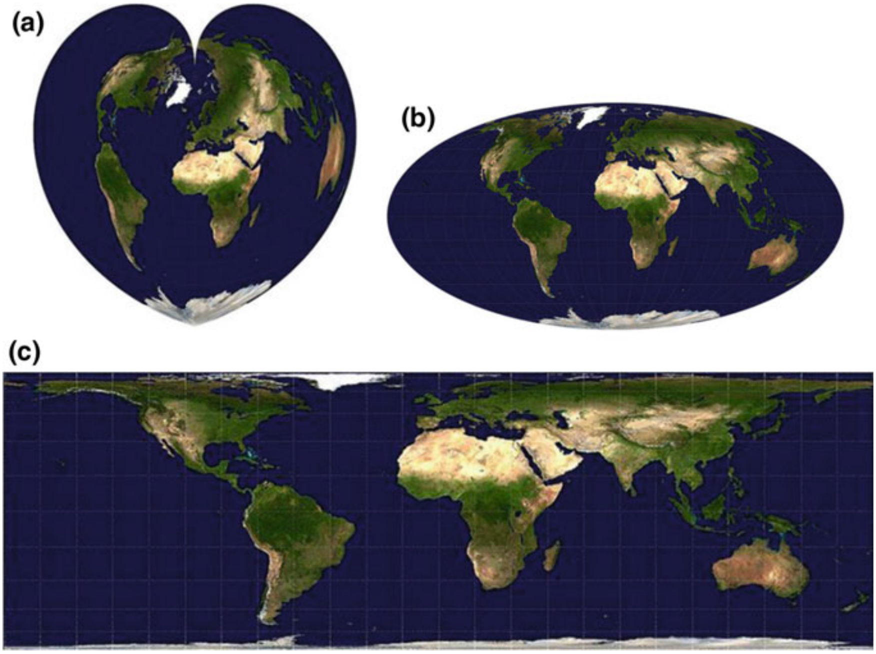

Fig. 2.5 (**a**) Werner, (**b**) Mollweide, and (**c**) Lambert (cylindrical) projections

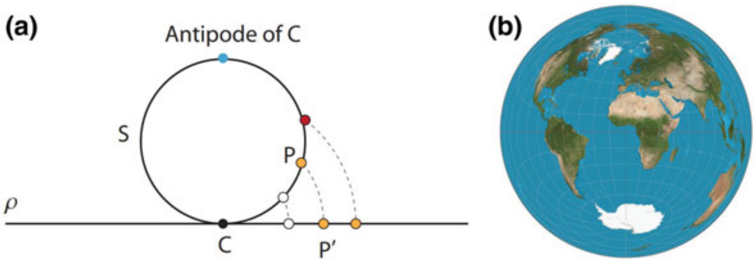

Fig. 2.6 (**a**) Lambert projection from sphere S to plane ρ. (**b**) 2D domain of the Earth resulting from Lambert Azimuthal equal-area projection. The second image is taken from Wikipedia

$$F(x, y, z) = \left(\sqrt{\frac{2}{1-z}}x, \sqrt{\frac{2}{1-z}}y\right),$$

$$F^{-1} = \left(\sqrt{1-\frac{X^2+Y^2}{4}}X, \sqrt{1-\frac{X^2+Y^2}{4}}Y, -1+\frac{X^2+Y^2}{2}\right).$$

2.2.4.2 Projection for Polyhedral Globes

A projection defined for a given polyhedron is characterized by a function F that maps each point P on the sphere to a face of the polyhedron. Consequently F^{-1} is defined as a function that maps points on the polyhedron to the sphere. Often, in order to construct these projections, a traditional projection defined between the sphere and a plane is used individually on each face. For instance, Snyder's equal-area projection (which is commonly used in DGGSs) employs Lambert azimuthal equal-area projection individually for each face. The problem is reduced to projection for right triangles by splitting the faces of the polyhedron along lines of symmetry (see Fig. 2.7). A scaling factor is then found between the radii of two spheres: one with the same area as the (spherical) polyhedron, and another that circumscribes the polyhedron. Finally, a triangle on the polyhedron (whose area matches that of the corresponding spherical triangle that encompasses point P) is generated. The final equation for Snyder's projection is presented in closed form as:

$$x = \rho \sin(Az'),$$

$$y = \rho \cos(Az'),$$

in which the ratio ρ and angle Az' are defined in terms of a set of trigonometric functions and known constants that are provided in (Snyder 1992).

While the forward form of the Snyder projection is presented in a simple closed form, its inverse calculation requires finding the roots of a nonlinear equation (Snyder 1992). Snyder suggests the use of the Newton-Raphson iterative technique to compute the inverse projection, which can slow down the process of mapping points from the polyhedron to the sphere. To reduce this inefficiency, Harrison et al. (Harrison et al. 2011, 2012) worked to optimize the inverse Snyder projection by providing initial estimates to the Newton-Raphson technique that are close to the roots of the nonlinear

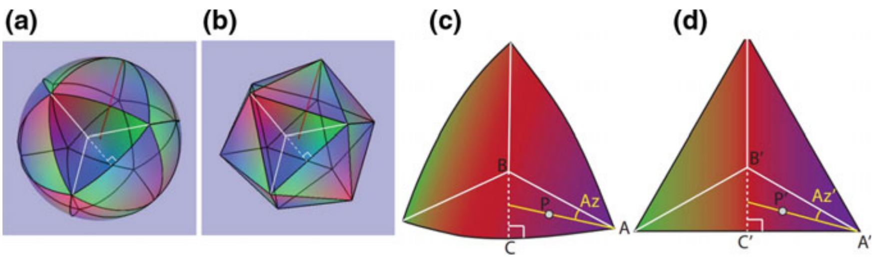

Fig. 2.7 An icosahedron (**a**) after and (**b**) before projection to the sphere. (**c**) The projection operates on right triangles by splitting the initial triangles. Each spherical triangle is associated with a triangle of the polyhedron. Each point P in (**c**) is associated with some point ṕ in (**d**). Az' is the angle between A and the great circle arc passing through P and A

equation. These initial estimates are found using a polynomial curve that fits the roots of the non-linear equation.

In addition to Snyder's projection, other types of equal-area projection have also been used in DGGSs. For instance, Roşca and Plonka's projection (Roşca and Plonka 2011) was used in the one-to-two Digital Earth, which is a cube-based Digital Earth (Mahdavi-Amiri et al. 2013), and extended to the octahedron in (Roşca and Plonka 2012). This equal-area projection describes a mapping from a cubic domain Ω to a spherical domain Δ. The main idea behind this projection is to map each face f of Ω onto a partition of Δ. To this end, an intermediate domain, called a curved square, is used. As a result, the projection involves two steps. First, f is mapped to a curved square on the tangent plane of Δ, parallel to f, using an equal-area bijection denoted by T. Then, the curved square is mapped to a partition of Δ using inverse Lambert azimuthal equal-area projection, denoted by F^{-1} (Fig. 2.8).

HEALPix (see Fig. 2.9) is also a cube-based equal-area projection, and is a hybrid projection of Lambert cylindrical equal-area projection and Collignon pseudo-cylindrical equal-area projection (Gorski et al. 2005). Lambert cylindrical projection is used for equatorial regions of the Earth while Collignon is used for the polar regions.

These equal-area projections are not the only projections that can be used in a DGGS but are examples of projections that have been used already. Naturally, a DGGS designer should always use a projection suited to the needs of their application.

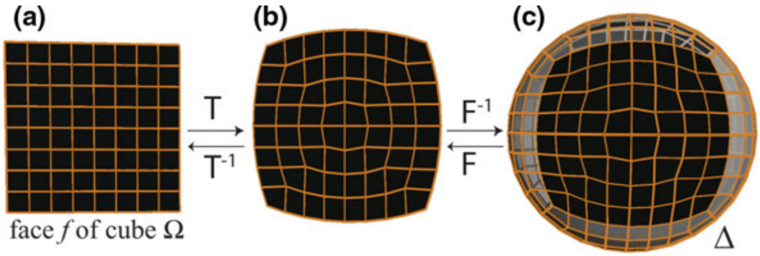

Fig. 2.8 Steps of the spherical projection. Points on a face f of Ω (**a**) are projected onto a curved square (**b**) and then projected onto a portion of the unit sphere Δ (**c**)

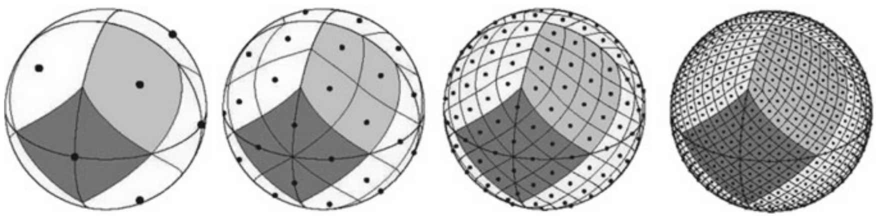

Fig. 2.9 HEALPix projection at four successive resolutions

2.2.5 Indexing

In order for a Digital Earth to handle queries related to location-based data efficiently, a hierarchical approach to data storage is needed. Hierarchical data structures such as quadtrees have been used in various Digital Earth frameworks (Fekete and Treinish 1990; Tobler and Chen 1986), but are typically shelved in favor of indexing methods in order to avoid the cost of expensive tree structures that record node dependencies. Given an indexing method for a DGGS, the method must ensure that, at each resolution, each cell receives an index that uniquely identifies the cell. This index may then be used with reference to a data structure or database in order to retrieve data associated with the cell.

Although various types of methods exist to index the cells of a DGGS, they are typically derived from three types of general indexing mechanisms: hierarchy-based, space-filling curve-based, and axes-based. In the following, we describe each category and provide some examples.

2.2.5.1 Hierarchy-Based Indexing

Applying refinements to a polyhedron produces a hierarchy that can be used to index cells. When a refinement is applied to a set of coarse cells, fine cells are created and assigned to coarse cells through a parent-child relationship. It is possible to use this relationship to define an indexing system by assigning an initial index to each cell at the first (i.e. lowest) resolution, and then using each cell's index as a prefix to the indices of its children. Formally, if a coarse cell has index $Id_0d_1 \ldots d_{r-1}$, then its children receive indices of the form $Id_0d_1 \ldots d_{r-1}d_r$, where d_r is an integer whose range is known as the base of the indexing method, denoted by b (i.e. $d_i \in [0, b-1]$).

The base is used to define algebraic operations on indices, such as conversion to and from the Cartesian coordinate system, or neighborhood finding (Tobler and Chen 1986; Vince and Zheng 2009). Hierarchy-based indexing is very efficient in supporting hierarchical queries, although neighborhood-finding tasks may require complex algorithms, depending on the base of the indexing method and the algebra defined for the indexing system. An example of this type of indexing was proposed in (Gargantin 1982) for quadrilateral cells resulting from 1-to-4 refinement (see Fig. 2.10). Here, the children resulting from 1-to-4 refinement on a quadrilateral with index I receive indices I_0, I_1, I_2, I_3.

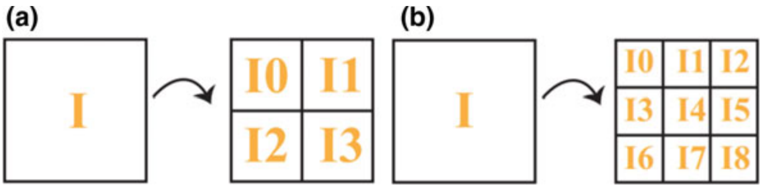

Fig. 2.10 Hierarchy-based indexing systems in (**a**) base four and (**b**) base nine

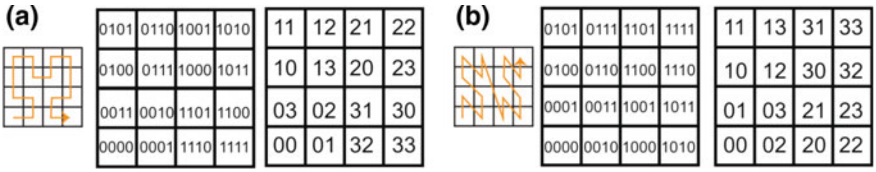

Fig. 2.11 (**a**) (Left) Hilbert SFC. (Middle) Indexing in base two. (Right) Indexing in base four. (**b**) (Left) Morton SFC. (Middle) Indexing in base two. (Right) Indexing in base four

2.2.5.2 Space-Filling Curve Indexing

Another method for indexing cells in a DGGS is to use a space-filling curve (SFC) as a reference for the indexing (Mahdavi-Amiri et al. 2015b). SFCs have been used in many applications, such as compression, rendering, and database management, and are 1D curves (often recursively defined) that cover a particular space.

Recursively defined SFCs start from a simple initial geometry defined on a simple domain (usually a square). The domain is then refined and the simple geometry is repetitively transformed to cover the entire refined domain. Typically, if the initial geometry covers i cells, a 1-to-i refinement is suitable for use in generating a refined domain. In this way, each SFC is associated with a refinement. To index cells based on an SFC, decimal numbers can be employed, though the corresponding indices do not directly encode the resolution. To resolve this issue and obtain a compact indexing, a base b for the indexing that is compatible with the refinement is often chosen. With a 1-to-i refinement, this usually means that the base of the indexing method is taken to be i or $\sqrt{i}$ (see Fig. 2.11). For instance, the refinement associated with the Hilbert and Morton curves is 1-to-4. Therefore, when using a Hilbert and Morton curve, a base four or base two indexing is appropriate.

Indexing methods derived from SFCs have been widely used in DGGS and terrain rendering. For instance, in (Bai et al. 2005; White 2000), Morton indexing was used to index cells resulting from 1-to-4 refinements on the icosahedron and octahedron, while in (Bartholdi III and Goldsman 2001), the Sierpinski SFC was used to index triangular cells refined with a factor of two.

2.2.5.3 Axes-Based Indexing

Another mechanism for indexing is to use a coordinate system with m axes, U_1 to U_m, that span the entire space on which the cells lie. Then the cells' indices can be expressed as m-dimensional vectors $(i_1, i_2, \ldots, i_m)$, in which the i_j are integer values that indicate the number of unit steps taken along each axis, U_j. If, alternatively, a 1D

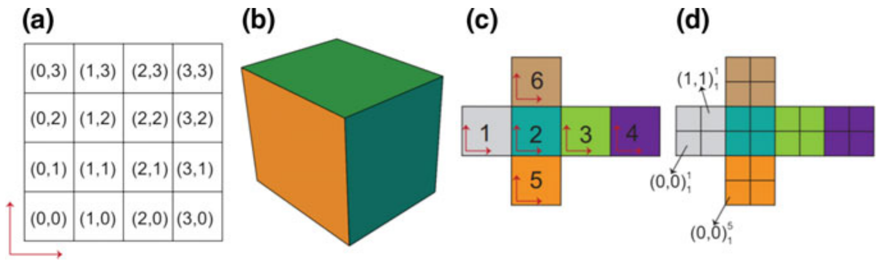

Fig. 2.12 (**a**) Integer indexing of cells using Cartesian coordinates. (**b**) A cube. (**c**) The unfolded cube in (**b**) and coordinate systems for each face. **d** Indices of some cells after one step of 1-to-4 refinement

index is required, these integer values can be appended together in a string, separated using a delimiter character. A simple example of such an indexing can be used to index a quadrilateral domain with Cartesian coordinates, as illustrated in Fig. 2.12a. When a refinement is applied to the cells, a subscript r is appended to the index in order to encode the resolution. In the proposed axes-based indexing methods for DGGSs, m is typically taken to be two or three. For instance, 3D indexing was used in (Vince 2006) by taking the barycentric coordinate of each cell to be its index.

A 2D indexing method can be applied on the polyhedron used to construct a DGGS by embedding the polyhedron's faces into a 2D domain and defining a coordinate system over that domain (Mahdavi-Amiri and Samavati 2012). In this way, each face can be given its own coordinate system (Mahdavi-Amiri et al. 2013, 2015a; Mahdavi-Amiri and Samavati 2014). Figure 2.12 illustrates an indexing for the quadrilateral cells of a cube after 1-to-4 refinement, where each face has its own coordinate system. In order to distinguish between the cells associated with each face, an additional component that refers to the initial polyhedral face can be added to the indices. For example, index $(a, b)_r^f$ refers to cell (a, b) in face f at resolution r (Fig. 2.12d).

2.2.5.4 Remarks on Categorization

Note that this categorization of index types is primarily intended to reflect the core idea used to construct the indexing methods and can be used to easily identify which operations can be handled naturally by a particular indexing system. For example, hierarchy-based indexing methods naturally lead to efficient hierarchical traversal operations. However, well-designed indexing methods must necessarily also consider other properties and support other operations. For example, it is certainly possible to handle neighborhood finding in hierarchy-based indexing methods, although not as efficiently or as naturally as with axes-based techniques. Based on the pattern of indices, some indexing methods can be interpreted as belonging to two categories (e.g. SFC or hierarchy-based). However, an indexing method is either constructed through use of a parametrized curve or it inherits the index of its parent. It is possible to use a parametrized SFC that indexes the children and prefixes the parent's index.

This indexing method is considered to be SFC-based, since the construction of the indexing is based on the parametrization of the SFC and not on the hierarchy of the cells.

2.3 Scientific Digital Earths

Now that we have discussed the various components that define different DGGSs, let us examine some specific DGGS constructions that have been proposed in the literature. Note that some proposed DGGSs are left for the following section, in which we survey some of the existing Digital Earth implementations.

Among the earliest proposed DGGSs are those designed by Digital Earth pioneers M. Goodchild and G. Dutton. Goodchild's HSDS (Hierarchical Spatial Data Structure (Goodchild and Shiren 1992)) is built upon an initial octahedron. Unlike many other DGGSs, the faces of this octahedron are inverse projected to the sphere before the generation of finer cells, and the refinement (a congruent, 1-to-4 refinement) is applied directly on the resulting spherical triangles (using geodesic rather than Euclidean midpoints). The child cells are also spherical triangles, and are indexed using a hierarchical base-4 numbering scheme (see Fig. 2.13). Unfortunately, the projection implied by the refinement method is neither equal-area nor conformal.

Dutton's QTM (Quaternary Triangle Mesh (Dutton 1999)) is also constructed using congruent 1-to-4 refinement on an initial octahedron but utilizes the more typical refine-then-project approach (see Fig. 2.14). Here, the employed projection is a specially designed projection that is also neither equal-area nor conformal—the ZOT (Zenithal Orthotriangular Projection (Dutton 1991))—which tries to have similar facets with vertices spaced uniformly in latitude and longitude, as well as low areal distortion. Indexing is performed similarly to the HSDS, with the faces of the initial octahedron indexed 1 through 8, and child cells indexed hierarchically in base 4.

SCENZ-Grid (SEEGrid 2019) is a DGGS that is constructed based on an initial cube polyhedron, and which was created through a collaboration between Landcare Research and GNS Science primarily for the purpose of environmental monitoring.

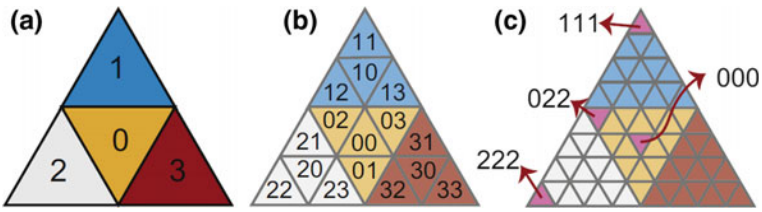

Fig. 2.13 (**a**, **b**) The hierarchical indexing system of the HSDS. (**c**) Indices of descendant cells after three refinements

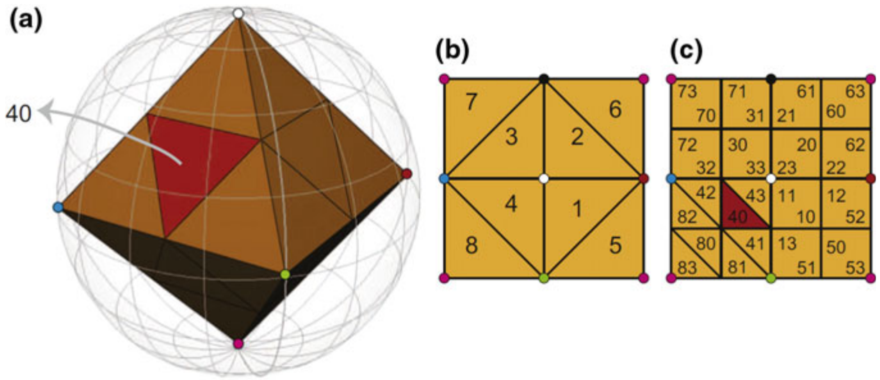

Fig. 2.14 The QTM DGGS. (**a**) The initial octahedron, embedded in a sphere. (**b**, **c**) The hierarchical indexing system of the QTM

The faces of the initial cube are refined using a 1-to-9 congruent and aligned quadrilateral refinement, and the resulting cells are inverse projected using the HEALPix projection method (see Sect. 2.2.4.2). A hierarchical base-9 indexing system is used to address the cells (see Fig. 2.15).

Quadrilateral cells are also found in Crusta (Bernardin et al. 2011), a DGGS based on a rhombic triacontahedron. Each of the initial 30 quadrilateral faces undergoes a 1-to-4 refinement, and the generated vertices are normalized to the geoid. Crusta's primary motivation includes support for high-resolution topographical data and images.

A number of hexagon-based DGGSs have also been proposed and have garnered much research attention. The ISEA3H (Icosahedral Snyder Equal Area Aperture 3 Hexagonal) DGGS is a particularly notable example which starts from an icosahedron (or truncated icosahedron) that undergoes an aligned 1-to-3 hexagonal refinement (US Patent No. 8400451, 2004; Sahr 2008). The resulting cells are inverse projected to the sphere using Snyder's equal-area projection. Note that as the refinement scheme

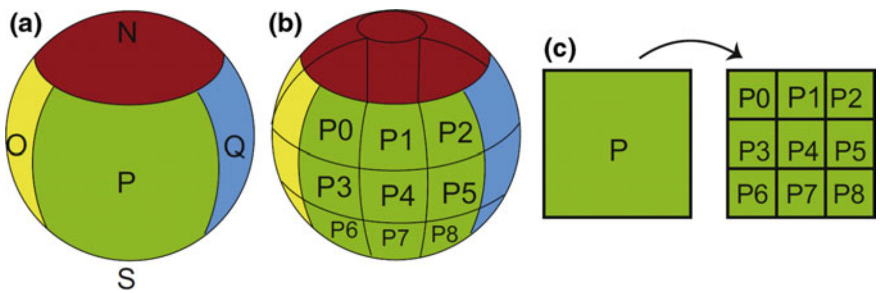

Fig. 2.15 (**a**), (**b**) SCENZ-Grid is created from a refined cube inverse projected to the sphere. (**c**) The hierarchical indexing system of SCENZ-Grid

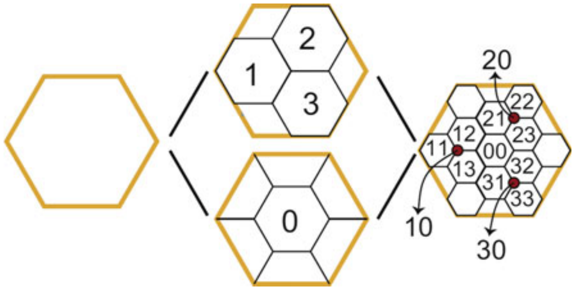

Fig. 2.16 Two types of 1-to-4 hexagonal refinement can be combined, allowing a triangular cell hierarchy to be established and indexed

(and, indeed, any hexagonal refinement scheme) is not congruent, special care must be taken to define the cell hierarchy and indexing scheme. Several different indexing schemes have been proposed for the ISEA3H DGGS. These include the hierarchical indexing of PYXIS (US Patent No. 8400451, Peterson 2004), CPI (US Patent No. 9311350, Sahr 2016), coordinate-based indexing mechanisms (Sahr 2008; Mahdavi-Amiri et al. 2015a; Vince 2006), or the algebraic encoding scheme of (Ben et al. 2018).

The icosahedron can also be refined using 1-to-4 hexagonal refinement, as in the construction of the HQBS (Hexagonal Quaternary Balanced Structure (Tong et al. 2013)). The resulting cells are also inverse projected using Snyder's projection. In order to mitigate the incongruity of the hexagonal refinement, two different 1-to-4 refinements are employed (aligned and unaligned; see Fig. 2.16). This allows a triangular hierarchy to be defined (aligned with the edges of the initial icosahedron) and for lattice points to be indexed. By taking the index of the point at the cell's centroid to be the cell's index, a base 4 hierarchical indexing system can be established on the cells.

Other hexagon-based DGGSs include the OA3HDGG and OA4HDGG (Octahedral Aperture 3/4 Hexagonal Discrete Global Grid (Vince 2006; Ben et al. 2010)). As implied by the name(s), both DGGSs are constructed from an octahedron that undergoes a hexagonal refinement. The OA3HDGG utilizes a 1-to-3 hexagonal refinement, and its cells are indexed using a coordinate-based system. The vertices of the initial octahedron are assigned the coordinates $(\pm 1, 0, 0)$, $(0, \pm 1, 0)$, and $(0, 0, \pm 1)$; and the cells are assigned indices based on their barycentric coordinates with respect to these vertices. A similar indexing system is applied to the OA4HDGG, which utilizes a 1-to-4 hexagonal refinement.

While most DGGSs discretize only the surface of the Earth, certain types of geospatial data (e.g. earthquake data, airspace delineations, etc.) are volumetric in nature and require a volumetric Earth representation. Hence, volumetric DGGSs such as SDOG (Spheroid Degenerated-Octree Grid (Yu and Wu 2009; Yu et al. 2012)) have also been proposed. SDOG, which was designed to represent the global lithosphere, divides the Earth into an initial set of eight octants. Each octant is associated with a degenerated octree, and undergoes a non-uniform refinement that prevents cell degeneracies at the Earth's core (see Fig. 2.17). Cells are indexed using two different

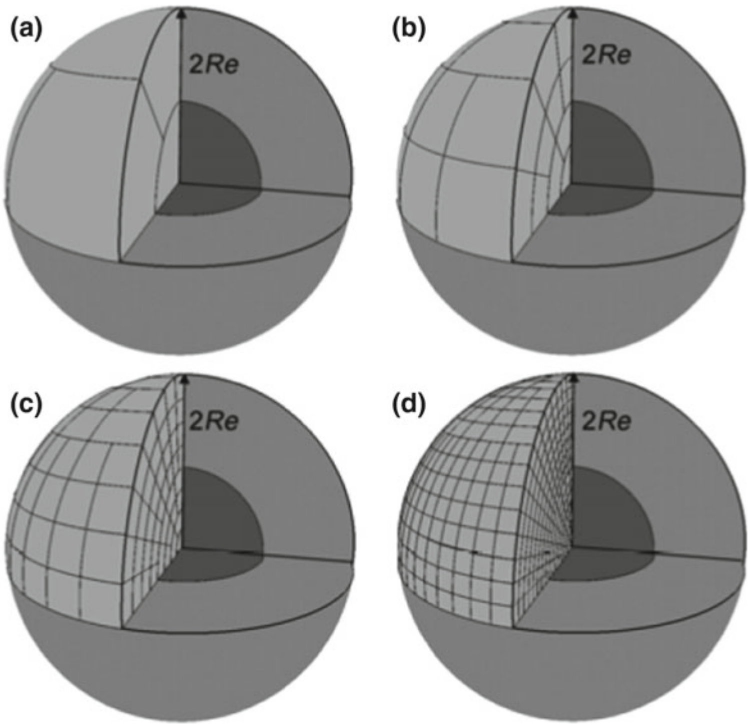

Fig. 2.17 The SDOG volumetric DGGS at three successive resolutions

curve-based schemes, both based on a modified Z-curve. The SDZ (Single Hierarchical Degenerated Z-Curve Filling) method indexes the cells of a single resolution in base 10 (see Fig. 2.18), while MDZ (Multiple Hierarchical Degenerated Z-Curve Filling) serves as a hierarchical indexing scheme in base 8 (see Fig. 2.19).

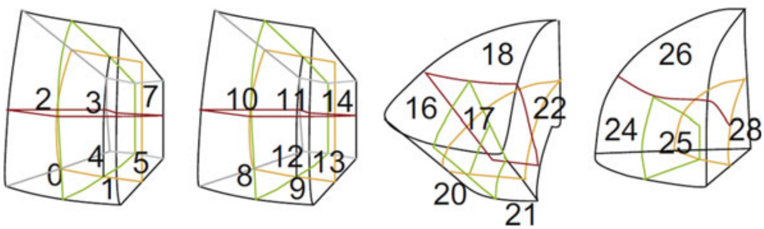

Fig. 2.18 SDZ defines a base 10 indexing for cells at a single resolution

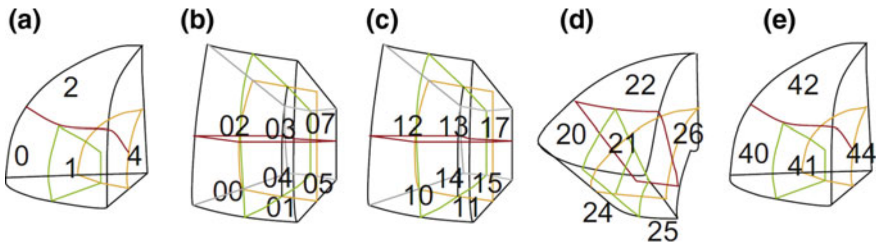

Fig. 2.19 MDZ defines a hierarchical indexing scheme on the SDOG cells. (**a**) A refined octant with child indices. (**b**), (**c**), (**d**) and (**e**) Cells 0, 1, 2, and 4, respectively, refined with child indices

2.4 Public and Commercial Digital Earth Platforms

Naturally, a number of DGGSs and other Digital Earth concepts have been implemented and made available for public use as either free or paid software.

2.4.1 Latitude/Longitude Grids

Due to their ease of use and long history, latitude/longitude grids remain a popular choice for Digital Earth implementations despite the potential issues associated with non-uniform DGGS cells. Chief among these implementations in terms of name recognition is Google Earth (Google Inc. 2019a). Google Earth is created upon a latitude/longitude grid using a simple cylindrical projection, with textures processed via clip-mapping (Bar-Zeev 2007). Clip-Maps are a modified form of mip-map that impose a maximum image size on the mip-map hierarchy (Tanner et al. 1998), causing the image hierarchy to more closely resemble an obelisk than the traditional pyramid (see Fig. 2.20). The capped image size ensures that textures can fit into memory and be rendered in real-time.

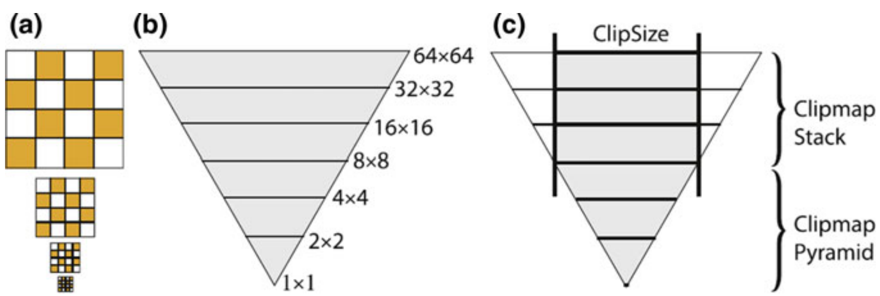

Fig. 2.20 (**a**) An image at multiple resolutions. (**b**) The image's mip-map pyramid. **c** Clip-Maps impose a maximum size on the mip-maps

Although not presented in 3D globe format, Google Maps and Bing Maps are supported using methods that echo the fundamentals of a DGGS (See Figs. 2.21 and 2.22). In particular, Google Maps uses the Mercator projection on a latitude/longitude grid that is refined using a 1-to-4 refinement. Each "tile" of the hierarchical grid is associated with a 256 × 256-sized texture, and is indexed using an axis-based coordinate system. Here, the top-left tile is indexed as (0, 0), with x values increasing towards the east, and y values increasing towards the south (Google Inc. 2019b).

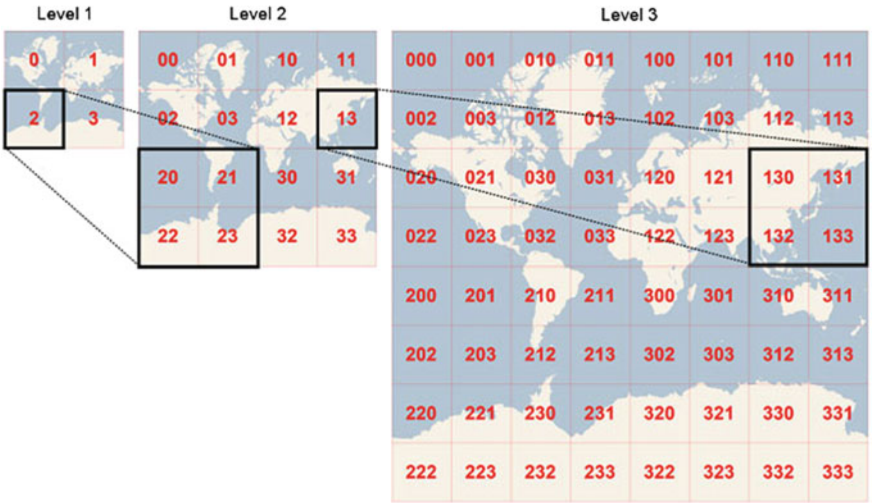

Fig. 2.21 Three resolutions of Bing Maps' hierarchy-based indexing

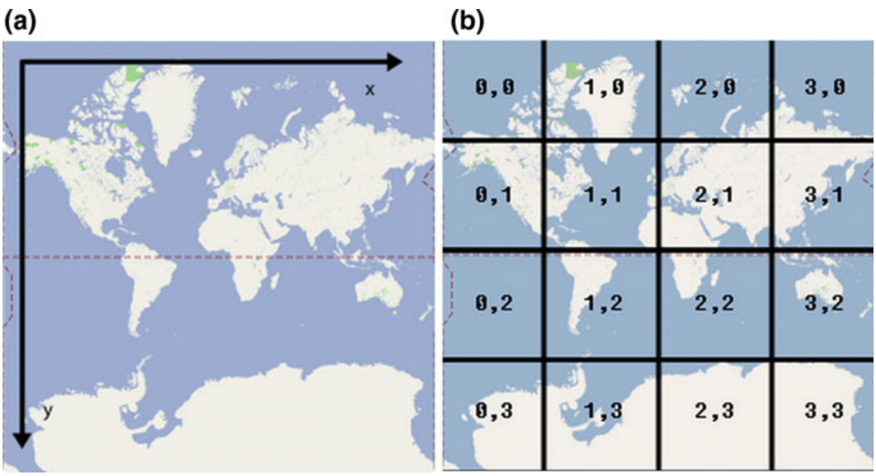

Fig. 2.22 (**a**) Google Maps' latitude/longitude grid. (**b**) Cell indices at the second resolution

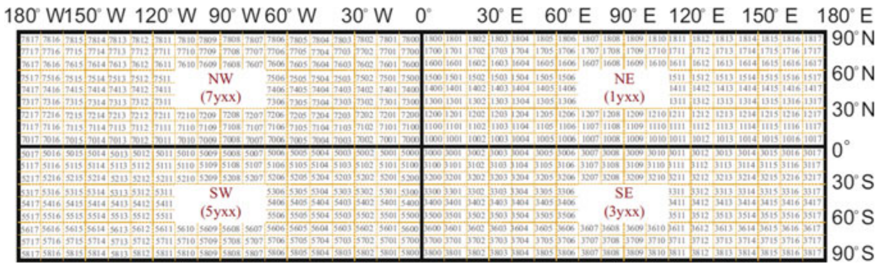

Fig. 2.23 C-squares indexing system

Bing Maps also uses the Mercator projection on a 1-to-4 refined grid, but its indexing system is hierarchical and based on quadtrees (Schwartz 2018). For an illustration, see Fig. 2.21.

The OGC CDB (Common Database) API from Presagis (2019) is designed to address one of the main issues with latitude/longitude DGGSs, namely the shrinking of cells near the poles. The CDB divides the Earth into five zones depending on proximity to the poles, with each zone utilizing a different spacing between lines of longitude. While the CDB is available as an open commercial standard, a Pro license can be purchased for additional features.

Unlike other DGGSs, C-squares (Concise Spatial Query and Representation System (Rees 2003)) discretizes only a single resolution of the Earth. Here, the latitude/longitude grid is divided into four quadrants (NE, NW, SE, and SW), which are then divided into finer grids based on latitude and longitude (Fig. 2.23). The cells of this discretization are indexed as *iyxx*, where *i* corresponds to the cell's quadrant, *y* to the cell's latitude, and *xx* to the cell's longitude. This system was created by CSIRO Marine and Atmospheric Research, Australia for the purposes of mapping, spatial search, and environmental assessment. Converters and source code can be found on their website (CSIRO 2019).

Other Digital Earths based upon latitude/longitude grids include NASA's open source WorldWind API (NASA 2019); Skyline's software products, TerraExplorer client and SkylineGlobe server (Skyline Software Systems 2019); and two DGGS libraries for web-based globe visualization—GlobWeb and CesiumJS (Telespazio 2019; Cesium Consortium 2019). GlobWeb is provided by Telespazio France under the GNU LGPL v3 license, while CesiumJS was founded by the Cesium Consortium and is open source.

CesiumJS in particular is a complete 3D mapping platform built using WebGL. It is a cross-platform and cross-browser map engine that runs on a web browser without plugins, and is now used in industries as diverse as archaeology, engineering, construction, and sports visualizations. An accompanying tool, Cesium ion, provides a point-and-click workflow to create 3D maps of users' geospatial data that can be visualized, analysed, and shared. It can be used to host datasets in 3D tiles, including imagery, terrain, photogrammetry, point clouds, BIM, CAD, 3D buildings, and vector data; and provides tools for analytics including measurements, volume and visibility computations, and terrain profiles.

2.4.2 Geodesic DGGSs

Of course, not all DGGSs are based on singular 2D domains such as a latitude/longitude grid; while comparatively rarer, different implementations of Geodesic DGGSs do exist and are available for use. For instance, a library that implements the well-studied ISEA3H DGGS—known as geogrid—is offered on GitHub (Mocnik 2019). This library is developed and maintained by Franz-Benjamin Mocnik, and is licensed under the MIT license.

A propriety implementation of the ISEA3H can be found at the core of the Digital Earth system developed by Global Grid Systems (formerly the PYXIS innovation (PYXIS innovation 2011; Global Grid Systems 2019)), and is one of the few commercially available Geodesic DGGSs (Fig. 2.24). This system indexes the ISEA3H's hexagonal cells using the patented PYXIS indexing scheme (US Patent No. 8400451, 2004).

Other software platforms include implementations of the ECM (Ellipsoidal Cube Map) and HEALPix (Hierarchical Equal Area isoLatitude Pixelization of the sphere) DGGSs. ECM (Lambers and Kolb 2012) is produced by applying 1-to-4 refinement on the quadrilateral faces of a cube that circumscribes the ellipsoidal Earth. Areal and angle distortions are minimized by using a Quadrilateralized Spherical Cube (QSC) projection. A Linux implementation is available on Martin Lambers' website, licensed under the GNU GPL v3 (Lambers 2019).

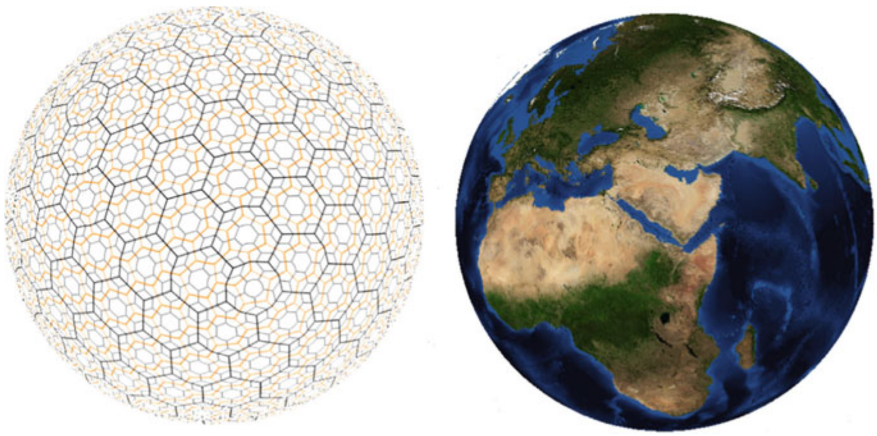

Fig. 2.24 Global Grid Systems' ISEA3H DGGS

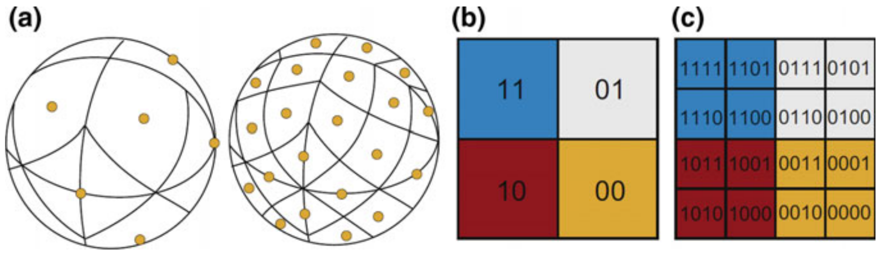

Fig. 2.25 The HEALPix DGGS. (**a**) HEALPix uses a 1-to-4 refinement. (**b**) The hierarchical HEALPix indexing system

The HEALPix DGGS (Gorski et al. 2005) is based on a rhombic dodecahedron that undergoes a congruent 1-to-4 refinement, indexed using a base-2 hierarchical indexing system (see Fig. 2.25). Two different projection schemes are employed: Lambert cylindrical equal-area projection for equatorial regions, and Collignon equal-area projection for polar regions. A software package from the Jet Propulsion Laboratory that supports spherical harmonics, pixel queries, data processing, and statistical analysis can be found online (Jet Propulsion Laboratory 2019).

2.4.3 Installations: DESP

One of the largest scale Digital Earth undertakings can be found at the Chinese Academy of Sciences (CAS), where an interactive visualization environment called the Digital Earth Science Platform was developed (Guo et al. 2017). Based on the Digital Earth Prototype System Initiative that launched in 1999 (Guo et al. 2009, 2010), the Digital Earth Science Platform (DESP) was established by the CAS in 2010 in order to integrate state-of-the-art techniques and meet the increasing requirements of geoscience applications.

The DESP is a technical platform that supports spatial data and information services, as well as associated applications. It integrates 2D and 3D geographic information systems, distributed storage and computing, virtual reality, wireless sensor networks, and other technologies. A 600 m^2 fully immersive, interactive visualization environment was established at the CAS Institute of Remote Sensing and Digital Earth (RADI) to support experiments with 3D visualization and to provide decision support for emergency response applications. This installation is equipped with VR/AR devices, sensors, a 3D Stereo Projection System, and a high-performance computing system, as shown in Fig. 2.26.

The DESP has already played an important role in the modeling of global change, evaluation of natural disasters, and monitoring of natural resources and human settlement through the integration of multi-sensor, multi-temporal remote sensing images, in situ ground survey data, socio-economic data, and interdisciplinary scientific models (Fan et al. 2009). For example, the influence of sea level rise on the Earth's major

Fig. 2.26 The DESP visualization environment at RADI

river deltas has been modeled and analyzed in a comparative study by using the DESP. Emergency monitoring and response systems based upon the DESP have been developed for disaster monitoring and post-disaster relief after earthquake events (Fig. 2.27).

As a part of the ongoing Big Earth Data Science Engineering (CASEarth) initiative (2018–2022), which is supported by the Strategic Priority Research Program of the CAS, a new generation of the Digital Earth Science Platform will be developed to provide a new impetus for interdisciplinary, cross-scale, macro-scientific discoveries in the Era of Big Data to promote sustainability (Guo 2017).

Fig. 2.27 The DESP was used for disaster assessment and relief after the 2013 Ya'an earthquake

2.5 Discrete Global Grid System Standards

The myriad ways in which one can construct a Digital Earth platform provide a great deal of flexibility that can help cater to a vast range of specific uses; however, this can also create barriers to interoperability. This creates a real challenge as we move into the Era of Big Data (and beyond), where interoperability and distributed analysis is critical.

In the Era of Big Data, geoscience can only achieve its full potential through the fusion of diverse Earth observation and socio-economic data together with information from a vast range of sources. In this type of environment with multiple data providers, fusion is only possible with an information system architecture based upon open standards (Percivall 2013). Without a common and standardized means of defining and integrating various Digital Earth Platforms, our ability to transform the increasingly massive amounts of data that are being acquired about the Earth into actionable information is significantly limited.

2.5.1 Standardization of Discrete Global Grid Systems

Recognizing the issues that non-standard global grid system implementations pose and their potential impacts, in 2014, the Open Geospatial Consortium embarked on the ambitious goal of standardizing DGGS. The goal of this endeavor was not to identify the one DGGS that ought to be used by everyone, but to define the common qualities of a variety of DGGSs that can be used to support interoperability while providing some flexibility in choice, thus allowing implementers to tailor DGGS infrastructures to their specific uses. In July 2017, the OGC published the first ever international standard governing the design and implementation of DGGS (Purss et al. 2017). This standard aims to promote awareness and reusability of DGGS implementations, and integration between them, and, through this, to demonstrate a path towards the realization of the "Digital Twin"—where our engagement and understanding of the physical Earth can seamlessly interact with the Digital Earth, and vice versa.

The core of the OGC DGGS standard is primarily based on an appropriate subset of the well-accepted criteria for optimal DGGS design proposed by Goodchild (2000) and Sahr et al. (2003).

2.5.2 Core Requirements of the OGC DGGS Abstract Specification

Along with the categorization provided earlier, under the OGC DGGS Abstract Specification, a compliant DGGS must define a hierarchical tessellation of equal area cells that both partition the entire Earth at multiple levels of granularity and provide a global spatial reference frame. In addition to these structural components, the system must also include encoding methods to address each cell, assign quantized data to cells, and perform algebraic operations on the cells and the data assigned to them.

The requirement of functional components for the infrastructure sets an OGC DGGS apart from other grid frameworks or Coordinate Reference Systems. It also provides a common operational basis for supporting communication and interoperability between different compliant DGGS infrastructures.

2.5.2.1 Structural Requirements

The reference frame of a DGGS consists of the fixed structural elements that define the spatial framework on which the DGGS functional algorithms operate. These fixed structural elements include:

1. **Domain completeness and position uniqueness**: The DGGS must be defined over a global domain without any overlapping cells. Goodchild defines a global domain to be achieved when the areal cells defined by the grid "*exhaustively cover the globe without overlapping or underlapping*" (Goodchild 2000);
2. **Multiple levels of resolution**: The DGGS must define multiple discrete global grids forming a system of hierarchical tessellations, each with progressively finer spatial resolution and linked via a common cell refinement method;
3. **Preservation of domain completeness and position uniqueness**: The DGGS must preserve the total surface area (i.e. the global domain) throughout the entire range of hierarchical tessellations. This facilitates the consistent representation of information at all resolutions within the DGGS;
4. **A simple geometric structure for each cell**: In order for the DGGS to achieve the requirement of a global domain, it is necessary for the shape of all cells defined by the DGGS to be simple polygons on the surface model of the Earth. The cell shapes derived from the five (5) Platonic solids and thirteen (13) Archimedean solids (triangle, quadrilateral, pentagon, hexagon, and octagon) are all simple polygons that have the following properties:

    a. The edges meet only at the vertices;
    b. Exactly two edges meet at each vertex; and,
    c. The polygons enclose a region which always has a measureable area.

5. **Equal-area cells**: The DGGS must be based on a hierarchy of equal-area tessellations. Equal-area cells provide global grids with spatial units that (at multiple resolutions) have an equal probability of contributing to an analysis. Equal-area cells also help minimize the confounding effects of area variations in spatial analyses, where the curved surface of the Earth is the fundamental reference frame;
6. **An initial polyhedral tessellation**: To consistently achieve equal-area cells, the DGGS must be constructed by mapping a polyhedron to the surface model of

the Earth. This initial tessellation can then be refined to produce equal-area child cells for all subsequent levels in the hierarchy of tessellations;

7. **Unique identifiers for each cell**: In order to efficiently operate as a spatial data integration engine, the cells of the DGGS must each be defined by a globally unique identifier. This ensures that the reference to each and every cell is immutable. While the OGC DGGS Abstract Specification requires each cell to be uniquely identified, it does not prescribe or enforce how the implementer must achieve this;
8. **Each cell referenced at its centroid location**: Each DGGS cell must be referenced at its centroid. This is because the centroid is the only location that provides a systematic and consistent spatial reference point for all cells, regardless of shape.

2.5.2.2 Functional Requirements

The ability to locate and perform algebraic operations on data assigned to a DGGS is critical for a DGGS to be able to support connectivity and hierarchical operations on cells and to facilitate interoperability between DGGS implementations (as well as other spatial data infrastructures or interfaces). Accordingly, the OGC DGGS Abstract Specification requires the DGGS to specify definitions for:

1. **Quantization operations**: Assigning data to and retrieving data from cells;
2. **Algebraic operations**: Performing algebraic operations on cells and the data assigned to them, in addition to performing cell navigation; and
3. **Interoperability operations**: Translating cell addresses to other Coordinate Reference Systems (CRS), such as conventional latitude/longitude.

Again, the OGC DGGS Abstract Specification enforces no specific implementations of these functional elements, but requires their inclusion (in some form) in any compliant DGGS implementation. This both facilitates flexibility and innovation in the design of individual DGGS implementations and ensures the widest scope for interoperability between compliant DGGS implementations. By focusing on endpoint functional requirements and not on the methods by which they are achieved, the OGC DGGS Abstract Specification supports interoperability across multiple social and technical domains. This approach also allows for advancements in the technologies that support these functional elements, without requiring the standard to be constantly re-written.

2.5.3 The Future of the DGGS Standard

In support of the wider adoption and implementation of compliant (and interoperable) DGGS implementations, there are a number of initiatives currently underway within both the OGC and the International Standards Organization (ISO). These initiatives include:

1. The publication of the OGC DGGS Abstract Specification as an ISO standard (ISO 19170). By publishing this standard as an ISO standard, it will be possible to reach a wider community of potential DGGS implementers and thus increase the adoption of DGGS technologies.
2. The establishment of an OGC Registry of compliant DGGS implementations. This will facilitate the certification and publication of compliant DGGS implementations and increase the awareness of the choices of available DGGS implementations that can be applied to a Spatial Data Infrastructure. This will be similar in nature to the Coordinate Reference System Registry. The first release of the OGC DGGS Registry is anticipated to occur by the end of 2018.
3. The development of a standardized specification of a common API language for DGGS. This work is in its early phase but is expected to result in the drafting and publication of a new OGC implementation standard that specifies a common API language supporting and facilitating interoperability between different DGGS implementations. A common API language for DGGS implementations will further lower the technical barriers to the wider implementation of DGGS technologies.

2.5.4 Linkages Between DGGS and Other Standards Activities

As a technology, DGGSs have the potential to impact on almost all spatial technologies and their related standards. Consequently, a number of international standards activities have included references to DGGSs and their potential applications to several scenarios relevant to these initiatives. Two examples of this include:

1. The Joint OGC-W3C Spatial Data on the Web Best Practices (Van Den Brink et al. 2019), where DGGS was proposed as an enabling component of QB4ST (an extension of existing RDF Datacube vocabularies to support spatio-temporal data).
2. The Global Statistical Geospatial Framework (GSGF), adopted during the 6th Session of the United Nations Committee of Experts on Global Geospatial Information Management in August 2016, refers to DGGS and acknowledges that these technologies have the potential to help realize the implementation of the GSGF.

As the number of DGGS implementations increases, so too will the suite of international standards that support them and their applications. The challenge for the International Standards Community will be to keep the number and complexity of these standards to an acceptable level in order to ensure that the DGGS standards do not become a barrier to adoption in themselves.

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Troy Alderson is a Ph.D. candidate in the Department of Computer Science at the University of Calgary, where he also received his M.Sc. in Computer Science (2014) and B.Sc.'s in Computer Science and General Mathematics (2010). His current work focuses on developing unified frameworks for subdivision and multiresolution for various types of geometric shapes.

Matthew Purss is a founding co-chair of the Open Geospatial Consortium's Discrete Global Grid Systems working groups. He holds a Ph.D. in Exploration Geophysics and throughout his 20+ year career he has been a leader in the theoretical development, practical implementation and standardisation of advanced spatial data infrastructures and grid systems.

Xiaoping Du is currently an Associate Professor with the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. His research interests include Digital Earth and geospatial big data analytics, coastal flooding risk assessment due to global climate change, and remote sensing for natural disasters & environmental monitoring.

Ali Mahdavi-Amiri is a University Research Associate at Computing Science department in Simon Fraser University. His research interests is in Computer Graphics with specialty in Geometric Modeling, Geospatial Modeling and Visualization, Digital Fabrication, and Machine Learning. Ali has received several awards including NSERC Postdoctoral Fellowship, Graduate Achievement Award, Michael A. J. Sweeney Award, and Teaching Excellence Award.

Faramarz Samavati is a professor of Computer Science at the University of Calgary. Dr. Samavati's research interests include Computer Graphics, Visualization, and Digital Earth. Over the past eight years, he has received seven best paper awards, Digital Alberta Award, Great Supervisor Award, and University of Calgary Peak Award.

Chapter 3
Remote Sensing Satellites for Digital Earth

Wenxue Fu, Jianwen Ma, Pei Chen and Fang Chen

Abstract The term remote sensing became common after 1962 and generally refers to nonintrusive Earth observation using electromagnetic waves from a platform some distance away from the object of the study. After more than five decades of development, humankind can now use different types of optical and microwave sensors to obtain large datasets with high precision and high resolution for the atmosphere, ocean, and land. The frequency of data acquisition ranges from once per month to once per minute, the spatial resolution ranges from kilometer to centimeter scales, and the electromagnetic spectrum covers wavebands ranging from visible light to microwave wavelengths. Technological progress in remote sensing sensors enables us to obtain data on the global scale, remarkably expanding humanity's understanding of its own living environment from spatial and temporal perspectives, and provides an increasing number of data resources for Digital Earth. This chapter introduces the developments and trends in remote sensing satellites around the world.

Keywords Remote sensing · Digital Earth · Satellite · Earth observation

3.1 Development of Remote Sensing

Remote sensing is a core technology for Earth observation. It covers information collection, in-orbit processing, information storage and transmission, ground reception, processing for applications, calibration, verification, applied research, and basic research, providing fundamental data resources for Digital Earth (Guo 2012).

W. Fu (✉) · J. Ma · F. Chen
Institute of Remote Sensing and Digital Earth, CAS, Beijing, China
e-mail: fuwx@aircas.ac.cn

P. Chen
School of Astronautics, Beihang University, Beijing, China

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3.1.1 Overview of Remote Sensing

3.1.1.1 Remote Sensing Platforms

Remote sensing refers to various observation and exploration activities of the environment involving humans and photoelectronic devices carried by satellites, spacecraft (including space shuttles), aircraft, near-space vehicles, and various terrestrial platforms. Artificial satellites that carry sensors to capture images of Earth's surface are referred to as remote sensing satellites. Satellites can successively observe the whole globe or an assigned part of it within a defined time period (Guo et al. 2016). Aircraft often have a definite advantage because of their mobilization flexibility. They can be deployed wherever and whenever weather conditions are favorable. Satellites and aircraft collect the majority of base map data and imagery used in remote sensing, and the sensors typically deployed on these platforms include film and digital cameras, light-detection and ranging (LiDAR) systems, synthetic aperture radar (SAR) systems, and multispectral and hyperspectral scanners. Many of these instruments can also be mounted on land-based platforms such as vans, trucks, tractors, and tanks. In the future, the Moon will also be an ideal remote sensing platform (Guo et al. 2014a, 2018).

3.1.1.2 Remote Sensing Sensors

There are several types of Earth observation sensors: photographic sensors, scanning imaging sensors, radar imaging sensors, and nonimaging sensors. Photographic sensors work like a digital camera. Scanning imaging sensors capture two-dimensional images by scanning point by point and line by line in a time sequence. These are widely used today; such sensors can be further divided into surface scanning and image scanning sensors. Imaging radar is an active sensor that emits electromagnetic waves to form a lateral profile. Currently, most Earth observation satellites carry SAR systems that feature very high resolutions.

In the early stage of spaceborne Earth observation, traditional film-based imaging devices, return beam vidicon (RBV) TV cameras, and optical scanners were the main devices used for Earth observation. Images obtained from these devices were mainly color and black-and-white representations of Earth's surface and cloud layer, covering the visible light and near infrared ranges. After the first land observation satellite, Landsat 1, was launched in 1972, the new multispectral scanner (MSS) it carried sent data that was processed in the form of a digital time sequence array. This marked a progressive step in the development of digital image processing.

Compared with optical remote sensors, SARs work in various weather conditions and can penetrate some surface objects. In contrast to passive sensor systems that only receive reflected solar light or infrared radiation, radar systems act as active sensors and emit electromagnetic waves on their own. A radar sensor sends pulses of energy to the Earth's surface and part of that energy is reflected and forms return signals. The strength of the return signal depends on the roughness and dampness of the Earth's surface and the inclination of surface objects toward the waves sent by radar.

3.1.2 Development of Remote Sensing Satellites

Based on a life cycle of approximately thirteen years, Earth observation satellites have gone through four generations (Fig. 3.1) (Zhou 2010).

(1) The first generation, beginning spaceborne Earth observation: 1960–1972

CORONA, ARGON, and LANYARD were the first three imaging satellite observation systems. Data obtained from these satellites were used for detailed terrestrial reconnaissance and regional mapping. In the early years, satellite images were made by combining hundreds or even thousands of photos, most of which were black-and-white, with a small number of color photos or three-dimensional image pairs. These images covered most parts of Earth. For example, images obtained using the KH-5 camera covered most of the Earth's surface with a 140-m pixel resolution. However, these images did not form systematic observations like those achieved later with Landsat data.

(2) The second generation, experimental and tentative application: 1972–1986

Landsat-1 was launched on July 23, 1972, marking the start of modern satellite-carried Earth observation. It provided a novel high-resolution Earth image database to international science organizations, making further exploration of Earth's resources possible. Landsat-1 carried an MSS that received four bands with wavelengths from 0.5 to 1.1 μm with a spatial resolution of 80 m, frame width of 185 km, and revisit cycle of eighteen days. Notably, Landsat-1 transmitted data in digital form for the first time. The foundation for multispectral processing was laid in the 1970s and organizations involved in this field included NASA, Jet Propulsion Laboratory (JPL), United States Geological Survey (USGS), Environmental Research Institute of Michigan (ERIM), and Laboratory for Applications of Remote Sensing (LARS). Ten years

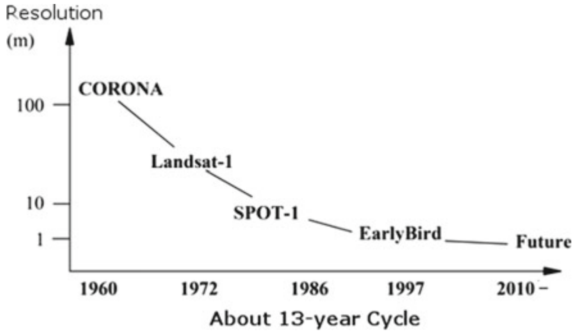

Fig. 3.1 History of the thirteen-year cycle of Earth observation satellite development (Zhou 2010)

later, Landsat accommodated four more MSS wavebands as Landsat TM emerged during 1982–1984 with a spatial resolution of 30 m covering seven spectral bands. Soon afterwards, the famous SPOT HRV system was launched in 1986 with a spatial resolution of 10 m for the panchromatic wavebands and 30 m for three other multispectral bands.

(3) The third generation, wide application: 1986–1997

After 1986, the technology and applications of satellite Earth observation developed rapidly. SPOT-1, launched on February 22, 1986, carried a high-resolution visual sensor and was the first use of pushbroom linear array sensors. It was also the first satellite system capable of cross-track three-dimensional observation. Later, the ESA launched the ERS-1 SAR on July 17, 1991. ERS-1 was an active microwave satellite that provided images with a spatial resolution of 30 m. Japan launched its JERS-1 in February 1992 with an L-band SAR, building up the overall observation capacity of SARs. Data provided by these active microwave sensors played an important role in enhancing the observation and understanding of environmental and climatic phenomena, and supported the categorization of sea ice and research on the coastal zone.

(4) The fourth generation, high-resolution and hyperspectral imaging: 1997–2010

This comprises the latest generation of Earth observation satellites equipped with the most advanced technologies that are still gradually maturing. The main features are a spatial resolution of 1 m or less, coverage of 200 wavebands ranging from 0.4 to 2.5 μm in wavelength, a spectral resolution of 10 nm, revisit cycles less than three days, capability of multiangle and three-dimensional observation, and precise spatial positioning with GPS. The major advantage of high-resolution imaging is that it allows for identification of buildings, roads, and modern construction projects as well as change detection. As a result, high-resolution imagery products are mainly used in GIS and special-purpose mapping.

At this stage, attention was primarily focused on spatial and temporal resolutions, spectral coverage, orbital height, revisit capability, mapping bandwidth, image dimensions, capacity for three-dimensional observation, imaging models, data storage, and the market demand for satellites.

(5) The fifth generation, a new era of satellite Earth observation

Next-generation Earth observation satellites are expected to be highly intelligent and integrate Earth observation sensors, data processing devices, and communication systems. Global surveying and real-time environmental analysis of Earth will become possible. More experts as well as casual users will be involved in remote sensing, photogrammetry and GIS, and data inversion products will also be updated more frequently. To achieve real-time data acquisition, improve applications and spare casual users the trouble of understanding complicated data processing, image providers will offer mature imaging products that directly meet various demands (Guo et al. 2014b).

3.2 Land Observation Satellites

Land observation satellites have been developed for land resource investigation, terrestrial environment research, crop condition forecasting, and natural disaster monitoring. Terrestrial variables have a specific "ground object spectrum" and radiation scattering; terrestrial variables can be retrieved by considering the direction, scale, and sensitivity to establish the relationship between electromagnetic waves and ground surface variables for space observation.

3.2.1 US Land Observation Satellites

The United States launched its first land satellite, Landsat 1, on July 23, 1972. For the first time in human history, satellites were consistently providing Earth images with a certain resolution, making it possible to use satellites to survey Earth's resources. Since then, the country has launched seven satellites in the Landsat series (the launch of Landsat 6 failed). They are currently the world's most widely used land observation satellites (Table 3.1).

Later, the United States launched a series of high-resolution commercial remote sensing satellites. The IKONOS satellite, launched on September 24, 1999, was the world's first commercial remote sensing satellite providing high-resolution images. After that, the country launched the QuickBird, WorldView-1, GeoEye-1, and Wor1dView-2 satellites in October 2001, September 2007, September 2008, and October 2009, respectively, with improved resolutions from 0.61 to 0.41 m (multispectral) (Aguilar et al. 2013).

3.2.1.1 Landsat Program

The Earth Resources Satellite Program involves a series of Earth observation satellites jointly managed by NASA and the United States Geological Survey (USGS). These satellites collect information about Earth from space. They have been providing digital photos of Earth's continents and coastal regions for more than 40 years, enabling researchers to study Earth from various aspects and evaluate the impacts of natural and human activities on the dynamics of the Earth system.

(1) Landsat 7

Landsat 7 moves around Earth on a near-polar sun-synchronous orbit, with an orbital altitude of 705.3 km and an operation cycle of 98.9 min, covering Earth once every sixteen days. During the day, it operates on a descending orbit, crossing the equator at 10:00 AM. The orbit is adjusted so that orbital inclination is kept within a certain limit and the deviation of the satellite transit time from the nominal time is kept within ±5 min.

Table 3.1 Land satellites launched by the United States

Satellite code	Type of orbit	Orbital altitude (km)	Orbital period (min)	Orbital inclination (°)	Launch date
Landsat-1	Sun-synchronous orbit	917	103.1	99.2	1972.6.23
Landsat-2	Sun-synchronous orbit	917	103.3	99.2	1975.1.22
Landsat-3	Sun-synchronous orbit	917	103.1	99.1	1978.3.5
Landsat-4	Sun-synchronous orbit	705	98.9	98.2	1982.7.16
Landsat-5	Sun-synchronous orbit	705	98.9	98.2	1984.3.1
TRMM	Inclined orbit	405	93.5	35	1997.11.27
Landsat-7	Sun-synchronous orbit	705	98.9	98.2	1999.4.15
Terra	Sun-synchronous orbit	705	99	98.2	1999.12.18
ACRIMSAT	Sun-synchronous orbit	716	90	98.13	1999.12.20
GRACE	Polar orbit	400	94	89	2002.3.17
Aqua	Sun-synchronous orbit	705	98.8	98.2	2002.5.4
ICESat	Inclined orbit	600	97	94	2003.1.12
SORCE	Inclined orbit	600	90	40	2003.1.25
Suomi NPP	Sun-synchronous orbit	824	101	98.7	2011.10.28
Landsat-8	Sun-synchronous orbit	705	99	98.2	2013.2.12

Table 3.2 ETM+ bands

Waveband	Wavelength range (μm)	Ground resolution (km)
1	0.45–0.515	30
2	0.525–0.605	30
3	0.63–0.690	30
4	0.75–0.90	30
5	1.55–1.75	30
6	10.40–12.50	60
7	2.09–2.35	30
Pan	0.52–0.90	15

The ETM+ of Landsat 7 was developed based on the TM of Landsats 4 and 5 and the ETM of Landsat 6. It is a multispectral vertical-orbit scanning radiometer that performs Earth imaging directly facing the nadir and obtains high-resolution ground images. Its scanning width is 185 km. Similar to the previous Landsats, the EMT+ uses a scan line corrector to eliminate the interline overlap or interline spacing caused by the scanning operation or orbital motion.

In the visible and near-infrared (VNIR) range, ETM+ has four color bands and one panchromatic band. Each of the six sounder arrays in the visible, near-infrared and SWIR bands has sixteen sounders staggered along the orbital direction, and each sounder corresponds to a ground area of 30 × 30 m. The LWIR sounder array has eight sounders, each corresponding to a ground area of 60 × 60 m, with a resolution twice as high as that of the previous thermal infrared TM. The panchromatic band was a new addition to Landsat 7. The sounder array consists of 32 sounders, each corresponding to a ground area of 15 × 15 m. The bands of ETM+ are described in Table 3.2.

(2) Landsat 8 (LDCM)

Landsat 8, also referred to as LDCM, carries two main payloads: one operational land imager (OLI) and one thermal infrared sensor (TIRS). Compared with the payloads of previous Landsats, the performance of the OLI and TIRS are much improved.

Landsat 8 can capture at least 400 images per day (its predecessors could only capture 250). This is because Landsat 8 is more flexible in monitoring an area (Ali et al. 2017). Previous Landsats could only monitor a certain swath of land directly under their flight path, but the remote sensor of Landsat 8 can capture information about land that deviates from the flight path by a certain angle, which the previous Landsats could do only in subsequent laps. This advantage helps capture imagery needed for multitemporal comparison (such as images concerning disasters).

The main parameters of Landsat 8 are: a Worldwide Reference System-2 (WRS-2) flight path/line system, a sun-synchronous orbital altitude of 705 km, global coverage cycle of sixteen days (except for high-latitude polar regions), 233 orbits per cycle, an orbital inclination of 98.2° (slightly to the right), an operation cycle of 98.9 min, and a 170 × 185 km imaging area. The satellite crosses the equator at 10:00 AM ±

15 min. Its image directory is prepared in the same way as those of Landsats 4, 5 and 7, and it supports the ability to capture the main image and images that deviate from the nadir point to a limited extent (±1 flight path/line).

3.2.1.2 GRACE Satellite Program

The Gravity Recovery and Climate Experiment (GRACE) satellite program aims to obtain the features of medium and long waves of Earth's gravity field and the time-varying characteristics of the global gravity field (Melzer and Subrahmanyam 2017) and to sound the atmospheric and ionospheric environment. The GRACE satellite was launched on March 17, 2002 from the Plesetsk Launch Center in northern Russia. Its working principle is shown in Fig. 3.2.

The satellite adopts a low-low satellite-to-satellite tracking mode with two simultaneously launched low Earth orbit satellites that travel on the same orbit with a distance of 220 km in between them. Satellite-borne GPS receivers can accurately determine the orbital position of the two satellites and measure their distance and the changes in distance accurate to the micron level. A triaxial accelerometer is used to measure nonconservative forces. The observation data of each satellite, including the data of gravity-related measurements and GPS occultation measurements, are transmitted to the ground station via S-band radio waves.

The scientific objectives of the GRACE satellite project are (1) to determine Earth's mediumwave and longwave gravity field with a geoid precision of 0.01 cm and 0.01 mm for 5,000 km and 500 km wavelengths, respectively, which is two orders of magnitude higher than that of the CHAMP satellite (Ditmar 2004); (2) to

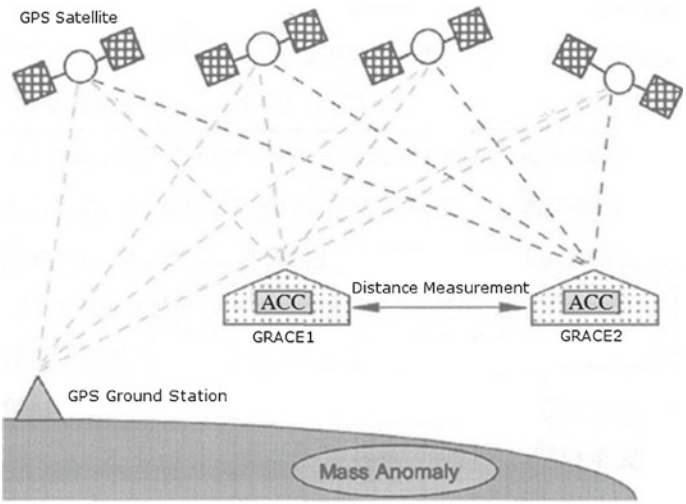

Fig. 3.2 GRACE working principle (Lu 2005)

determine changes in the global gravity field based on observation data from 2 to 4 weeks or longer, with an expected geoid determination precision of 0.001 mm/y; and (3) to sound the atmospheric and ionospheric environment. As the GRACE satellites provide highly accurate information about Earth's mediumwave and longwave gravity field and its time-dependent changes, they mark the beginning of a new era of satellite-based gravity research (Liu 2009).

3.2.1.3 Commercial Remote Sensing Satellites

On September 24, 1999, the IKONOS satellite was successfully launched at Vandenberg Air Force Base, marking the start of the era of high-resolution commercial satellites. On March 31, 2015, IKONOS was retired after 15 years of over service, a working lifetime more than twice of that in the design. IKONOS was a commercial satellite that acquired 1-m resolution panchromatic images and 4-m resolution multispectral images. Additionally, the resolution of the integrated color image with the panchromatic and multispectral images was up to 1 m. The IKONOS revisit period was 1–3 days imaging from the 681 km orbit.

The QuickBird satellite was launched in October 2001 with a panchromatic spatial resolution of 0.61 m and multispectral resolution of 2.44 m. The WorldView-1 satellite, launched on September 18, 2007, was the commercial imaging satellite with the highest resolution and the fastest response speed in the world at that time. WorldView-1 has an average revisit period of 1.7 days in a sun-synchronous orbit at an altitude of 496 km and inclination angle of 98°. The large-capacity panchromatic system can capture images up to 550,000 km^2 with 0.5-m resolution every day. The satellite also has high geolocation accuracy and quick response, which provides quick aiming at the target to effectively perform on-track stereo imaging. Its acquisition capacity is four times that of the QuickBird satellite. Parameters of the WorldView-1 satellite are shown in Table 3.3.

WorldView-2, launched in October 2009, was the first commercial remote sensing satellite in the world to provide 8-band high resolution data, greatly enhancing the customer service ability of DigitalGlobe. In June 2014, with the consent of the US Department of Defense and the State Department, the US Department of Commerce formally approved DigitalGlobe's application for the sale of 0.25-m resolution satellite image data.

With the implementation of the new policy, WorldView-3, the third-generation remote sensing satellite, was successfully launched in August 2014 and is the world's first commercial multipayload, hyperspectral and high resolution satellite, providing 0.31-m panchromatic imagery and 1.24-m multispectral imagery. The WorldView-4 commercial remote sensing satellite was launched in November 2016 and has greatly improved the overall data acquisition capability of the DigitalGlobe constellation group. It can image any point on the Earth 4.5 times a day, with a ground sampling distance (GSD) of less than 1 m.

Table 3.3 WorldView-1 satellite parameters

Parameter	Value
Orbit	Solar synchronization at a height of 450 km
Satellite size, weight and power supply	3.6 m high, 2.5 m wide; the total span of the solar panels is 7.1 m; weight of 2500 kg; 3.2 kw solar cells
Remote sensor band	Panchromatic
Resolution	Subsatellite point: 0.45 m (GSD)
Swath	Subsatellite point: 16 km
Altitude measurement and control	Tri-axial stability
Data transmission	Image and auxiliary data: 800 Mbit/s, X-band
Data acquisition for each orbit	331 Gbit
Maximum continuous imaging area of a single-circle orbit	60 × 60 km (equivalent to 4 × 4 square images); 30 × 30 km (equivalent to 2 × 2 square images)
Revisit period	While imaging with 1 m GSD: 1.7 days

3.2.1.4 Satellite Images for Google Earth

Google Earth's images come from multisource data composed of satellite images and aerial data. Its satellite images mainly come from the QuickBird commercial satellite, GeoEye satellite and IKONOS satellite of the DigitalGlobe Company of the United States, as well as the SPOT-5 satellite of France.

The GeoEye series of satellites are the next generation of the IKONOS and OrbView satellites. The GeoEye-1 satellite, launched on September 6, 2008 from Vandenberg Air Force Base in California can acquire black-and-white (panchromatic) imagery with 0.41-m resolution and color (multispectral) imagery with 1.65-m resolution, and can accurately locate the target position with 3 m accuracy. Therefore, it has become the most powerful commercial imaging satellite with the highest resolution and accuracy in the world. The GeoEye-1 satellite runs in a solar synchronous orbit with an altitude of 681 km and inclination angle of 98°, an orbit period of 98 min and a revisit period of less than 3 days. The satellite's launch mass was 1955 kg, and the design life is 7 years. The payload of the GeoEye-1 satellite is a pushbroom imaging camera consisting of an optical subsystem (telescope module, aperture 1.1 m), a focal plane module and a digital electronic circuit. The main parameters of the GeoEye-1 satellite are shown in Table 3.4.

Table 3.4 The main parameters of the GeoEye-1 satellite

Parameter		Values
Resolution		Subsatellite point panchromatic: 0.41 m, side-looking 28° panchromatic: 0.5 m, subsatellite point multispectral: 1.65 m
Swath		Subsatellite point: 15.2 km; single scene 225 km^2 (15 × 15 km)
Camera mode		Panchromatic and multispectral simultaneous (panchromatic fusion), monochromatic and monochromatic
Revisit period		2–3 days
Wavelength	Panchromatic	450–800 nm
	Multispectral	Blue: 450–510 nm
		Green: 510–580 nm
		Red: 655–690 nm
		Near-infrared: 780–920 nm

3.2.2 European Land Observation Satellites

3.2.2.1 ESA Satellites

(1) *CryoSat-2*

On April 8, 2010, the ESA launched CryoSat-2 using a Dnepr rocket. As one of the primary missions of the European Earth Observation Program (EOP), CryoSat uses a radar altimeter to measure the thickness of Earth's land ice and sea ice sheets, especially polar ice and oceanic floating ice, to study the effects of global warming. Earlier, in October 2005, the launch of CryoSat-1 was unsuccessful due to a rocket failure.

SIRAL is the main payload of CryoSat-2, weighing 62 kg (Dibarboure et al. 2011). It is mainly used to observe the internal structure of ice shields and study sea ice and landforms. SIRAL has three measurement modes: the low-resolution measurement (LRM) mode, which is only used to measure relatively flat polar and oceanic ice sheets; the SAR mode that is used to measure sea ice with an along-track resolution of 250 m; and the InSAR mode that is used to study ice sheets in more complex and steep areas with a measurement accuracy of 1 to 3 cm (Wingham et al. 2006). In contrast to traditional radar altimeters, the delay Doppler radar altimeter (DDA) adopted by SIRAL can emit continuous pulse trains and can make efficient use of Earth's surface reflection power via full Doppler bandwidth. SIRAL was designed based on existing instruments but has improved performance compared with the radar altimeters on board ERS-1, ERS-2 and ENVISAT. SIRAL has two pairs of Cassegrain antennas that are used to transmit radar signals and receive signals reflected from the ground to obtain accurate information about polar and sea ice thickness. SIRAL can accurately measure irregular and steep edges of land ice, and can obtain data from sea and river ice. The characteristics of SIRAL are shown in Table 3.5.

Table 3.5 SIRAL characteristics

Parameter	Mode of measurement		
	LRM	SAR	InSAR
Receiving chain	1 (left)	1 (left)	2 (left and right)
Sampling interval (m)	0.47	0.47	0.47
Bandwidth (MHz)	350	350	350
Pulse repetition frequency (PRF) (Hz)	1,970	17.8	17.8
Transmitter pulse width (μs)	49	49	49
Effective echo width (μs)	44.8	44.8	44.8
Pulse duration (ms)	None	3.6	3.6
Color synchronization pulse	None	64	64
Color synchronization pulse period (ms)	None	11.7	46.7
Tracking pulse bandwidth (MHz)	350	350	40
Average tracking pulse/46.7 ms	92	32	24
Data transmission rate (Mbps)	0.051	11.3	11.3 (2)
Power consumption (W)	95.5	127.5	127.5

(2) *Copernicus Program*

The Copernicus program, formerly Global Monitoring for Environment and Security (GMES), was a major space development program launched by the European Union in 2003. Its main purpose is to ensure Europe's sustainable development, enhance international competitiveness, security and to realize real-time dynamic monitoring of the environment by coordinating, managing and integrating the observation data of existing and future European and non-European (third-party) satellites.

In terms of EOS infrastructure development, the GMES program is divided into three parts. The first part is the space-based observation for which ESA is responsible. New satellites will be launched and the existing satellites are divided into six mission groups (see Table 3.6). The second part is the ground-based observation for which the European Environment Agency (EEA) is responsible. The third part is data sharing, which calls for building capacity for comprehensive and sustainable observation data applications and the construction of network entrances for data access; data services are mainly provided by the ESA, French Space Agency (CNES), and EUMETSAT.

3.2.2.2 France's Satellites

On February 22, 1986, France launched its first Earth resources observation satellite, SPOT-1. Thus far, seven SPOT satellites have been sent into space. The sounders adopted by these satellites have unique characteristics and the imaging method is also unique. Additionally, SPOT satellites are the world's first remote sensing satellites

Table 3.6 The Copernicus (GMES) space segment

Satellite	Function	Purpose	Launch date
Sentinel 1	SAR imaging	Continuous all-weather monitoring of ships and oil spills, other applications	Sentinel 1A: 2014.4.3 Sentinel 1B: 2016.4.25
Sentinel 2	Multispectral imaging	Land applications such as for cities, forests, agriculture, etc.	Sentinel 2A: 2015.6.23 Sentinel 2B: 2017.3.7
Sentinel 3	Ocean and land monitoring	Ocean color, vegetation, sea surface and land surface temperatures, sea wave height, etc.	Sentinel 3A: 2016.2.16 Sentinel 3B: 2018.4.25
Sentinel 4	Geosynchronous orbit—atmospheric monitoring	Monitoring of atmospheric composition and boundary layer pollution	
Sentinel 5	Low-orbit atmospheric research satellite	Monitoring of atmospheric composition	Sentinel 5P: 2017.10.13
Sentinel 6	Non-sun-synchronous orbit at 1,336 km mean altitude	Providing reference continuity and a high-precision ocean topography service after Jason-3	

to have stereo imaging capability. Basic information on the SPOT series is shown in Table 3.7.

The CNES launched the SPOT-5 remote sensing satellite in May 2002, with a design life of five years and total mass of 3,030 kg. Compared with the first four SPOT satellites, SPOT-5 has significantly improved observation capability and incorporated new instruments (Table 3.8), including the following: (1) An HSR with a panchromatic spectral resolution of 10 m, (2) two HRGs with working bands that differ from HRV and HRVIR, and (3) a VEGETATION-2 imager that could achieve global coverage almost every day with an imaging resolution of 1 km.

SPOT-6 was launched by India's Polar Satellite Launch Vehicle on flight C21 on September 9, 2012 and SPOT-7 was launched on PSLV flight C23 on June 30, 2014. They form a constellation of Earth-imaging satellites designed to provide continuity of high-resolution, wide-swath data up to 2024. EADS Astrium took the decision to build this constellation in 2009 based on a perceived government need for this kind of data. SPOT-6 and SPOT-7 are phased in the same orbit as Pléiades 1A and Pléiades 1B, which are at an altitude of 694 km, forming a constellation of 2-by-2 satellites that are 90° apart from one another.

Table 3.7 SPOT satellite information

Satellite	Launch date	Sensor	Service period (year)	Width (km)	Altitude (km)
SPOT-1	1986.02.22	Stereo imaging system with a pushbroom scanner (HRV)	1986–1990	2 × 16	830
SPOT-2	1990.01.22	Stereo imaging system with a pushbroom scanner (HRV)	1990–2006	2 × 16	830
SPOT-3	1993.09.26	Improved HRV, solid altimeter, laser reflector	1993–1996	110–2,000	832
SPOT-4	1998.03.24	Improved HRV, HRVIR	1998–2013	110–2,200	1,334
SPOT-5	2002.05.03	HRG, HRVIR, HSR	Still in operation	60 × 60–60 × 120	830
SPOT-6	2012.09.09	Multispectral Imagery	Still in operation	60 × 60	695
SPOT-7	2014.06.30	Multispectral Imagery	Still in operation	60 × 60	695

Table 3.8 Technical parameters of the three sensors on board SPOT-5

Type of remote sensor	Waveband	Wavelength range (μm)	Resolution (m)	Width (km)
HRG	Panchromatic	0.49–0.69	2.5 or 5	60
HRVIR	Multispectral	0.49–0.61	10	60
		0.61–0.68	10	60
		0.78–0.89	10	60
		1.58–1.75	20	60
		0.43–0.47	1,000	2,250
		0.61–0.68	1,000	2,250
		0.78–0.89	1,000	2,250
		1.58–1.75	1,000	2,250
HSR	Panchromatic	0.49–0.69	10	120

3.2.2.3 Germany's Satellites

CHAMP is a small satellite mission for geoscience research, atmospheric studies, and applications headed by the German Research Centre for Geosciences (GFZ) (GFZ 2018; Guo et al. 2008). As a near-polar, low Earth orbit satellite equipped with high-precision, multifunction, completely satellite-borne instruments (magnetometer, accelerometer, STAR sensor, GPS receiver, laser mirror, ion drift meter). CHAMP had a design life of five years, and ended on September 19, 2010. Its shape and onboard instruments are shown in Fig. 3.3. It could simultaneously measure Earth's gravitational and magnetic fields with high precision and detect their temporal and spatial changes (Baduraet al. 2006).

The CHAMP mission had three main goals: (1) to accurately determine the long-wavelength characteristics of the Earth's gravitational field and its temporal changes; (2) to estimate, with unprecedented accuracy, temporal and spatial variations of the magnetic field of the Earth's main body and crust, and all components of the magnetic field; and (3) to study temperature, water vapor, and electrons using a large amount of globally distributed GPS signal refraction data generated by the atmosphere and ionosphere.

TerraSAR-X is a German SAR satellite mission for scientific and commercial applications that was launched on June 15, 2007. The project is managed by the DLR (German Aerospace Center). In 2002, EADS Astrium GmbH was awarded a contract to implement the X-band TerraSAR satellite (TerraSAR-X) on the basis of a public-private partnership agreement (PPP). In this arrangement, EADS Astrium funded part of the implementation cost of the TerraSAR-X system.

The science objectives are to make multimode and high-resolution X-band data available for a wide spectrum of scientific applications in fields such as hydrology, geology, climatology, oceanography, environmental and disaster monitoring, and cartography (DEM generation) using interferometry and stereometry.

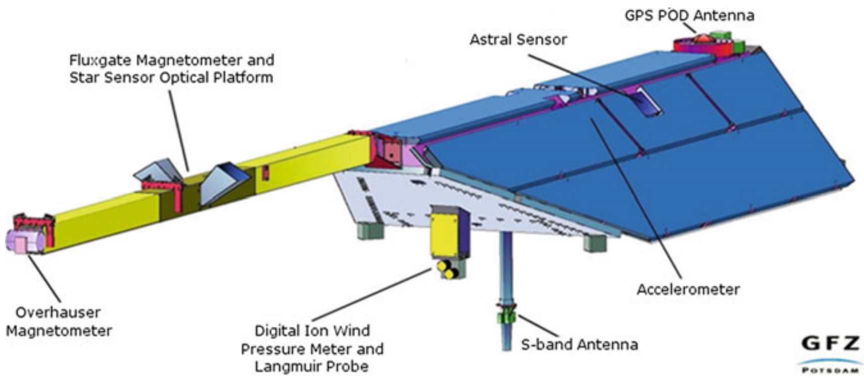

Fig. 3.3 CHAMP satellite structure (GFZ 2018)

3.2.3 *China's Land Observation Satellites*

3.2.3.1 Resource Satellites

Resource satellites are used to survey the Earth's natural resources and carry out scientific research on the Earth system. China has developed a series of satellites for land observation.

(1) *CBERS satellites*

The China-Brazil Earth Resource Satellites (CBERS) were jointly developed by China and Brazil using their combined investment in accordance with an agreement signed by both countries in 1988. CBERS was shared by the two countries after being put into operation. The first CBERS (CBERS-1) was successfully launched in 1999 as China's first-generation transmission-type Earth resource satellite. CBERS-02 was the successor to CBERS-01 and had the same function, composition, platform, payload, and nominal performance parameters as its predecessor. CBERS-02 was launched from the Taiyuan Satellite Launch Center on October 21, 2003.

The payload and orbital parameters of CBERS-01/2 are listed in Table 3.9 (China Center for Resource Satellite Data and Applications 2012; China Academy of Space Technology 2004). The CBERS-1/02 payload included three kinds of sensors: a charge-coupled device (CCD), an infrared multispectral scanner (IRMSS), and a

Table 3.9 Basic parameters of the CBERS-01/2 sensors

	CCD camera	Wide field imager (WFI)	Infrared multispectral scanner (IRMSS)
Type of sensor	Pushbroom	Pushbroom (discrete camera)	Oscillating scanning (forward and reverse)
Visible/near infrared band (μm)	1: 0.45–0.52 2: 0.52–0.59 3: 0.63–0.69 4: 0.77–0.89 5: 0.51–0.73	10: 0.63–0.69 11: 0.77–0.89	6: 0.50–0.90
Shortwave infrared band (μm)	N/A	N/A	7: 1.55–1.75 8: 2.08–2.35
Thermal infrared band (μm)	N/A	N/A	9: 10.4–12.5
Radiation quantization (bit)	8	8	8
Swath (km)	113	890	119.5
Number of pixels per band	5,812 pixels	3,456 pixels	Bands 6, 7 and 8: 1,536 pixels; band 9: 768 pixels
Spatial resolution (nadir) (m)	19.5	258	Bands 6, 7 and 8: 78 m; band 9: 156 m

Table 3.10 CBERS-02B technical parameters

Payload	Band no.	Spectral range (μm)	Resolution (m)	Swath (km)	Side view ability	Repetition period (d)	Data transmission rate
Panchromatic multispectral camera	B01	0.45–0.52	20	113	±32°	26	2 × 53
	B02	0.52–0.59	20				
	B03	0.63–0.69	20				
	B04	0.77–0.89	20				
	B05	0.51–0.73	20				
High-resolution camera (HR)	B06	0.5–0.8	2.36	27		104	60
Wide field imager (WFI)	B07	0.63–0.69	258	890		5	1.1
	B08	0.77–0.89	258				

wide field imager. Other loads included a high-density digital recorder (HDDR), a data collection system (DCS), a space environment monitor (SEM), and a data transmission system (DTS).

(2) *CBERS-02B*

CBERS-02B was an Earth observation satellite jointly developed by China and Brazil. The satellite was sent into orbit on September 19, 2007 from the Taiyuan Satellite Launch Center, and the first batch of Earth observation images was received on September 22, 2007. The satellite is no longer in operation. Its technical parameters are shown in Table 3.10.

CBERS-02B was equipped with three spatial resolutions: high, medium, and low. A combination of the CCD and HR images sent back from the satellite helped accurately identify and interpret residential areas, roads, forests, mountains, rivers, and other ground features. It could monitor the expansion of urban areas and provide a basis for urban planning and construction. Furthermore, it could provide support for decision making for precision agriculture. CBERS-02B could also be used to produce detailed maps such as dynamic land use maps and to update large-scale topographic maps.

(3) *ZY-1 02C*

The ZY-1 02C resource satellite was launched on December 22, 2011. It weighs approximately 2,100 kg and had a design life of three years. ZY-1 02C carries a panchromatic multispectral camera and a high-resolution panchromatic camera.

The satellite has two notable features. First, its 10-m resolution P/MS multispectral camera boasts the highest resolution of the multispectral cameras installed on China's civilian remote sensing satellites. Second, the two 2.36-m resolution HR cameras it carries make the monitoring swath as wide as 54 km, which greatly increased the data coverage and significantly shortened the satellite's repetition period. ZY-1 02C's payload parameters are shown in Table 3.11 (China Center for Resource Satellite Data and Applications 2012; China Academy of Space Technology 2004).

Table 3.11 ZY-1 02C sensor parameters

Parameter		P/MS camera	HR camera
Spectral range (μm)	Panchromatic	B1: 0.51–0.85	0.50–0.80
	Multispectral	B2: 0.52–0.59	
		B3: 0.63–0.69	
		B4: 0.77–0.89	
Spatial resolution (m)	Panchromatic	5	2.36
	Multispectral	10	
Width (km)		60	Single camera: 27; double camera: 54
Side view ability (°)		±32	±25
Repetition period (d)		3–5	3–5
Coverage period (d)		55	55

(4) *ZY-3*

The ZY-3 resource satellite was launched on January 6, 2012. It weighs approximately 2,650 kg and had a design life of five years. The satellite's mission is to continuously, reliably, and rapidly capture high-resolution stereo images and multispectral images of all parts of the country for a long period of time.

ZY-3 is China's first high-resolution civilian optical transmission-type stereo mapping satellite that integrates surveying, mapping, and resource investigation functions. The onboard front-view, rear-view, and vertical-view cameras can capture stereoscopic pairs in the same region from three different viewing angles to provide a wealth of three-dimensional geometric information. The image control and positioning precision are greater than one pixel. The swath of the front-view and rear-view stereoscopic pairs is 52 km wide and the baseline-height ratio is 0.85–0.95. The vertical image is 2.1 m, meeting the demand for 1:25,000 topographic map updates. ZY-3's payload parameters are shown in Table 3.12 (China Center for Resource Satellite Data and Applications 2012; China Academy of Space Technology 2004).

In 2012, ZY-3 sent back 1,590 batches of raw data, totaling 250 TB. The valid data covered 7.5 million square kilometers in China and 30 million square kilometers across the world. Imagery of Dalian, China, captured by the ZY-3 satellite is shown in Fig. 3.4.

3.2.3.2 Environment and Disaster Reduction Satellites

The environment and disaster reduction satellites are collectively referred to as the "China Small Satellite Constellation for Environment and Disaster Monitoring and Forecasting" ("Small Satellite Constellation" for short). The constellation is capable of using visible, infrared, microwave remote sensing and other means of observation

Table 3.12 ZY-3 sensor parameters

Platform	Payload	Band no.	Spectral range (μm)	Spatial resolution (m)	Width (km)	Side view ability (°)	Revisit time (d)
ZY-3	Front-view camera	–	0.50–0.80	3.5	52	±32	3–5
	Rear-view camera	–	0.50–0.80	3.5	52	±32	3–5
	Vertical-view camera	–	0.50–0.80	2.1	51	±32	3–5
	Multispectral camera	1	0.45–0.52	6	51	±32	5
		2	0.52–0.59				
		3	0.63–0.69				
		4	0.77–0.89				

Fig. 3.4 Image of Dalian, China, acquired by the ZY-3 satellite

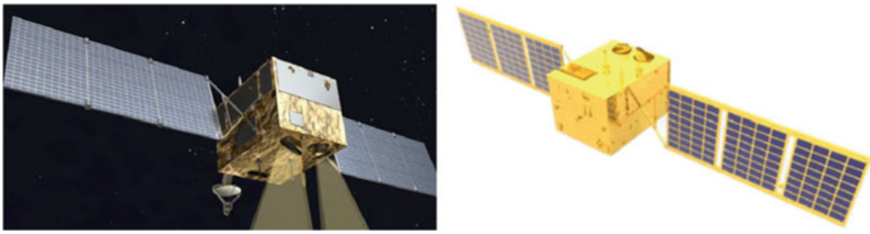

Fig. 3.5 The HJ-1A (left) and HJ-1B (right) satellites

to meet the needs of all-weather, 24-h observation and forecasting of natural disasters and environmental events.

(1) *HJ-1A/B*

The HJ-1A and HJ-1B environment and disaster reduction satellites were launched at 11:25 on September 6, 2008. HJ-1A carries a CCD camera and hyperspectral imager (HSI) and HJ-1B is equipped with a CCD camera and infrared scanner (IRS). HJ-1A and HJ-1B are equipped with the same type of CCD camera. The two cameras were placed symmetrically across the nadir, equally dividing the field of view. The cameras make parallel observations to achieve pushbroom imaging in four spectral bands with a 700-km Earth observation swath and a ground pixel resolution of 30 m. Additionally, the HSI on HJ-1A realizes pushbroom imaging in 110–128 spectral bands with a 50-km Earth observation swath and a ground pixel resolution of 100 m. HSI has a side view ability of ±30° and an onboard calibration function. The IRS on board HJ-1B completes imaging in four spectral bands (near, short, medium and long) with a 720-km Earth observation swath and a ground pixel resolution of 150/300 m. The two satellites are shown in Fig. 3.5.

(2) *HJ-1C*

HJ-1C is China's first S-band small SAR and environment and disaster reduction satellite, launched on November 9, 2012. HJ-1C has a mass of 890 kg and a sun-synchronous orbit at an altitude of 500 km. The local time of the orbital descending node is 18:00. Together with HJ-1A and HJ-1B, HJ-1C constitutes the first stage of China's environment and disaster reduction satellite constellation.

HJ-1C is equipped with an S-band SAR. Its payload works in two modes (strip mode and scanning mode) and employs a 6 × 2.8 m foldable mesh parabolic antenna. The SAR antenna was unfolded once HJ-1C entered orbit. It went into a swath imaging work mode after preparation. The onboard SAR has two imaging swaths: 40 and 100 km. The SAR's single-view spatial resolution is 5 m and the four-view spatial resolution is 20 m. Most of the HJ-1C's SAR images are taken in a multiview mode. The HJ-1C satellite is shown in Fig. 3.6.

The payload parameters of HJ-1C are shown in Table 3.13 (Satellite Environment Center, Ministry of Environmental Protection 2010a).

Fig. 3.6 The HJ-1C satellite

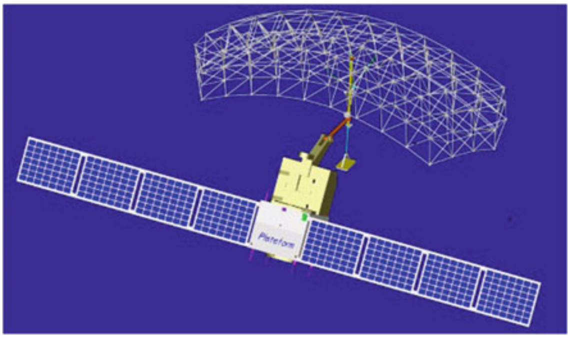

Table 3.13 HJ-1C's payload parameters

Parameter	Value
Operating frequency (MHz)	3,200
Side view	Side-looking
Spatial resolution (m)	5 m (single-view); 20 m (four-view)
Width of imaging swath (km)	40 (strip mode); 100 (scanning mode)
Radiometric resolution (dB)	3
Polarization mode	VV
Viewing angle (°)	25–47

3.2.3.3 Satellites of the High-Resolution Earth Observation Program

Globally, the United States was the first country to develop high-resolution Earth observation systems. Other countries such as Israel, France, and India have only one or two of these satellites each. Currently, China has no high-resolution satellites. According to the China Geographic Surveying and Mapping Information and Innovation Report (2012), although China has achieved success in satellite remote sensing technology, it is still behind in high-resolution civilian remote sensing satellite technology and its commercial applications.

GF-1 (Gaofen-1) was the first satellite of China High-resolution Earth Observation System (CHEOS) and was launched using an LM-2D rocket from the Jiuquan Satellite Launch Center on April 26, 2013. GF-1's development helped China master key technologies such as high spatial resolution, multispectral sensors, optical sensors, wide coverage, multipayload image mosaic fusion, precise and stable altitude control, and high-resolution data processing. Additionally, the development of GF-1 helped improve the capability for independent development of high-resolution satellites, and enhanced the self-sufficiency of high-resolution remote sensing data. The design life of GF-1 is five to eight years (Ding 2013).

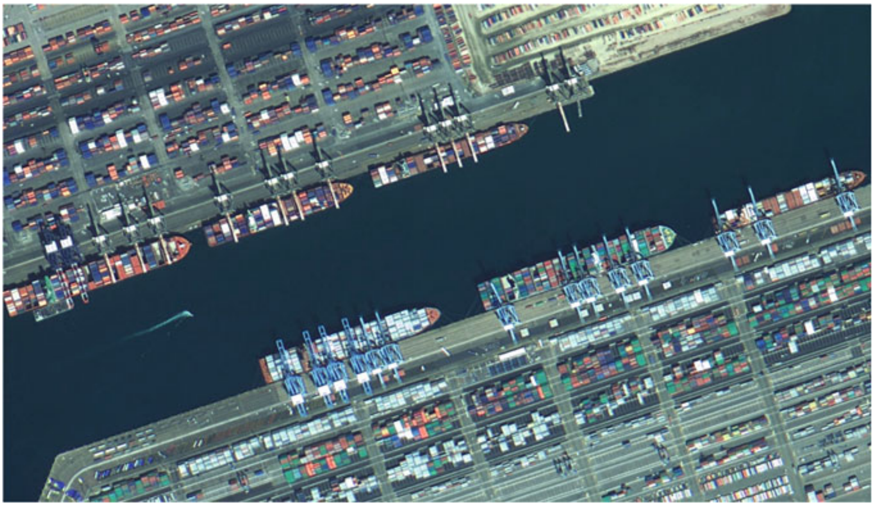

Fig. 3.7 GF-2 image (resolution: 0.8 m)

On April 28, 2013, GF-1 began imaging and sending data. Data were received by the RADI Miyun Ground Station and processed by the China Center for Resource Satellite Data and Application. The first batch of images included four types: 2 m panchromatic, 8 m multispectral, 16 m multispectral, and 2 m panchromatic fused with 8 m multispectral.

GF-2 was launched successfully from Taiyuan Satellite Launch Center using an LM-4B carrier rocket on August 19, 2014. The successful launch was a result of special high-definition projects, indicating that Chinese remote sensing satellites were entering a submeter "high-definition era". GF-2's spatial resolution was 1.0 m and the swath width was 45 km, which was the largest imaging width of similar satellites of other countries (Fig. 3.7). GF-2 will be used for geographic and resource surveillance, environmental and climate change monitoring, precision agriculture, disaster relief, and city planning. The satellite is equipped with two cameras with the same resolution. The GF-2 camera can "twist its neck" to observe a range of ±35° in 180 s. GF-2 can swivel on its axis 35° to either side. Additionally, GF-2's five-year lifetime is longer than that of most other Chinese satellites, but the desired goal is eight years.

The GF-3 satellite is a new high-resolution SAR imaging satellite launched by an LM-4C rocket at 06:55 on August 10, 2016. It blasted off at the Taiyuan Satellite Launch Center in Taiyuan, the capital of northern China's Shanxi Province. As China's first C-band SAR imaging satellite that is accurate to one meter, it covers the globe with an all-weather, 24-h observation service and will be used for disaster warning, weather forecasting, water resource assessments, and the protection of maritime rights. With 12 imaging modes, the high-definition observation satellite can take wide pictures of the Earth and photograph detailed scenarios of specific areas. GF-3 is also China's first low orbit remote sensing satellite that has a lifespan

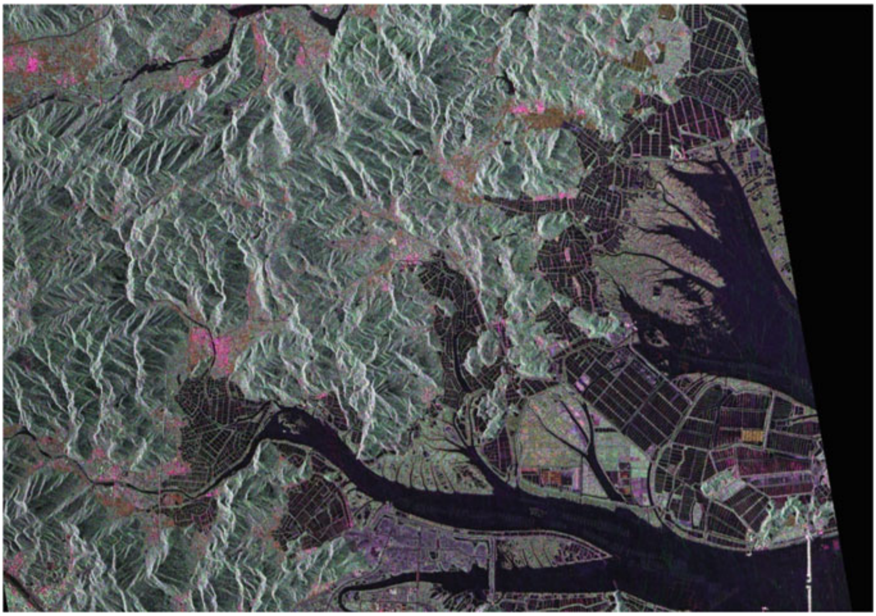

Fig. 3.8 GF-3 image (full polarization)

of eight years. It provides high-definition remote sensing data for its users over long periods of time. GF-3 is a polar orbit satellite with a high spatial resolution (Fig. 3.8) that can play a role in observing slowly changing objects such as water bodies, ice, and snow.

On June 26, 2015, China successfully launched the high-definition Earth observation satellite GF-8 into orbit from the Taiyuan Satellite Launch Center. GF-8 is an optical remote sensing satellite used in land surveying, urban planning, land delineation, highway and railway network design, crop yield estimation, disaster prevention and reduction, and other fields. The GF-9 satellite was launched from the Jiuquan Satellite Launch Center using an LM-2D carrier rocket on September 14, 2015. GF-9 is also an optical remote sensing satellite under CHEOS. The satellite can provide pictures with a ground pixel resolution of less than 1 m. It will be used in land surveying, urban planning, road network design, agriculture, and disaster prevention and relief.

On December 29, 2015, GF-4 was launched from the Xichang Satellite Launch Center in the southwestern province of Sichuan on board an LM-3B carrier rocket. It was the 222nd flight of the Long March rocket series. In contrast to GF-1 and GF-2, which orbit at low elevations (600–700 km) around Earth, GF-4 orbits 36,000 km away and moves synchronously with Earth. It can spot an oil tanker at sea using the CMOS camera, and features the best imaging capability among global high-orbit remote sensing satellites. GF-4 is China's first geosynchronous orbit HD optical imaging satellite and the world's most sophisticated HD geosynchronous orbit remote

Table 3.14 GF satellite parameters

Satellite	Sensor
GF-1	2 m panchromatic/8 m multispectral/16 m wide-swath multispectral
GF-2	1 m panchromatic/4 m multispectral
GF-3	1 m C-SAR
GF-4	50 m stationary gazing camera
GF-5	Visible shortwave infrared hyperspectral camera Full-spectrum spectral imager Atmospheric aerosol multiangle polarization detector Atmospheric trace gas differential absorption spectrometer Main atmospheric greenhouse gas monitor Ultrahigh-resolution infrared atmospheric sounder
GF-6	2 m panchromatic/8 m multispectral/16 m wide-swath multispectral
GF-7	High space three-dimensional mapping instrument

sensing satellite. It will be used for disaster prevention and relief, surveillance of geological disasters and forest disasters, and meteorological forecasting.

The GF-5 and GF-6 satellites were launched on May 9 and June 2, 2018, respectively. GF-5 was designed to run on a sun-synchronous orbit and carries six payloads: an advanced hyperspectral imager (AHSI), a visual and infrared multispectral imager (VIMI), an atmospheric infrared ultraspectral sounder (AIUS), a greenhouse gases monitoring instrument (GMI), an environmental trace gases monitoring instrument (EMI), and a directional polarization camera (DPC). The GF-6 satellite has a similar function to the GF-1 satellite but has better cameras, and its high-resolution images can cover a large area of the Earth, according to the State Administration of Science, Technology and Industry for National Defence. GF-6 can observe the nutritional content of crops and help estimate the yields of crops such as corn, rice, soybeans, cotton and peanuts. Its data will also be applied in monitoring agricultural disasters such as droughts and floods, evaluation of agricultural projects and surveying of forests and wetlands.

Parameters of the GF satellites are shown in Table 3.14.

3.2.3.4 Remote Sensing Microsatellites

Microsatellites are a new type of satellite that is low-cost and has a short development time and more flexible operation than conventional spacecraft that are heavy, costly, and time-consuming to develop. The spatial and temporal resolutions of Earth observation can be significantly improved using a distributed constellation of microsatellites. As a result, microsatellites are becoming more widely used around the world. China has launched several series of microsatellites for Earth observation, such as the "SJ" series, "Tsinghua-1", "NS-2", and "Beijing-1", which have improved and enriched the Chinese satellite observation system.

SJ-9A and SJ-9B are a new generation of microsatellite launched in 2012. They are the first satellites in the "New-tech Civilian Experimental Satellite" series. SJ-9A is equipped with a high-resolution multispectral camera with a panchromatic resolution of 2.5 m and multispectral resolution of 10 m. SJ-9B carries longwave infrared focal plane components for optical imaging with a resolution of 73 m. As of August 2013, the "SJ" satellite series had developed up to SJ-11E and provided adequate services for China's space science and technology experiments (Guo et al. 2013).

3.2.3.5 Remote Sensing from the Shenzhou Spacecraft

China has successfully developed and launched ten Shenzhou spacecraft, representing the country's achievements and capability in space science and technology. A series of scientific experiments such as space measurement, environmental monitoring, and Earth observation have been carried out in space with the support of the Shenzhou spacecraft. The Shenzhou spacecraft have accelerated the development of Earth observation technology in China.

In 2011, China's first space laboratory, Tiangong-1, was successfully launched. It was the starting point for Chinese space station development and signified that China had the ability to build short-term untended space stations. In the same year, Tiangong-1 successfully docked with the Shenzhou-8 unmanned spacecraft, revealing that China had achieved a series of key technologies such as space rendezvous and docking and operation of combined bodies. Shenzhou-9 and Shenzhou-10 were launched in 2012 and 2013, respectively. Shenzhou-11 was launched on October 17, 2016. For the first time, China realized space rendezvous and docking of manned spacecraft, and Chinese astronauts carried out teaching activities in space, marking an important step forward in China's space laboratory development (Jiang 2013). Figure 3.9 shows the development timeline of the Shenzhou series of spacecraft.

3.2.3.6 Commercial Remote Sensing Satellites

China's government is encouraging more participation from the private sector in commercial space programs to ensure the sustainable growth of the nation's space industry, and some commercial remote sensing satellites and missions have been launched or are planned, including Jilin-1, Beijing-2, SuperView-1, and Lishui-1.

The Jilin-1 satellites are China's first self-developed remote sensing satellites for commercial use and were launched from the Jiuquan Satellite Launch Center in northwestern China's Gansu Province on Oct. 7, 2015. The system includes one optical remote sensing satellite, two satellites for video imaging and another for testing imaging techniques. Jilin Province is one of China's oldest industrial bases and is developing its satellite industry as a new economic driver. The Jilin-1 GP 01 and 02 satellites for multispectral imaging were launched on a Long March 11 rocket from the Jiuquan Satellite Launch Center on January 21, 2019. By 2020, the plans

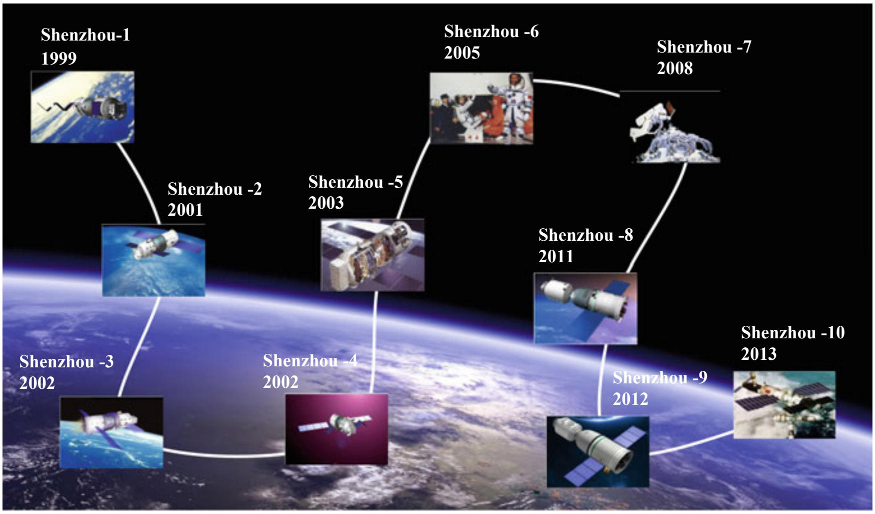

Fig. 3.9 Roadmap of the Shenzhou spacecraft program

indicate a 60-satellite orbital constellation capable of a 30-min update. From 2030, the Jilin constellation will have 138 satellites in orbit, forming a 24-h, all-weather, full-spectrum acquisition segment with the capability of observing any arbitrary point on the globe with a 10-min revisit capability, providing the world's highest spatial and temporal resolution space information products.

The Beijing-2 remote sensing satellite constellation comprises three identical optical EO satellites, which makes it possible to target any place on Earth once per day. The constellation provides less than 1-m high-resolution imagery products with a 23.4-km swath. The constellation was launched on July 10, 2015 from the Dhawan Space Centre in Sriharikota, India. The space and ground segments were designed to efficiently deliver timely information. The satellites were developed by the UK-headquartered Surrey Satellite Technology Ltd. (SSTL), which is the world's leading small satellite company and part of the Airbus Group. The Twenty First Century Aerospace Technology Company (21AT) will manage the satellites' operation, which includes observation and control, data reception and production, and related services. The satellites will provide the best combination of spatial resolution and temporal resolution to stimulate monitoring applications such as urban planning and intelligent management at a very high resolution. The main parameters of the constellation are shown in Table 3.15.

The SuperView-1 01 and 02 satellites were launched by one rocket on December 28, 2016, and two better performing satellites will be launched in the future to comprise four 0.5-m resolution satellites phased 90° from each other on the same orbit to provide services to global clients.

The Lishui-1 satellites, developed by the privately owned Zhejiang Lishui Electronic Technology Co Ltd, are commercial remote sensing satellites that were

Table 3.15 Parameters of the Beijing-2 satellite constellation

Feature	Parameter
Number of satellites	3
Satellite orbit	Sun-synchronous orbit Altitude: 651 km LTAN: 10:30
GSD	<1 m PAN <4 m MS
Bands	B/G/R/NIR
Swath width	23.4 km
MTF	PAN: 10% MS: 20%
Signal-to-noise	>100
Off-pointing capacity	±45°
Revisit	1 day
Lifetime	7 years

launched by an LM-11 solid-fuel rocket from the Jiuquan Satellite Launch Center in northwest China on November 10, 2016. The company plans to build a constellation of up to 80 to 120 commercial satellites to obtain images of the Earth and data to serve business purposes.

3.2.4 Other Land Observation Satellites

3.2.4.1 Japan's Satellites

In 1992, Japan's first Earth resource satellite, JERS-1, was launched into orbit. It carried next-generation SAR and optical sensors with a ground resolution of 18 m. During satellite operation, SAR transmits more than 1,500 microwave pulse signals per second to the surface and receives signals reflected from the ground with the same antenna. The optical sensor is composed of a VNIR radiometer and a shortwave infrared radiometer, and Earth observation is carried out in eight wavebands. Japan's Advanced Earth Observation Satellite (ADEOS), launched on August 17, 1996, was a next-generation large-scale Earth observation satellite that followed Japan's marine observation satellite, MOS, and Japan's Earth resource satellite, JERS-1.

On January 24, 2006, the Japan Space Agency launched the ALOS-1 satellite. ALOS-1 used advanced land observation technologies to obtain flexible, higher resolution Earth observation data that could be applied to mapping, regional observation, disaster monitoring, resource surveys, technical development, and other fields. The basic parameters of the ALOS-1 satellite are shown in Table 3.16.

The JAXA completed operation of ALOS-1 on May 12, 2011. The technologies acquired from ALOS-1 operation were succeeded by the second Advanced Land Observing Satellite (ALOS-2). The PALSAR-2 on board ALOS-2 is an L-band SAR

Table 3.16 ALOS-1 characteristics

Parameter	Value
Launch date	2006.01.24
Type of orbit	Sun-synchronous orbit
Repetition period (d)	46
Altitude (km)	691.65
Inclination (°)	98.16
Attitude control precision (°)	2.0×10^{-4} (in coordination with ground control point)
Positioning accuracy (m)	1.0
Data rate (Mbps)	240 (via data relay satellites)
Onboard data storage	Solid-state data recorder (90 GB)

sensor, a microwave sensor that emits L-band radio waves and receives their reflection from the ground to acquire information. The PALSAR-2 has three modes: (1) Spotlight mode—the most detailed observation mode with 1 by 3 m resolution (25 km observation width); (2) Strip Map mode—a high-resolution mode with the choice of 3, 6 or 10 m resolution (observation widths of 50 or 70 km); and (3) ScanSAR mode—a broad area observation mode with observation widths of 350 or 490 km and resolution of 100 or 60 m, respectively.

3.2.4.2 India's Satellites

Resourcesat is part of the Indian remote sensing satellite system. The first of the Resourcesat satellites, Resourcesat-01, was launched on October 17, 2003. This series is used for disaster forecasting, agriculture, water resources, forest and environment monitoring, infrastructure development, geological exploration, and mapping services.

The second satellite of this series, Resourcesat-02, was the 18th remote sensing satellite designed and developed by ISRO (Fig. 3.10). With a total mass of 1,206 kg, Resourcesat-02 adopts three-axis stabilization technology and was designed to work for five years. Its sensors and related subsystems were jointly developed by the ISRO Satellite Center (ISAC) and the Space Application Center (SAC). The Indian National Remote Sensing Center (NRSC) is responsible for receiving and preprocessing the satellite's image data as well as for production and distribution of products. Resourcesat-02 enhanced the Earth observation capability of the country's remote sensing satellite system to better serve India's economic development and national defense.

Resourcesat-02 replaced Resourcesat-01 after a series of on-orbit tests, and expanded ISRO's remote sensing data services. The Resourcesat-02 satellite's payload includes: linear imaging self-scanning sensors (LISS-3 and LISS-4), an

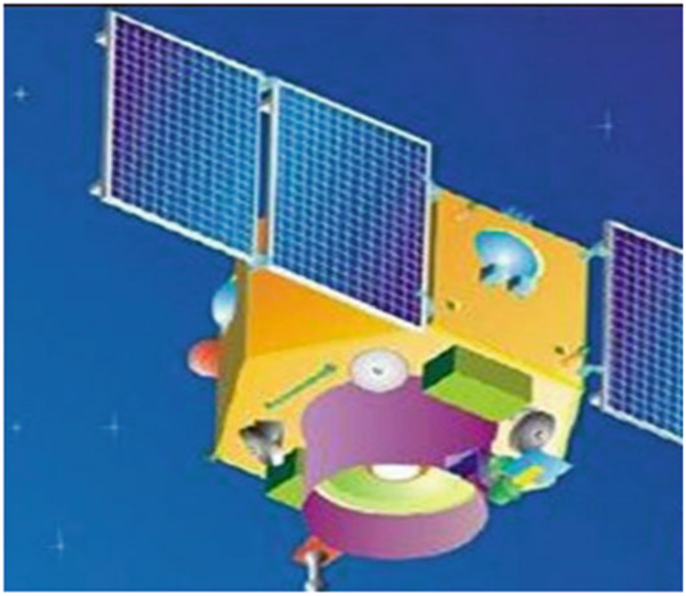

Fig. 3.10 The Resourcesat-02 satellite

advanced wide field-of-view sensor (AWIFS), three high-resolution multispectral cameras, and a marine automatic identification system (AIS). LISS-4 has a spatial resolution of 5.8 m and scanning width of 70 km, can work in the VNIR spectral range, and can obtain cross-track stereo images (Goward et al. 2012).

3.2.4.3 Russia's Satellites

The Resurs-F series of satellites are tasked with monitoring crop growth, ice cover, landforms, and other features. They also undertake scientific research missions. For example, the two Resurs-F1 satellites launched in May and July 1989 were passive atmospheric research satellites, 70 mm in diameter and 78 kg in mass, that were used to study the density of the upper atmosphere. The two satellites also carried scientific instruments from other countries for scientific experiments.

The first Resurs-F satellite was launched on September 5, 1979 from the Plesetsk Launch Site using an SL-4 rocket. The satellite was 7 m long, 2.4 m in diameter, 6,300 kg in mass and was composed of three compartments. The central part of the satellite was a 2.3-m diameter sphere that housed the imaging system, electronic control system, and recovery system. One side was connected to the 3 m long and 2 m wide propulsion module via a fixing mechanism that unlocked when the retarding rocket was ignited. The other side was 1.9 m long and the propulsion unit occupied up to 1.0 m. The propulsion unit was used for orbital adjustment and was cast off when the return capsule re-entered the atmosphere. The remaining 0.9 m of space was

Fig. 3.11 The Resurs-F1 satellite

used to carry additional releasable secondary payloads of up to 30 kg or more. These secondary payloads could be placed inside or outside the return capsule and carried back to the ground. An overview of the Resurs-F1 satellite is shown in Fig. 3.11.

The imaging system on board the Resurs-F1 satellite included an SA-20M long-focus wide imaging system with a KFA-1000 camera and an SA-34 wide mapping and imaging system with a KATE-200 camera. Compared with Resurs-F1, the Resurs-F2 satellite's biggest improvement is the addition of two solar panels, which extended its service life to nearly one month. The first Resurs-F2 satellite, also known as Cosmos-1906, was launched into space in 1987. However, the launch was unsuccessful and the satellite was destroyed in orbit. Resurs-F2 satellites are operating in 170–240 km low Earth orbits and near-polar circular orbits with an orbital inclination of 82.3°. An outline of the Resurs-F2 satellite is shown in Fig. 3.12.

The Resurs-F2's imaging system is significantly different than that of Resurs-F1 and includes a KFA-1000 camera and a high-resolution MK-4 mapping camera. Equipped with a passive remote sensor, the MK-4 camera can record images on three separate pieces of film and perform imaging in any three of the following six spectral bands: 0.63–0.69 μm, 0.81–0.90 μm, 0.52–0.57 μm, 0.46–0.51 μm, 0.58–0.80 μm, and 0.40–0.70 μm. The camera's focal length is 300 m, the spatial resolution is greater than 10 m, the panchromatic spectral resolution is 8 m, and the ground width is 120–180 km. One scan can generate 2,700 images and the image size is 180 × 180 mm with an overlap ratio of 60%. The satellite can be used for mapping, environmental monitoring, and geographic surveys.

The Resurs-O series of satellites were mainly used in geology, cartography, fire detection, ice detection, hydrology, and agriculture. They were designed and manufactured by the then National Institute of Electronics in the former Soviet Union.

Fig. 3.12 The Resurs-F2 satellite

3.3 Ocean Observation Satellites

Ocean satellites are the best tools for understanding Earth's oceans, and can be economically used for real-time, synchronous, and continuous monitoring of large areas. At present, ocean satellites are the primary means of marine environment monitoring, making their development a necessity. Ocean satellites can enhance scientists' capability for marine environment and disaster monitoring, forecasting, and early warning, and can provide efficient services for marine resource surveying, development, and management. These satellites can conduct global surveys of fisheries, scientifically estimate fishery potential, and provide a basis for the development of fishery policies. Furthermore, they can effectively and affordably measure the marine gravity field to provide an understanding of submarine tectonics and oil and gas reserves, and assist in developing offshore oil fields.

3.3.1 US Ocean Observation Satellites

3.3.1.1 Development Stages of US Ocean Satellites

The development of US ocean satellites has experienced four stages (Dong 2012): (1) preparation stage (before 1978); (2) experiment stage (1978–1985); (3) application research stage (1985–1999), and (4) comprehensive oceanographic observation stage (1999–present).

(1) Preparation stage

The first US meteorological satellite, TIROS-I, was launched by NASA in April 1960, followed by TIROS-II, which started sea surface temperature observation. In 1961, the United States began to implement the Mercury Program, making it possible for astronauts to observe the ocean from a high altitude. In 1969, NASA began to promote a marine observation plan; in 1975, GOES-3 was equipped with an altimeter for measuring the distance from the satellite to the sea surface. In 1973, the Skylab space station confirmed the potential of visible and infrared remote sensing in continuous Earth observation.

(2) Experiment stage

In this stage, marine remote sensors were mainly installed on US ocean satellites such as Seasat, Nimbus-7, TIROS-N, and GEOS. The main marine elements inversed in this stage included sea surface temperature, ocean color, and sea ice. In 1981, NOAA satellites began using the multichannel sea surface temperature (MCSST) algorithm to forecast sea surface temperature.

(3) Application research stage

The main ocean satellites launched in this stage were equipped with a variety of microwave monitoring instruments, infrared radiometers and ocean color imagers to monitor the sea surface, submarine topography, sea waves, sea wind, ocean currents, marine pollution, primary oceanic productivity, and other factors. In 1985, the United States launched an ocean topography satellite called Geosat, which was mainly used to measure significant wave height, wind velocity and meso-scale oceanic features. Over the years, Geosat provided a wide range of altimeter data. Other meteorological satellites were also involved in marine observation. For instance, NOAA meteorological satellites were used for sea surface temperature inversion, sea condition monitoring, and sea pollution research. In 1987, the SeaWiFS Working Group of NASA and the Earth Observation Satellite Company (EOSAT) jointly proposed a systematic plan for spaceborne wide-field-of-view marine observation. In August 1997, the United States launched an ocean satellite, SeaSTAR, (also called OrbView-2), which was later included in the EOS program as the first ocean color satellite of the program. Subsequently, the United States developed the navy remote ocean sensing system (NPOSS) and, in cooperation with France, NASA developed TOPEX/Poseidon for observing ocean topography.

(4) Comprehensive oceanographic observation stage

According to the research objectives of the EOS and ESE, the period from 1999 to the present is the comprehensive oceanographic observation stage in the development of ocean remote sensing. The first satellite of the next-generation international Earth observation satellite system, Terra (EOS-AM1), was launched on December 18, 1999, marking the beginning of a new era of human observation of Earth. The second polar-orbiting environmental remote sensing satellite, Aqua (EOS-PM1), was launched on May 4, 2002. Both Terra and Aqua are equipped with a Moderate Resolution Imaging Spectroradiometer (MODIS) that has 36 wavebands ranging from visible to thermal infrared light, nine of which can be used for ocean color remote sensing. Compared with SeaWiFS, MODIS is more advanced and is known as the third-generation ocean color (and meteorological element) sensor (DeVisser 2013). The Jason program was proposed to meet the requirements for establishing a global marine observation system and the demands of oceanic and climatological research. The Jason-2 ocean altimetry satellite (also used for accurate determination of ocean topography) was jointly developed by the Centre National d'Etudes Spatiales (CNES), EUMETSAT, NASA, and NOAA and launched on June 20, 2008. As a follow-up to TOPEX/Poseidon and Jason-1, it is an important observation platform for global oceanographic studies.

3.3.1.2 Typical US Ocean Satellite Systems

(1) Seasat-1

Launched on June 27, 1978, Seasat-1 operated on orbit for 105 days and stopped working on October 10, 1978, due to an electrical system fault. It was launched to demonstrate global monitoring technologies including the observation of oceanic dynamics and satellite orbit characteristics and to provide oceanographic data for the development and application of an operational ocean dynamics monitoring system.

Seasat-1 was the first ocean satellite to use synthetic aperture radar (SAR) for ocean observation by means of remote sensing (Fig. 3.13). Its purpose was to prove the feasibility of using satellites to monitor global oceanic phenomena and help determine the requirements of ocean remote sensing satellite systems. The goal was to collect data about ocean surface wind, sea surface temperature, atmospheric water, sea ice characteristics, ocean topography, and similar parameters. Seasat-1 could cover 95% of the world in a 36-h observation cycle.

(2) OrbView-2

Also called SeaStar, OrbView-2 was launched into a 705 km sun-synchronous orbit on August 1, 1997. The mass of the parent capsule was 155 kg, the mass of the instruments was 45.4 kg, and that of the satellite was 317 kg. The outer dimensions of the satellite were 1.15 × 0.96 × 1.6 m, and the solar wing plate had a span of 3.5 m when unfolded (Fig. 3.14).

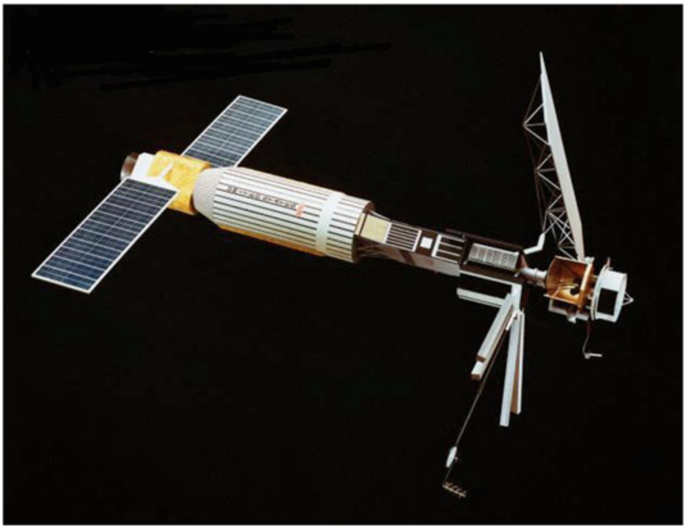

Fig. 3.13 Seasat-1

The satellite carried only one remote sensing instrument, SeaWiFS, which could monitor ocean color, generate multispectral images of the land and sea surface, and analyze the impacts of ocean color changes on the global environment, atmosphere, carbon cycle, and other ecological cycles. SeaWiFS consisted of optical remote sensors and an electronic module, and the satellite covered the global ocean area once every two days.

OrbView-2 was the world's first satellite that could generate color images of the Earth every day. The imager had eight spectral segments, six of which were visible and two of which were near infrared. With a spatial resolution of 1.1 km and a 2,800 km scanning width, OrbView-2 data could be used in the fishing industry, agriculture, scientific research, and environmental monitoring.

(3) Jason-1

As an ocean satellite, Jason-1 is used to study the relationship between the ocean and the atmosphere, monitor global ocean circulation, improve global weather prediction and forecasting, and monitor El Niño, ocean eddies, and other events (Chander et al. 2012). With a total weight of 500 kg and payload of 120 kg, Jason-1 was launched on December 7, 2001 (Fig. 3.15). It was the world's first satellite to use the French Alcatel PROTEUS multifunctional microplatform and carried five scientific instruments: one dual-frequency solid-state spaceborne radar altimeter (Poseidon-2), which was the main payload of Jason-1, one triple-channel microwave radiometer (JMR) used to measure atmospheric water vapor content and provide water vapor correction for the radar altimeter, and three other instruments for accurate orbit determination that comprise one Doppler orbitography by radio positioning integrated by satellite

Fig. 3.14 OrbView-2

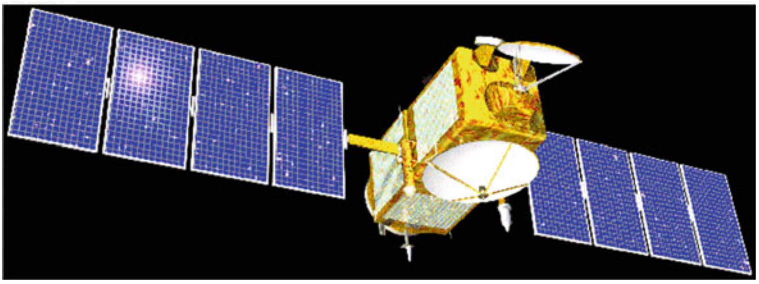

Fig. 3.15 Jason-1 ocean satellite

(DORIS), one laser retro reflector array (LRA), and one turbo rogue space receiver (TRSR).

As the main payload of the Jason-1 satellite, Poseidon-2 was developed by the CNES as an improved model of the Poseidon-1 radar altimeter. In addition to inheriting all the advantages of its predecessor, Poseidon-2 used dual-frequency technology, with working frequencies of 13.575 GHz (Ku-band) and 5.3 GHz (C-band). Compared to other radar altimeters, Poseidon-2 was smaller in volume and lighter weight and had more efficient power consumption. It is mainly used to measure sea surface height, wind velocity, significant wave height, and ionospheric corrections. The main technical parameters of the Poseidon-2 radar altimeter are shown in Table 3.17.

Table 3.17 Main technical parameters of the Poseidon-2 radar altimeter

Satellite feature	Parameter
Operating frequency (GHz)	13.575 (Ku), 5.3 (C)
Pulse repetition frequency (PRF) (Hz)	2,060
Pulse duration (μs)	105
Bandwidth (MHz)	320
Antenna diameter (m)	1.2
Antenna wave width (°)	1.28 (Ku), 3.4 (C)
Power (W)	7

3.3.2 European Ocean Observation Satellites

The successful launch of the first meteorological satellite, Meteosat, in 1977 marked the beginning of the implementation of the European Earth Observation Program (EOP). The main task of Meteosat was to monitor the atmosphere over Europe and Africa. Implementation of the ERS missions in the early 1990s marked the EOP's entry into a new stage. The launch of an ENVISAT satellite in 2002 sped up the pace of EOP implementation. The ESA proposed the Living Planet Programme (LPP) in 1998. Compared with the ERS and ENVISAT missions, the LPP used smaller satellites, was less costly and had better defined targets.

3.3.2.1 ERS-1/2

The ERS-1/2 satellites operated on a near-polar sun-synchronous orbit, with an average orbital altitude of 785 km and an orbital inclination of 98.50°. The local time when the satellite moved from north to south across the equator was 10:30 AM. The ERS-1 launch involved a number of adjustments to the orbital altitude instruments. The three months after launch, the satellite used a three-day period for trial operation at an orbital altitude of 785 km (reference orbit). The orbital adjustment period of the sun-synchronous satellite was 3–176 days, and the main working period was 35 days. The average orbital altitude for the three-day period was 785 km, the orbital altitude above the equator was 909 km, and the satellite circled Earth 43 times. The main parameters of ERS-1/2 are shown in Table 3.18.

The satellite platform carried the following seven instruments (Fig. 3.16): (1) an active microwave instrument (AMI) with an SAR that had a 100-km mapping swath; (2) a wind scatterometer that used three groups of antennas to measure the direction and velocity of sea surface winds; (3) a radar altimeter that was used to accurately measure sea surface topography and elevation, wave height, sea surface wind velocity, and characteristics of sea ice; (4) an orbit-tracking scanning radiometer and microwave sounder; (5) a precision ranging velocimeter that was used to accurately measure the satellite position, orbital characteristics, and the position of fixed ground stations; (6) a laser reflector that used laser beams emitted from the

Table 3.18 ERS-1/2 parameters

Satellite parameter	Value
Weight (kg)	2,400
Total length (m)	11.8
Solar cell array	Area: 11.7 × 2.4 m^2; power: 1.8 KW; service life: 2 years
SAR antenna (m)	10 × 1
Scatterometer antenna (m^2)	Anterio-posterior direction: 3.6 × 0.25; middle direction: 2.3 × 0.35
Radar altimeter antenna diameter (m)	1.2
Communication frequency band	S-band
Orbit	800 km sun-synchronous orbit
Orbital period (d)	35

Fig. 3.16 ERS-1

ground station to measure the satellite orbit and position; and (7) an onboard data processing system.

3.3.2.2 ENVISAT Satellite

Launched on March 1, 2002, ENVISAT was a polar-orbiting Earth observation satellite and the largest Earth observation satellite built (Fig. 3.17). ENVISAT had ten

Fig. 3.17 ENVISAT satellite

Table 3.19 The working modes and characteristics of the ASAR sensor on the ENVISAT satellite

Feature	Image	Alternating Polarization	Wide Swath	Global Monitoring	Wave
Imaging swath width (km)	Max. 100	Max. 100	Approx. 400	Appr. 400	5
Downlink data rate (Mbps)	100	100	100	0.9	0.9
Polarization mode	VV or HH	VV/HH or VV/VH or HH/HV	VV or HH	VV or HH	VV or HH
Resolution (m)	30	30	150	1,000	10

instruments that constituted an observation system that captured lithosphere, hydrosphere, atmosphere, biosphere, and ice layer information.

At the time, the ASAR on board ENVISAT was the world's most advanced spaceborne SAR sensor with new features including multipolarization, multiple modes, and multiple incident angles. The ground resolution of data reached 25 m, and the widest coverage was 400 km. The multipolarization SAR imaging system could acquire copolarization and cross-polarization information of ground objects and more accurately detect features of a target. The five working modes and characteristics of the ENVISAT satellite's ASAR sensor are listed in Table 3.19.

3.3.2.3 The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)

The GOCE was a satellite that adopted new technologies to map the Earth's gravitational field (Fig. 3.18). The GOCE was launched on March 17, 2009 (Metzler and Pail 2005). The satellite started scientific observation activities on September 30, 2009 and carried out its functions during its service life. In October 2010, the first batch of GOCE satellite data was released freely to scientific researchers and noncommercial users across the world, opening up a new historical period for Earth gravity field research.

The GOCE moved on a low, nearly-circular, twilight sun-synchronous orbit. The orbital plane's eccentricity was less than 0.001 and its inclination was 96.7°, leaving a nonobservable area with a spherical radius of approximately 6.7° in the northern and southern polar regions. The satellite's working time was twenty months, including three months of commissioning and calibration followed by a period of scientific measurement and period of dormancy. Due to its energy supply, trial operation, gradiometer calibration, orbital adjustment and other reasons, the time period for scientific observation was only twelve months. Once the satellite's working time period had expired, it was decided to extend the GOCE's operational period based on the working state of all systems and the quality of data products obtained. The original plan was to extend the mission by ten months and increase the observation tasks accordingly (Floberghagen et al. 2011).

The goal of the GOCE mission was to provide a high-precision, high-resolution static Earth gravity model (Bouman et al. 2009). Such models can be obtained based

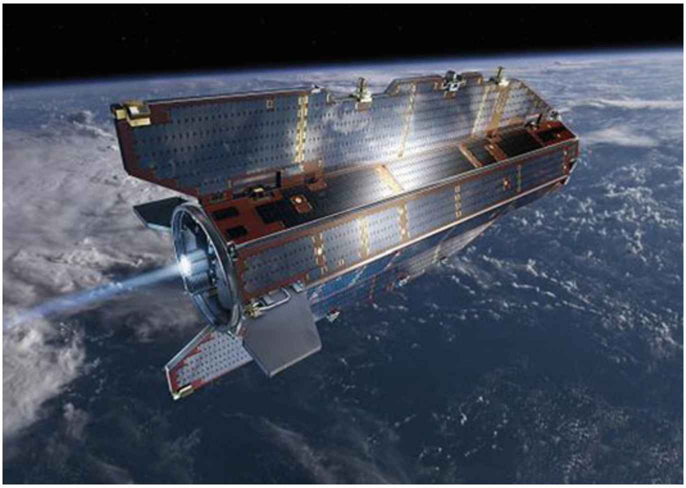

Fig. 3.18 GOCE

on the gravity gradient and GPS tracking data. The specific goals were to: determine global gravity anomalies with a precision of 1 mGal, determine the global geoid with a precision of 1–2 cm, and fulfil these goals with a spatial resolution above 100 km (half-wavelength) (Visser 2010; Gooding et al. 2007).

3.3.3 *China's Ocean Observation Satellites*

China's first independently developed ocean satellite, HY-1A, was launched on May 15, 2002. As an experimental satellite, HY-1A was used to monitor ocean color and temperature. HY-1B was launched on April 11, 2007, and was positioned for operation on September 3. HY-1B was the successor to HY-1A, with a design life of three years, and its technical indicators and functions were superior to those of HY-1A. The HY-2A satellite was launched on August 16, 2011. As a marine dynamic environment satellite, HY-2 worked to detect the sea surface wind field, temperature field, sea surface height, wave field, and flow field. It adopted the platform of the ZY-1 satellite. A roadmap of ocean satellite development is shown in Fig. 3.19.

(1) HY-1A

The ten-band Chinese ocean color and temperature scanner (COCTS) was used to detect ocean color environmental factors (concentration of chlorophyll, content of suspended sediments, and presence of soluble organic matter) and temperature field. The satellite had a nadir ground resolution of 1,100 m, 1,024 pixels per line,

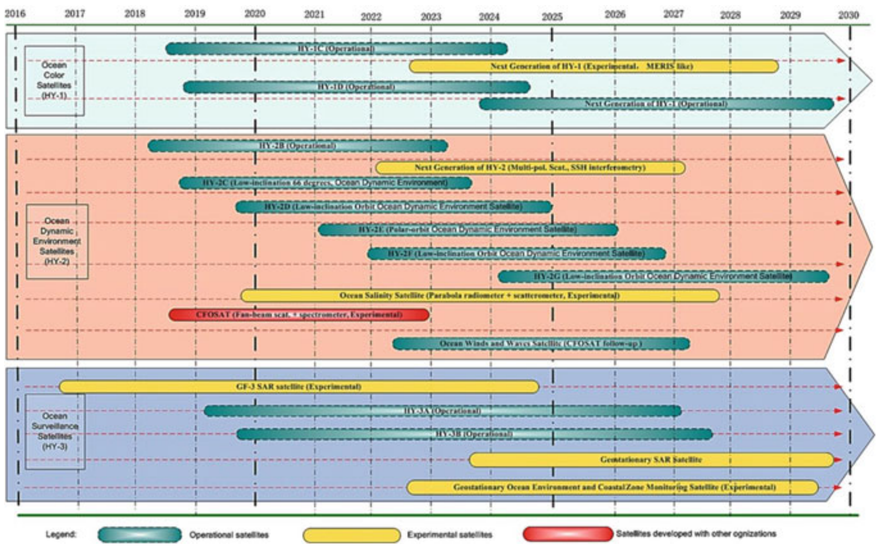

Fig. 3.19 Roadmap of ocean satellite development

Table 3.20 Ocean color and temperature scanner parameters

Parameter	Value
Spectral range (μm)	B1: 0.402–0.422, B2: 0.433–0.453 B3: 0.480–0.500, B4: 0.510–0.530 B5: 0.555–0.575, B6: 0.660–0.680 B7: 0.740–0.760, B8: 0.845–0.885 B9: 10.30–11.40, B10: 11.40–12.50
Band-center wavelength shift (nm)	≤2(B1-B8)
Nadir ground resolution (m)	≤1100
Number of pixels per line	1664
Quantization level (bit)	10
Radiometric precision	Visible light: Infrared: ±1 K (when the onboard calibration accuracy is 300 K)

a quantization level of 10 bits, and a radiometric precision of 10% of the visible light. The four-band CCD imager was used to monitor coastal zone dynamics to obtain relatively high-resolution images of land-sea interaction areas. The imager had a nadir ground resolution of 250 m, 2,048 pixels per line, and ≤5% degrees of polarization.

(2) HY-1B

As the successor of HY-1A, the HY-1B ocean satellite was launched on April 11, 2007, and had a design life of three years. Its payload parameters are shown in Table 3.20 (National Satellite Ocean Application Service 2007, 2011). HY-1B monitors the Bohai Sea, the Yellow Sea, the East China Sea, the South China Sea, and their coastal zones to detect chlorophyll, suspended sediments, soluble organic matter, and sea surface temperature.

(3) HY-2A

The HY-2A ocean satellite was China's first marine dynamic environment satellite to integrate active and passive microwave remote sensors and is capable of high-precision orbital measurement and determination, and all-weather, 24-h global detection. Its mission is to monitor and investigate marine environments and obtain dynamic ocean environment parameters including sea surface wind, wave height, ocean current, and sea surface temperature. HY-2A also provides data for the pre-warning and forecasting of disastrous sea conditions, and offers supportive services for the prevention and mitigation of marine disasters, protection of marine rights and interests, development of marine resources, protection of the marine environment, marine scientific research, and national defense. HY-2A was launched at 06:57 on August 16, 2011 from the Taiyuan Satellite Launch Center using a CZ-4B rocket.

The satellite is equipped with a scanning microwave radiometer, a radar altimeter, a microwave scatterometer, a calibrated microwave radiometer, DORIS, dual-frequency GPS, and a laser range finder. The parameters of the radar altimeter are shown in Table 3.21.

Table 3.21 Technical parameters of the HY-2 radar altimeter

Parameter	Value
Operating frequency (GHz)	13.58, 5.25
Pulse limited footprint (km)	≤2
Altitude measurement precision (cm)	<4
Effective wave height measurement range (m)	0.5–20

3.3.4 Other Ocean Observation Satellites

In addition to the United States and the ESA, Russia, Japan, Canada, and India have launched various ocean satellites into space. Generally, modern ocean satellites have an accurately determined sun-synchronous orbit, use a variety of remote sensors for measurement, and adopt a comprehensive remote sensing platform.

3.3.4.1 Japan's Satellites

On February 19, 1987, Japan launched its first ocean observation satellite, MOS-1, on an N-l rocket from the Tanegashima Space Center (Fig. 3.20).

MOS-1 was loaded with two optical remote sensors: a multispectral electronic self-scanning radiometer (MESSR) and a visible thermal infrared radiometer (VTIR). Other payloads included a microwave scanning radiometer (MSR), a data collection system (DCS), and a visible thermal infrared repeater. The MESSR is an electronic scanning optical observation remote sensor that uses a CCD to capture land and ocean information. Wavelengths ranging from visible light to near infrared are divided into four spectral bands (see Table 3.22). On board the satellite were two identical devices

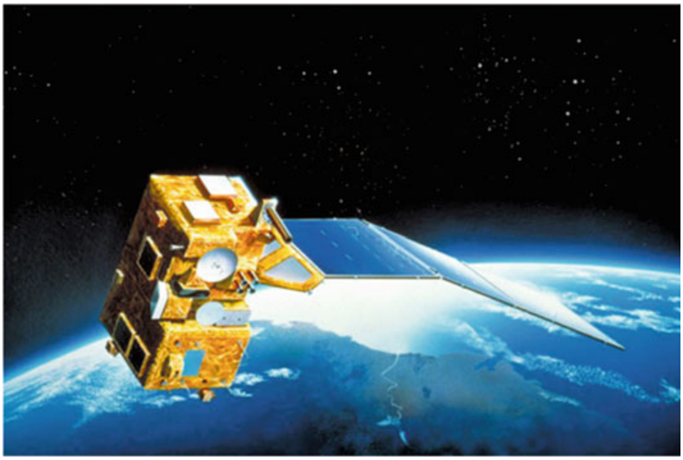

Fig. 3.20 MOS-1

Table 3.22 MOS-1 sensor characteristics

	MESSR	VTIR		MSR
Observation purpose	Ocean color, land use, etc.	Sea surface temperature, etc.		Water vapor, ice, snow, etc.
Observed wavelength (μm)	0.51–0.59	0.5–0.7	6–7	
	0.61–0.69			
	0.72–0.80		10.5–11.5	
	0.80–1.1		11.5–12.5	
Instantaneous field of view (km)	0.05	0.9	2.7	32, 23
Radio wave resolution	39–15 dB	55 dB	0.5 K	<1.5 K
Observation width (km)	100	1500		317
Scanning mode	Electronic scanning	Mechanical scanning		Mechanical scanning

with a land observation width of 100 km, coordinated coverage of 185 km, and ground resolution of 50 m.

3.3.4.2 India's Satellites

OceanSat-1 was launched for the study of marine physics and marine biology on May 26, 1999 using a PSLV-C2 rocket (Dash et al. 2012). It was equipped with an ocean color monitor (OCM) and a multifrequency scanning microwave radiometer (MSMR) (Fig. 3.21). The OCM was used to collect data and worked at 402–422 nm, 433–453 nm, 480–500 nm, 500–520 nm, 545–565 nm, 660–689 nm, 745–785 nm, and 845–885 nm with a spatial resolution of 360 m and width of 1,420 km.

OceanSat-2 was launched on September 23, 2009 using a PSLV-C14 rocket. It functions on a circular near-polar sun-synchronous orbit 720 km above Earth, and continuously provides effective IRS-P4 services (Gohil et al. 2013; Sathiyamoorthy et al. 2012). The observation data from OceanSat-2 are applied to new areas of ocean research such as tornado trajectory prediction, coastal area mapping, and atmospheric research. The OCM and ROSA provide several geophysical parameters such as suspended sediment, yellow matter, phytoplankton, sea surface temperature (SST), sea wind, sea conditions, significant wave height, and atmospheric profiles derived from GPS radio occultation.

Fig. 3.21 OceanSat-1

3.3.4.3 Russia's Satellites

Since 1979, the Soviet Union/Russian Federation has launched a series of ocean color satellites known as the Okean-O1 series of satellites for marine and polar ice observation (Fig. 3.22). Twelve Okean-O1 satellites were launched (including one launch failure) by the end of August 1995 and four satellites were launched between May 1988 and October 1994, referred to as Okean-1 to Okean-4. The satellite payloads included an X-band side-looking radar with 350/1,500 m resolution and 1,380/1,930 km scanning width, and a microwave radiometer with an 8 mm working

Fig. 3.22 Okean-O1 Satellite

frequency and a 550 km scanning width. The Okean-O1 series of satellites functioned at an orbital altitude of 650 km and an inclination of 82.5°. Each satellite weighed 1.95 t and had a design life ranging from six months to a year. In 1999, Russia launched a new type of ocean satellite, Okean-O, whose design life and weight were increased to three years and 6.5 t, respectively. The Okean-O series of satellites adopted a sun-synchronous orbit with an altitude and inclination of 670 km and 98°, respectively. Each satellite was equipped with nine remote sensors, leading to improved optical resolution (25–200 m for visible light and 100–600 m for infrared).

3.3.4.4 Canada's Satellites

RADARSAT is a joint research project conducted by Canada (Canadian Space Agency/Canada Centre for Remote Sensing) and the United States (NASA). The radar is designed to provide detailed information for sea ice, land ice, and climate studies, and the radar images can be used in fields such as oceanography, agriculture, forestry, hydrology, geology, and geography and to provide real-time ice surveillance of the Arctic ocean.

RADARSAT-1 was launched by Canada on November 4, 1995 (Fig. 3.23). Satellite-borne SAR is an active remote sensing device. Because it actively emits electromagnetic waves to obtain information, it can penetrate clouds and fog and overcome night barriers and is capable of all-weather, 24-h observation. It can observe the surface on a regular basis and obtain real-time observation data. The SAR on board RADARSAT-1 was a C-band multiangle sensor with an HH polarization mode and

Fig. 3.23 RADARSAT-1

seven working modes used for coastal zone observation, sea ice monitoring, topographic surveys, and other uses.

RADARSAT-2 was launched in December 2007 as Canada's next-generation commercial radar satellite offering powerful technical advancements for mapping in Canada and around the world. This satellite is a follow-up to RADARSAT-1. It has the same orbit and is separated by half an orbit period (~50 min) from RADARSAT-1 (in terms of the ground track, this represents ~12 days of separation). RADARSAT-2 is a C-band imaging radar system, with a nominal imaging swath from 20 to 500 km, incidence angles from 10° to 60°, and fully polarimetric imaging capability; it is an indispensable tool for managing natural resources and monitoring the environment in the twenty-first century. It fills a wide variety of roles, including in sea ice mapping and ship routing, iceberg detection, agricultural crop monitoring, marine surveillance for ship and pollution detection, terrestrial defense surveillance and target identification, geological mapping, land use mapping, wetlands mapping, and topographic mapping.

3.4 Meteorological Observation Satellites

Meteorological satellites have become an indispensable part of the basic and strategic resources for national economic and social development in countries across the world. As the problems of environmental pollution, resource shortages, and natural disasters become increasingly worse, the role of meteorological satellites in weather forecasting, environmental monitoring, and disaster mitigation and prevention has become more important than ever.

3.4.1 US Meteorological Observation Satellites

Since the launch of its first meteorological satellite in April 1960, the United States has developed two series of meteorological satellites: geostationary meteorological satellites and polar-orbiting meteorological satellites. The former is the Geostationary Operational Environmental Satellite (GOES) series and the latter comprises NOAA satellites in the Defense Meteorological Satellite Program (DMSP).

3.4.1.1 The DMSP Satellite System

DMSP satellites operate on sun-synchronous orbits. Some of the orbital parameters are listed in Table 3.23.

The DMSP satellite series adopts a double-satellite operation system. One satellite operates on a 06:00 AM orbit and the other on a 10:30 AM orbit, both with a repeat observation cycle of twelve hours and seven payloads, which are shown in Table 3.24.

Table 3.23 Orbits of the current DMSP system satellites

Satellite code	Orbital altitude (km)	Orbital period (min)	Orbital inclination (°)	Launch time	Orbiting direction
DMSP 5D 3/F14	833	101	98.7	20:29	Clockwise
DMSP 5D 3/F15	833	101	98.9	20:29	Clockwise
DMSP 5D 3/F16	833	101	98.9	21:32	Clockwise
DMSP 5D 3/F17	850	101	98.7	17:31	Clockwise
DMSP 5D 3/F18	850	101	98.7	17:31	Clockwise

Table 3.24 Payloads of the DMSP system satellites in orbit

Satellite code	Payloads
DMSP 5D 3/F14	OLS, SSB/X-2, SSI/ES-2, SSJ/4, SSM, SSM/I, SSM/T-1, SSM/T-2
DMSP 5D 3/F15	OLS, SSI/ES-2, SSJ/4, SSM, SSM/I, SSM/T-1, SSM/T-2
DMSP 5D 3/F16	OLS, SSI/ES-3, SSJ/5, SSM, SSM/IS, SSULI, SSUSI
DMSP 5D 3/F17	OLS, SSI/ES-3, SSM, SSM/IS, SSULI, SSUSI
DMSP 5D 3/F18	OLS, SSI/ES-3, SSM, SSM/IS, SSULI, SSUSI

The DMSP satellite series uses two data transmission modes: direct reading mode and storage mode. The former can transmit data to the ground station in real time and the latter transmits the data stored in the satellite-borne magnetic tape unit to the ground station when the satellite is flying over it. These ground stations include the Fairchild Air Force Base in the state of Washington, the Loring Air Force Base in Maine, and the Ka'ena Point Satellite Tracking Station in Hawaii. Then, the ground stations transmit the data, via relay satellites, to the Air Force Global Weather Center (AFG-WC) at the Offutt Air Force Base in Nebraska and the Fleet Numerical Oceanographic Center (FNOC) in Monterey, California.

3.4.1.2 The NOAA Satellite System (POES)

Satellites of the Polar-orbiting Operational Environmental Satellite (POES) system operate on sun-synchronous orbits. The NOAA satellite system adopts a double-satellite operation system. The local time of the orbit descending node of one of the satellites is in the morning, and that of the other is in the afternoon. Currently, the POES system satellites carry six kinds of payloads, which are shown in Table 3.25.

Table 3.25 Payloads of the POES system satellites

Satellite	Payloads
NOAA- K	AMSU-A, AMSU-B, ARGOS, ATOVS (HIRS/3 + AMSU + AVHRR/3), AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA)
NOAA- L	AMSU-A, AMSU-B, ARGOS, ATOVS (HIRS/3 + AMSU + AVHRR/3), AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)
NOAA- M	AMSU-A, AMSU-B, ARGOS, AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)
NOAA- N	AMSU-A, ARGOS, AVHRR/3, HIRS/4, MHS, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)
NOAA- N'	A-DCS4, ARGOS, AVHRR/3, HIRS/4, LRIT, MHS, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)

In these payloads, AVHRR/3 is used to detect clouds, and cloud-top, sea surface and land surface temperatures. Its channel characteristics are shown in Table 3.26.

HIRS/3 is used to sound the vertical profiles of atmospheric temperature and humidity on cloudless or partly cloudy days. With a quantization level of 13 bits, the instrument has 20 channels and a resolution of 17.4 km.

AMSU consists of AMSU-A and AMSU-B. AMSU can sound temperature and humidity on cloudy days, sound precipitation on the land and sea, recognize sea ice and determine its scope, and sound soil moisture to a certain degree.

SEM is used to measure solar protons, alpha particles, electron flux density, the energy spectrum, and the total particle energy distribution in the satellite orbit to study the satellite's physical environment in space, predict proton events, and ensure the safe operation of spacecraft working in orbit.

ERBS is used to observe incident solar shortwave radiation, solar shortwave radiation reflected to outer space, and longwave radiation transmitted from the Earth-atmosphere system. SBUV is used to measure the total amount and vertical distribution of ozone. The instrument detects the 160–400 nm band and measures two aspects: the ultraviolet backscatter of the atmosphere in the O_3 absorption band and the ultraviolet radiation of the Sun.

Table 3.26 Channel characteristics and applications of AVHRR/3

Channel	Wavelength (μm)	Resolution (km)	Typical application
1	0.58–0.68	1.09	Daytime cloud imaging
2	0.725–1.00	1.09	Ice and snow monitoring
3A	1.58–1.64	1.09	Aerosol, snow, and ice monitoring
3B	3.55–3.93	1.09	Fire and nighttime cloud imaging
4	10.30–11.30	1.09	Daytime and nighttime cloud imaging, land surface and sea surface temperature sensing
5	11.50–12.50	1.09	Daytime and nighttime cloud imaging, land surface and sea surface temperature sensing

Table 3.27 Payloads of third-generation GOES satellites in orbit

Satellite code	Payloads
GOES-12	DCS (NOAA), GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder, SXI, WEFAX
GOES-13	A-DCS4, GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder, SXI
GOES-14	A-DCS4, GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder
GOES-15	A-DCS4, GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder, SXI

3.4.1.3 The GOES Satellite System

The United States is now using the third generation of geostationary meteorological satellites. These satellites adopt a three-axis stabilization mode and a satellite-borne vertical sounder, and the imager can perform sounding separately at the same time. There are four main kinds of payloads. The orbital information and payloads of the Geostationary Operational Environmental Satellite (GOES) satellites currently in operation are shown in Table 3.27.

3.4.2 European Meteorological Observation Satellites

The European meteorological satellite program began in 1972. The initial goals of the program were to meet European countries' need for weather analysis and forecasting and meet the demand for global atmospheric monitoring and research in accordance with the WMO's World Weather Watch (WWW) program and the Global Atmospheric Research Program (GARP).

3.4.2.1 Typical Geostationary Meteorological Satellites of Europe

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) has launched ten Meteosat satellites since the first geostationary meteorological Meteosat satellite was launched in November 1977. The European geostationary meteorological satellites are the Meteosat series of satellites launched by EUMETSAT; Meteosat-7 belongs to the first generation (Fig. 3.24) and Meteosat-8, Meteosat-9 and Meteosat-10 belong to the second generation.

The main instrument installed on the first generation of Meteosat operational satellites is a three-channel imager, MVIRI. The parameters of each channel are listed in Table 3.28. The satellites' main tasks are to (1) provide 48 full-disk images of Earth daily; (2) transmit near-real time digital and analog images to primary data user stations and secondary data user stations; (3) relay image data transmitted from

Fig. 3.24 First-generation Meteosat system

Table 3.28 Features of first-generation Meteosat operational satellites

Channel	Spectrum (μm)	Pixel × scan line
Visible (VIS)	0.5–0.9	5000 × 5000
Infrared (IR)	10.5–12.5	2500 × 2500
Water vapor (WV)	5.7–7.1	2500 × 2500

other meteorological satellites; (4) collect data transmitted from the data acquisition platform; (5) send meteorological products to users; and (6) perform meteorological data distribution (MDD), which is mainly intended to improve the transmission of African meteorological data.

The second-generation Meteosat satellites entered Phase A (system design phase) before 1993 and entered Phase B (sample satellite development phase) soon after. Phase C was developed as the launch and implementation phase, and Phase D was the postlaunch application and improvement phase.

MSG is a spin-stabilized satellite (Fig. 3.25), similar to the first generation of meteorological satellites. Its design was improved in many aspects. For instance, the satellite-borne radiometer SEVIRI has much higher performance, the spectral channels were increased from three to twelve, the resolution was greatly improved (1 km in the wideband high-resolution visible light channel), and the scanning time was halved from thirty minutes to fifteen minutes. The data transmission system was also improved, making data transmission and broadcast much faster (3.2 Mbps and 1 Mbps, respectively).

Fig. 3.25 MSG satellite

3.4.2.2 Polar-Orbiting Meteorological Satellite System

The European Union's polar-orbiting meteorological satellite system, MetOp, and EUMETSAT teams are working closely together to develop a European polar-orbiting meteorological satellite system and launch the MetOp series of satellites which, starting in 2002, began replacing older meteorological satellites (TIROS series) launched earlier by NOAA. Satellites owned and operated by EUMETSAT will be part of an American-European three-satellite operating system, in which one US satellite will appear at dawn, MetOp will appear in the morning and another US satellite will appear in the early afternoon.

MetOp is being designed to carry instruments provided by the ESA, EUMETSAT, NOAA, and CNES. These satellites have a larger carrying capacity, improved payload, and better performance than the NOAA system. The MetOp series consists of three satellites; the first, MetOp-A (Fig. 3.26), was launched on October 19, 2006, with a design life of five years and the second, MetOp-B (Fig. 3.27), was launched on September 1, 2012.

The EUMETSAT polar-orbiting satellite system is an integral part of the global observing system (GOS) that is designed to provide long-term global observation

Fig. 3.26 MetOp-A

Fig. 3.27 MetOp-B

data in conjunction with NOAA satellites. The operational instruments on board the EUMETSAT polar-orbiting system are designed to be the same as those on board NOAA satellites to ensure the consistency of observation data. The first one or two satellites are large-capacity, nonoperational polar-orbiting platforms (EPOP/POEM), and subsequent satellites are smaller MetOp satellites.

3.4.3 China's Meteorological Observation Satellites

China's polar-orbiting meteorological satellites (FY-1 and FY-3 satellite series) are also referred to as sun-synchronous orbiting meteorological satellites, those whose orbital plane is usually 98°–99° from the equatorial plane and whose orbit crosses the north and south poles. Geostationary meteorological satellites (FY-2 satellite series) move at the same speed as Earth's rotation at an altitude of 36,000 km above the equator. Information on the FY satellite series is shown in Fig. 3.28 (National Satellite Meteorological Center, China Meteorological Administration 2013a).

3.4.3.1 Polar-Orbiting Satellites

(1) *FY-1A/1B*

FY-1A was launched on September 7, 1988, as an experimental meteorological satellite. Although it only worked in orbit for 39 days due to a control system failure, the successful launch of FY-1A was considered a milestone in China's development of meteorological satellites. The satellite was equipped with an infrared and visible light scanning radiometer, a data collection system, a space environment detector, and other instruments. Technical parameters of the multispectral infrared and visible light scanning radiometer are shown in Table 3.29 (National Satellite Meteorological Center, China Meteorological Administration 2013b).

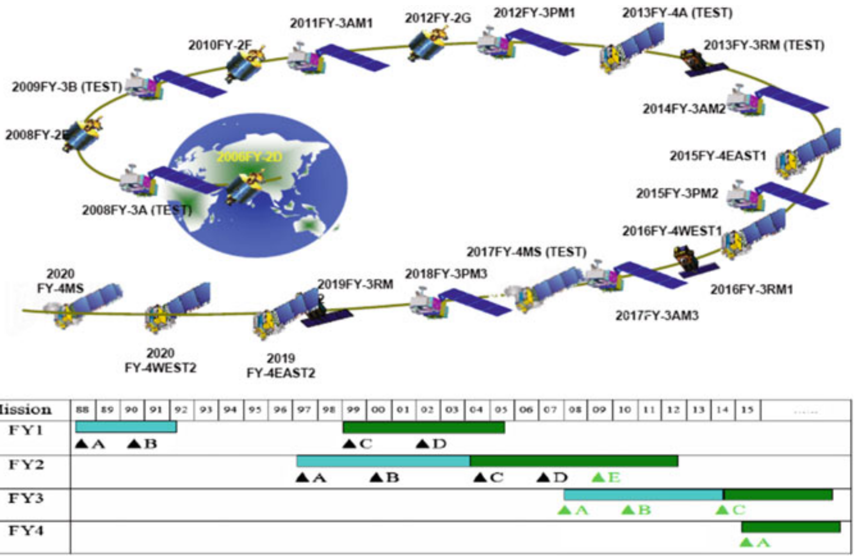

Fig. 3.28 FY satellite series (CMA)

Table 3.29 Technical parameters of FY-1A's visible and infrared scanning radiometer

Component	Parameter
Sensor	Multispectral infrared and visible light scanning radiometer
Tasks	To acquire day-and-night visible light, infrared cloud imagery, snow and ice cover, vegetation, ocean color, sea surface temperature, etc.
Scan rate	6 scanning lines/second
Earth-scanning angle (°)	±55.4
Nadir ground resolution (km)	1.1
Data quantization level (bit)	10
Calibration accuracy	Visible and near infrared channels 10% (reflectance); infrared channels 1 K (300 K)
Wavelength (μm)	0.58–0.68, 0.725–1.1, 0.48–0.53, 0.53–0.58, and 10.5–12.5
Data transmission	For high-resolution picture transmission (HRPT), the bit rate is 0.6654 Mbps and the operating frequency is 1,670–1,710 MHz. In low-resolution image transmission (APT), delay picture transmission (DPT), high-resolution picture transmission (APT) and DPT are analog signals

The FY-1B satellite was successfully launched on September 3, 1990. As China's second experimental meteorological satellite, FY-1B was an improvement over FY-1A. Compared with FY-1A, FY-1B's attitude control system was improved and its visible cloud images were clearer. The performance of the satellite's sensors and the main functions of the satellite were similar to those of the United States' third-generation polar-orbit meteorological satellites. The satellite's performance was at a level similar to that of commercial applications, its visible channel image quality was high, and its signal-to-noise ratio was above the design requirement. However, the satellite's system lacked reliability.

(2) *FY-1C*

FY-1C was successfully launched from the Taiyuan Satellite Launch Centre on May 10, 1999. Compared with FY-1A/B, the FY-1C satellite had significantly improved performance, with increased detection channels and accuracy. Its design life was two years. A series of technical measures were taken that led to improvements in the product quality, adaptability to space environments, and system reliability. FY-1C functioned stably in orbit until June 24, 2004, when the reception of FY-1C cloud images ceased.

The satellite was equipped with a space particle composition detector and a multichannel visible infrared scanning radiometer (MVISR). The number of MVISR channels for FY-1C was increased from five (FY-1A) to ten, and included four visible light channels, one shortwave infrared channel, and two longwave infrared channels. Table 3.30 lists the wavelength and use of each channel. The field of view was 1.2 microradians, the nadir resolution was 1.1 km, and the scanning speed was six scan lines per second, with each line containing 20,480 pixel points. The calibration

Table 3.30 Technical parameters of FY-1C's multispectral infrared and visible scanning radiometer

Channel no.	Wavelength (μm)	Main purpose
1	0.58–0.68	Daytime clouds, ice, snow, vegetation
2	0.84–0.89	Daytime clouds, vegetation, water
3	3.55–3.93	Heat sources, nighttime clouds
4	10.3–11.3	Sea surface temperature, day/nighttime clouds
5	11.5–12.5	Sea surface temperature, day/nighttime clouds
6	1.58–1.64	Soil moisture, ice and snow recognition
7	0.43–0.48	Ocean color
8	0.48–0.53	Ocean color
9	0.53–0.58	Ocean color
10	0.90–0.965	Water vapor

accuracy of the visible and near infrared channels reached 10%, and the infrared radiometric calibration accuracy reached 1 K, as technically required. The spatial resolution of the HRPT and GDPT images was greater than 1.1 km and 4 km, respectively. The Chinese high-resolution picture transmission (CHRPT) had a frequency of 1,700 MHz, a bit rate of 1.3308 Mbps, and real-time reception from anywhere in the world. The delay picture transmission (DPT) had a frequency of 1,708 MHz and a bit rate of 1.3308 Mbps and was divided into two types: GDPT and LDPT (National Satellite Meteorological Center, China Meteorological Administration 2013b).

(3) *FY-1D*

Design of the FY-1D flight model began in 2000 based on FY-1C technology and previous experience. Fourteen technical improvements were made that led to improved stability. The 950 kg satellite was launched from the Taiyuan Satellite Launch Center on May 15, 2002, using an LM-4B rocket. FY-1D functioned normally for ten years, exceeding its design life and completing all tasks. It is no longer in operation.

FY-1D's main onboard sensor was a multichannel visible infrared scanning radiometer (MVISR), whose main technical parameters are listed in Table 3.31. Data were transmitted using two methods: HRPT and DPT. The HRPT's bit rate was 1.3308 Mbps, and the carrier frequency was 1,700.4 MHz. The DPT's bit rate was 1.3308 Mbps, and the carrier frequency was 1,708.46 MHz. Global meteorological data could be acquired through four channels (Channels 1, 2, 4 and 5), with a spatial resolution of 3.3 km (National Satellite Meteorological Center, China Meteorological Administration 2013b).

(4) *FY-3A*

The FY-3 satellites (FY-3) were China's second-generation polar-orbiting meteorological satellites used for weather forecasting, climate prediction, and environmental monitoring. The FY-3 series comprised two satellites: FY-3A and FY-3B. The satellites were used to conduct 3D atmospheric detection, greatly improved China's ability

Table 3.31 Technical parameters of FY-1D's multispectral infrared and visible scanning radiometer

Component	Parameter
Sensor	Multispectral infrared and visible light scanning radiometer
Tasks	To acquire day-and-night visible light, infrared cloud imagery, snow and ice cover, vegetation, ocean color, sea surface temperature, etc.
Scan rate	6 scanning lines/second
Earth-scanning angle (°)	±55.4
Nadir ground resolution (km)	1.1
Data quantization level (bit)	10
Calibration accuracy	Visible and near infrared channels 10% (reflectance); infrared channels 1 K (300 K)
Wavelength (μm)	0.58–0.68, 0.84–0.89, 3.55–3.93, 10.3–11.3, 11.5–12.5, 1.58–1.64, 0.43–0.46, 0.48–0.53, 0.53–0.58, and 0.900–0.965
Data transmission	For high-resolution picture transmission (HRPT), the bit rate is 0.6654 Mbps and the operating frequency is 1,670–1,710 MHz. In low-resolution image transmission (APT), delay picture transmission (DPT), high-resolution picture transmission (APT) and DPT are analog signals

to acquire global information and further enhanced its cloud area and surface feature remote sensing capabilities. These features enabled the country to obtain global, all-weather, three-dimensional, quantitative, multispectral data on atmospheric, land surface, and sea surface characteristics.

FY-3A was the first FY-3 meteorological satellite launched using an LM-4C rocket from the Taiyuan Satellite Launch Center at 11:02 on May 27, 2008. Although it was developed based on the FY-1 meteorological satellites, FY-3A was substantially superior in both technology and function. The satellite was capable of three-dimensional atmospheric detection, greatly improving the capability for global information acquisition and cloud area and surface feature remote sensing.

(5) *FY-3B*

FY-3B is the second satellite in the FY-3 meteorological satellite series. It was launched from the Taiyuan Satellite Launch Center in the early morning of November 5, 2010, using an LM-4C rocket. FY-3B is China's first afternoon-orbit meteorological satellite, making it the first polar-orbiting meteorological satellite to conduct observations at this time. FY-3B is useful for accurate monitoring and numerical forecasting of rainstorms in southern China that usually occur in the afternoon. Working in conjunction, FY-3B and FY-3A increased the global scan frequency from twice a day to four times a day. Thus, China's ability to monitor disastrous weather events such as typhoons and thunderstorms was enhanced markedly. The satellite had a design life of three years but is still operating in orbit.

FY-3B is equipped with eleven advanced remote sensing instruments and 99 spectral detection channels, five of which have a resolution of 250 m. FY-3B is similar to FY-3A in terms of the satellite platform, payload configuration, and main performance parameters. However, as the first next-generation, polar-orbiting meteorological satellite, FY-3A showed weak operation of some onboard instruments. FY-3B was developed by meteorological satellite experts based on their experience acquired from the development of the FY-3A satellite. As a result, FY-3B demonstrated improved performance for the infrared spectrometer, microwave radiation imager, and solar backscatter ultraviolet sounder.

(6) *FY-3C/3D*

FY-3C is a sun-synchronous orbit satellite launched on September 23, 2013 by the carrier rocket Chinese Long March 4C from the Taiyuan Satellite Launch Center in Shanxi province. The FY-3C orbital satellite joins its predecessors FY-3A and FY-3B. It replaced FY-3A to operate, after undergoing tests, in a morning orbit with FY-2B, which is in an afternoon orbit, to provide temporal resolution of global observation data of up to six hours.

The FY-3C missions primarily include Earth surface imaging and atmospheric sounding, and its observational data will be used in weather forecasting, and in monitoring of natural disasters and ecological and environmental factors. Compared with FY-3A and FY-3B, the payload on board FY-3C features 12 sensing instruments, including a visible infrared radiometer, a microwave scanning radiometer, a microwave temperature sounder (MWTS), a microwave humidity sounder (MWHS), a microwave imager, and a medium resolution imaging spectrometer. It also includes a UV-O-zone sounder, a total O-zone UV detector, a solar radiation and Earth radiation detector, space environmental monitoring suits, and GNSS occultation detectors.

FY-3D was launched on November 14, 2017 as China's fourth second-generation polar-orbiting meteorological satellite and will replace the orbiting FY-3B satellite. The satellite is designed to provide weather forecasts in medium- and long-range numerical weather prediction (NWP) models, enabling high-impact weather forecasting up to a week in advance, and alleviate the impacts of natural disasters on the economy and society and improve livelihood.

Equipped with greenhouse gas probing capacity, FY-3D was also developed to help tackle climate change, in addition to serving ecological, civilization, and construction needs and the 'Belt and Road' initiative. FY-3D features ten instruments, including a microwave temperature sounder (MWTS), a microwave humidity sounder (MHTS), a microwave radiation imager (MWRI), a space environment monitor (SEM), and a global navigation satellite system occultation sounder (GNOS).

3.4.3.2 Geostationary Orbit Satellites

(1) *FY-2A/2B*

The FY-2A satellite was the first experimental satellite in China's first-generation geostationary meteorological satellite series, FY-2, and was launched on June 10, 1997. FY-2A had a three-channel scanning radiometer and a design life of three years at a stable spinning altitude. The satellite began to have issues after working for three months and then worked intermittently, only operating for six to eight hours each day. Ultimately, FY-2A failed to meet the requirements for commercial meteorological services.

The main payload of FY-2A was a visible and infrared spin-scan radiometer (VISSR), whose technical parameters are shown in Table 3.32 (National Satellite Meteorological Center, China Meteorological Administration 2013b).

The FY-2B satellite was the second experimental satellite in China's first-generation geostationary meteorological satellite FY-2 series. FY-2B was launched on June 25, 2000 from the Xichang Satellite Launch Center using an LM-3 rocket. The first original cloud image was received on July 6. FY-2B only had a three-channel scanning radiometer and a design life of three years in a stable spinning altitude. It functioned in orbit for less than eight months before a problem occurred with one of the components on board the satellite; from then onward, the signals it sent back were too weak to receive. Ultimately, FY-2B failed to meet the requirements for commercial meteorological services. However, FY-2B's operation provided valuable experience for the development of subsequent FY-2 meteorological satellites.

The technical parameters of the FY-2B and FY-2A satellites were identical. The cloud images sent from FY-2B played an important role in monitoring typhoons and marine weather, forecasting rainstorms, preventing floods, analyzing the weather system above the Qinghai-Tibetan Plateau, providing meteorological support for aviation, and predicting climate change.

(2) *FY-2C/2D/2E/2F/2G/2H*

FY-2C was the first commercial-use satellite in the FY-2 meteorological satellite series. After a successful launch on October 19, 2004, FY-2C was positioned at an altitude of 36,000 km above the equator at 105° east longitude on October 24.

Table 3.32 Technical parameters of FY-2A's visible and infrared light spin-scan radiometer (VISSR)

Channel	Visible light	Infrared	Water vapor
Wavelength (μm)	0.55–1.05	10.5–12.5	6.2–7.6
Resolution (km)	1.25	5	5
Field of view (μrad)	35	140	140
Scan line	2,500 × 4	2,500	2,500
Detector	Si-photo-diode	HgCdTe	HgCdTe
Noise resolution	S/N = 6.5 (Albedo = 2.5%) S/N = 43 (Albedo = 95%)	NEDT = 0.5–0.65 k (300°K)	NEDT = 1 K (300°K)
Quantitative byte (bit)	6	8	8
Scanning step	140 μrad (N-S scanning)		

FY-2C occupied FY-2B's former position to monitor weather conditions in the Asia Pacific Region. Four days after it was positioned, adjustments were made to the ground application system to technically coordinate it with the satellite. The satellite's service monitoring, data transmission, and forwarding channels were opened, and the scanning radiometer was switched on. FY-2C could observe changes in sea surface temperature, and one of its channels was designed for measuring 3.5–4 μm light waves to observe high-temperature heat sources on the ground. It was possible to use spectral channels to observe ground heat sources to promptly discover forest fires in remote and desolate places, monitor their situation, and predict their development trends.

FY-2D was the fourth satellite in the FY-2 meteorological satellite series. FY-2D was also the country's second application-oriented geostationary-orbiting meteorological satellite. It was launched using an LM-3A rocket at 08:53 on December 8, 2006. After 1,421 s of flying, it successfully separated from the rocket, entering into a large elliptical transfer orbit with a perigee altitude of 202 km, apogee altitude of 36,525 km, and inclination of 24.97°. At 01:24 on December 9, the apogee engine was ignited for orbital transfer, and secondary separation was successfully completed. After four batches of orbit trimming, the satellite was positioned at an altitude of 36,000 km above the equator at 86.5° E longitude at 17:00 on December 13. It is currently no longer in operation.

On December 23, 2008, and January 13, 2012, China's third and fourth service-oriented geostationary meteorological satellites, FY-2E and FY-2F, respectively, were launched from the Xichang Satellite Launch Center using LM-3A rockets. The two satellites were of great significance for the continuous and stable operation of China's geostationary meteorological satellite observation services. FY-2F boasted flexible capability for scanning specific regions with a high temporal resolution and could monitor disastrous weather conditions such as typhoons and severe convections. FY-2F played an important role in China's meteorological disaster monitoring, early warning, prevention, and mitigation. The space environment monitor continuously monitored solar X-rays and the flow of high-energy protons, electrons, and heavy particles, and the data were used for space weather monitoring, forecasting, and early warning services.

The geostationary meteorological satellites FY-2C, FY-2D, FY-2E, and FY-2F working in orbit formed a "double-satellite observation with mutual backup" service pattern. These satellites helped modernize China's comprehensive meteorological observation system. During flood season, the double-satellite observation mode allowed for spinning the satellite, enabling it to provide a cloud picture every fifteen minutes. This intensified observation mode played a key role in monitoring disastrous weather systems such as typhoons, rainstorms, thunderstorms, and small- and medium-scale local convective systems. The FY-2 meteorological satellite series played a crucial role in combating heavy rain, freezing snow, and other extreme weather events. The satellites also provided assistance in the Wenchuan earthquake relief operations and in providing meteorological services for the Beijing Olympics and Paralympics.

The FY-2G satellite was launched on December 31, 2014 from the Xichang Satellite Launch Center. Based on the technology of FY-2 F satellite, the FY-2G satellite was improved by reducing infrared stray radiation, uplifting the observation frequency for the blackbody, and improving the telemetry resolution of optical components. These improvements increase the retrieval accuracy of FY-2G satellite quantitative products and enhance the quantitative application of satellite data products.

FY-2H was launched on June 5, 2018. It is positioned over the Indian Ocean and has realized the sustained observation of one-third of the Earth's territories from Oceania to central Africa. It can provide favorable observation perspectives and custom-made high-frequency subregional observation for countries and regions such as western Asia, central Asia, Africa, and Europe. Equipped with a scanning radiometer and a space environment monitor, FY-2H can supply data for dozens of remote sensing products such as cloud images, clear sky atmospheric radiation, sand and dust, and cloud motion wind (CMW) for weather prediction, disaster warning, and environmental monitoring, enriching the data sources for global NWP models.

The main payload of FY-2C/2D/2E/2F was a visible and infrared spin-scan radiometer (VISSR), whose technical parameters are shown in Table 3.33 (National Satellite Meteorological Center, China Meteorological Administration 2013b).

(3) *FY-4A*

FY-4A was launched on December 11, 2016, as the first Chinese second-generation geostationary meteorological satellite. FY-4A is China's first quantitative remote sensing satellite with a three-axis stabilization structure on a geostationary orbit. Four new instruments are on board the latest independently developed weather satellite, namely, an advanced geosynchronous radiation imager (AGRI), a geosynchronous interferometric infrared sounder (GIIRS), a lightning mapping imager (LMI) and a space environment package (SEP).

FY-4A is the first satellite in China that can capture lightning. The onboard Lightning Mapping Imager enables this function. It is the first geostationary optical remote sensing instrument in China and has filled the gap in terms of lightning observation and satellite-borne detection. FY-4A can detect lightning over China and neighboring areas and take 500 lightning pictures per second. By real-time and consecutive observation of lightning, it can aid in observation and tracking of severe convective weather and provide early warning for lightning disasters.

Table 3.33 Technical parameters of the radiometer on board FY-2C/2D/2E/2F

Channel	Waveband (μm)	Resolution (km)
Visible light	0.55–0.90	1.25
Infrared 1	10.3–11.3	5
Infrared 2	11.5–12.5	5
Infrared 3	6.3–7.6	5
Infrared 4	3.5–4.0	5

3.4.4 *Other Meteorological Observation Satellites*

3.4.4.1 Japan's Satellites

Since Japan launched its first geostationary meteorological satellite, GMS-1, in 1977, it has put five geostationary meteorological satellites into orbit. The GMS-4 satellite is positioned at 140°E above the equator and is equipped with visible and infrared scanning radiometers that observe a fourth of Earth to monitor cloud distribution, height and dynamics. The satellite can obtain information about winds below and above clouds, and detect sea surface temperature distribution.

Similar to other GMS satellites, GMS-5 is a spin-stabilized satellite. Its total mass is 756 kg, the design life is five years, and the main onboard instrument is a visible and infrared light spin-scan radiometer (VISSR). The VISSR was significantly improved by building upon the radiometer on board GMS-4. One 6.5–7 µm WV channel was added to observe water vapor radiation in the middle layer of the troposphere. The original 10.5–12.5 µm infrared window area was split into a 10.5–11.5 µm channel and an 11.5–12.5 µm channel to observe radiation from Earth's surface and the atmosphere. The nadir spatial resolution of GMS-5 is 1.25 km for the visible light channel and 5 km for the WV channel. The main parameters of the VISSR on board GMS-5 is listed in Table 3.34.

After GMS-5 was launched, Japan suspended the development of single-function meteorological satellite systems. The Japan Meteorological Agency and Japan Civil Aviation Administration jointly developed a new large, multifunctional, integrated satellite system called MTSAT. MTSAT-1, the first satellite of this system, was scheduled to be launched on November 15, 1999. However, the launch was unsuccessful due a fault with the rocket and both the satellite and rocket were destroyed. Japan manufactured another MTSAT satellite named MTSAT-1R (Kim et al. 2011). The satellite was not launched until February 26, 2005 due to the time required to remove the fault and improve the rocket. The satellite began to broadcast images two to three months after launch. It was followed by MTSAT-2, which was launched on December 26, 2006 (Fig. 3.29). The MTSAT satellites are equipped with VISSR, cloud image broadcasting, DCS, aviation communication, and other subsystems mainly used for meteorological exploration and aviation communication and are the largest geostationary satellites with meteorological sounding functions (Crespi et al. 2012).

Table 3.34 VISSR parameters of the GMS-5 satellite (Huang et al. 2004)

Channel	Wavelength (µm)	Quantization level (bit)	Spatial resolution (nadir) (km)
Visible light	0.55–0.90	8	1.25
Water Vapor (WV)	6.5–7.0	8	5
Infrared window area	10.5–11.5	8	5
Infrared window area	11.5–12.5	8	5

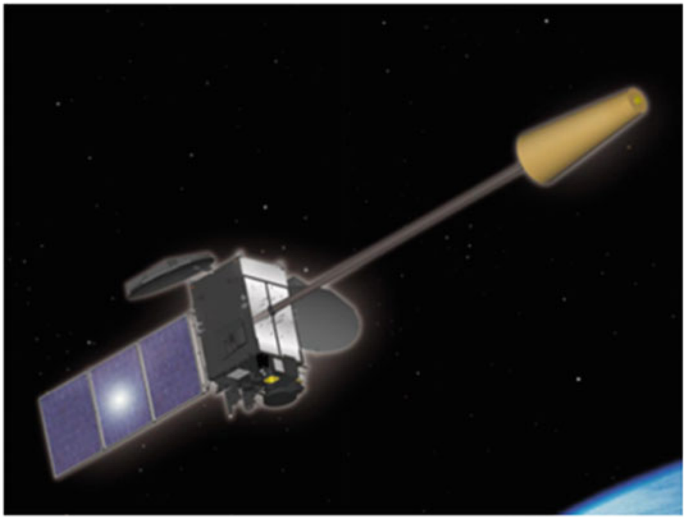

Fig. 3.29 The MTSAT-2 satellite

3.4.4.2 India's Satellites

INSAT is a multiagent multitarget satellite system and is one of the largest satellite systems in Asia. The INSAT satellite system has played an increasingly important role in the Indian aerospace industry with the continuous development and improvement of the INSAT-1, INSAT-2, and INSAT-3 series of satellites.

INSAT provides services such as domestic long-distance communication, meteorological and Earth observation data relay, augmented television receiver national direct satellite broadcasting, TV education, rural communications, meteorology, and disaster alarms.

The first-generation INSAT satellites, the INSAT-1 series, were manufactured by Ford Motor Co. in the United States and comprised four satellites: INSAT-1A, INSAT-1B, INSAT-1G, and INSAT-1D. The second-generation INSAT satellites, INSAT-2, were independently developed by India to meet the needs of the 1990s. The INSAT-2 series consisted of five satellites: INSAT-2A, INSAT-2B, INSAT-2C, INSAT-2D, and INSAT-2E. In addition to normal C-band transponders, the INSAT-2 satellites also adopted the high-frequency section of the C-band, or the extended C-band. The third-generation INSAT satellites, INSAT-3, were also made by the Indian Space Research Organization (IRSO) and comprise five satellites: INSAT-3A, INSAT-3B, INSAT-3C, INSAT-3DR, and INSAT-3DS.

INSAT-3A is a multipurpose satellite launched on April 10, 2003 using an Ariane rocket. The satellite is fixed at 93.50° E and has the following payloads (Fig. 3.30). Of the twelve C-band transponders, nine provide coverage that extends from the Middle East to southeast Asia with an EIRP of 38 dBW, and three provide coverage of India with an EIRP of 36 dBW. The six extended C-band transponders provide

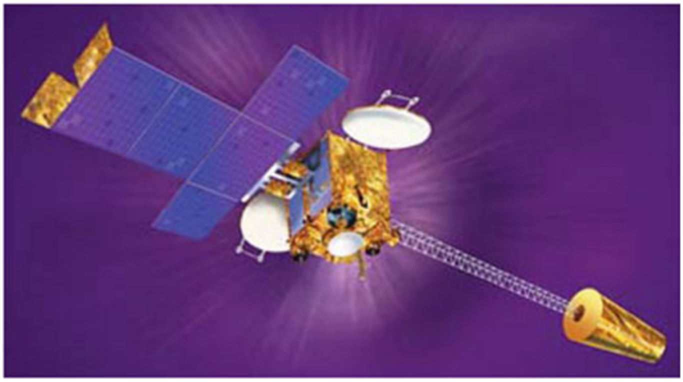

Fig. 3.30 The INSAT-3A satellite

Indian coverage, with an EIRP of 36 dBW. The six Ku-band transponders also provide coverage of India, with an EIRP of 48 dBW. The one very high-resolution radiometer (VHRR) can perform imaging in the visible light channel (0.55–0.75 μm), thermal infrared channel (10.5–12.5 μm), and water vapor channel (5.7–7.1 μm) with ground resolutions of 2 × 2 km, 8 × 8 km, and 8 × 8 km, respectively. The CCD camera has a ground resolution of 1 × 1 km in the visible (0.63–0.69 μm), near infrared (0.77–0.86 μm), and SWIR (1.55–1.70 μm) channels.

3.4.4.3 Russia's Satellites

(1) *Russia's polar-orbiting meteorological satellites*

The "Meteor" series of polar-orbiting meteorological satellites was developed by the Soviet Union/Russian Federation and has gone through four generations. Most of the previous three generations of satellites do not function in sun-synchronous orbit. However, the fourth-generation of satellites is known to work in a sun-synchronous orbit.

As early as 1962–1969, the Soviet Union had launched more than 20 COSMOS satellites for meteorological observation. In March 1969, it launched its first-generation polar-orbiting meteorological satellite: Meteor-1. The first generation consisted of 31 satellites (Meteor-1-31) launched from 1969 to 1981, most of which had an orbital inclination of 81.2°. The second generation (Meteor-2) comprised 24 satellites launched after 1975. In most cases, two or three satellites were simultaneously operating on orbit, with an orbital inclination of 82.0° and orbital altitude of 950 km. The third-generation (Meteor-3) polar-orbiting meteorological satellites were launched in 1984. The third generation was composed of eight satellites, which had an orbital inclination of 82° and orbital altitude of 1,200 km.

Meteor-3 M N1, the first satellite of the fourth generation of Russian meteorological satellites, (the Meteor-3 M series) was launched on December 10, 2001 (Fig. 3.31).

Major changes in the Meteor-3 M series of satellites include: 99.6° orbital inclination, 1,024 km sun-synchronous orbit, and a broadcast data format that is compatible with NOAA's high-resolution picture transmission (HRPT).

(2) *Russia's geostationary orbit meteorological satellites*

Russia's first geostationary orbit meteorological satellite (GOMS) was successfully launched in November 1994. It is a three-axis stabilized satellite positioned at 76°E. A problem occurred with the attitude control after launch, but the satellite resumed working after some remedial measures were taken. Unfortunately, its scanning radiometer's visible light channel has been unable to acquire any images due to an optical design error; thus, the satellite can only capture infrared images.

On January 20, 2011, Russia launched the geostationary hydrological and meteorological satellite Elektro-L from the Baikonur Launch Center in Kazakhstan (Fig. 3.32). Fixed at a position 36,000 km above Earth, the satellite is used to monitor climate change in Russia's Asian region. The visible light and infrared photographic devices installed on the satellite can capture 1-km and 4-km resolution ground images, respectively. Under normal circumstances, the satellite takes a photo once every 30 min. The shooting frequency can be increased to once every 10–15 min in the event of a natural disaster. The satellite is also responsible for forwarding and exchanging weather information as well as receiving and forwarding signals from the international search and rescue satellite COSPAS-SARSAT. GOMS has a life span of ten years and the data distribution mode is HRPT/LRPT. Its mission is to observe

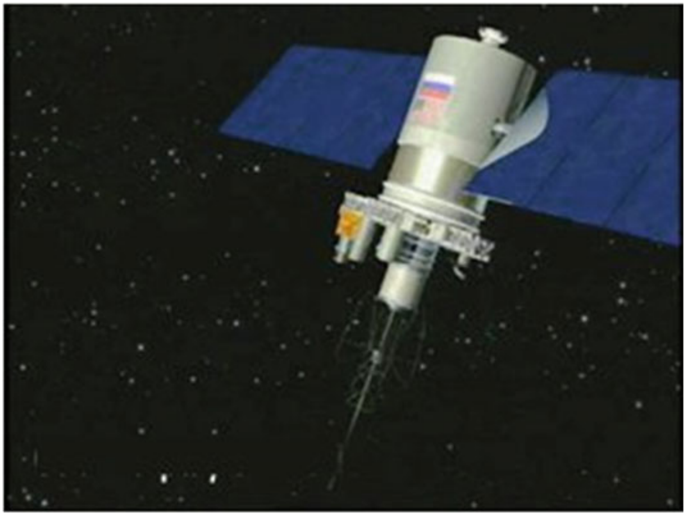

Fig. 3.31 The Meteor-3 M satellite

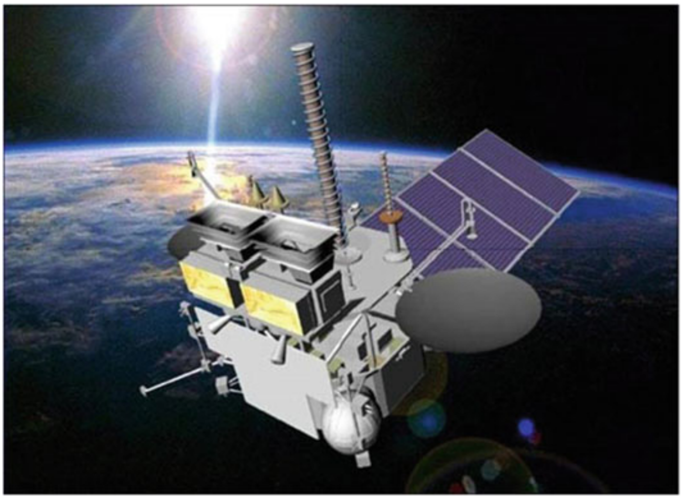

Fig. 3.32 The Electro-L satellite

Earth's surface and atmosphere, perform solar-geophysical measurement, and support the data collection system and COSPAS-SARSAT services. The satellite's main payload is an optical imaging radiometer, MSU-GS, which provides imaging data in three VNIR channels and seven infrared channels. Its nadir spatial resolution (sampling distance) is approximately 1 km (for visible light) and 4 km (for VNIR and infrared), with a new Earth image provided once every 30 min.

3.5 Trends in Remote Sensing for Digital Earth

Looking back on the past five decades of spaceborne remote sensing, every step along the way has been based on the national backgrounds and political and economic conditions of each country. During this period of development, the purpose of Earth observation shifted from single-field surveying toward serving the demands of the overall development of human society (Guo 2014). Since entering the period of globalization, remote sensing technologies have developed into a complete system (Guo et al. 2013), which will provide more abundant data for Digital Earth.

Countries and regions with leading Earth observation technologies, such as the United States and Europe, have formulated Earth observation plans for long-term development. In 2013, the United States and European organizations were expected to launch 34 Earth observation satellites, and India and China planned to launch 25 and 26 satellites, respectively. Russia, Japan, and Canada also had plans for over ten launch missions (Fig. 3.33). Russia will remain a major contributor to satellite launches in Europe, but European organizations will launch significantly more, and there will be a greater emphasis on cooperation and coordination between European

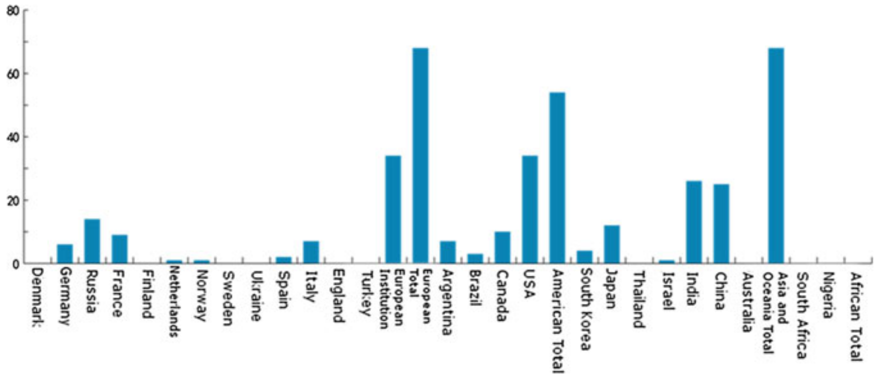

Fig. 3.33 Global launch plans for Earth observation satellites by 2035

countries. In America, the United States will remain a leading force, and Canada will occupy a secondary role. In Asia, the existing trend will continue, with China, India, Japan, and South Korea continuing to be major contributors. Currently, no African countries have plans to launch new satellites.

All of the aforementioned satellite programs have clearly defined services. For example, the United States' Earth observation program for 2016–2020 focuses on measuring global ozone conditions and other relevant gases (GACM program), atmospheric pollution monitoring (3D-Winds), geological disasters (LIST), weather forecasts (PATH), and water resource utilization (GRACE-II/SCLP) (Neeck et al. 2008). The European GMES program covers the six service fields of land, ocean, emergency management, security, atmosphere, and climate change (Veefkind et al. 2012). In addition, Russia, Japan, India, and some other countries have issued strategic plans for Earth observation, forming systems with their own characteristics. The Russian Federal Space Agency (Roscosmos) intends to form a satellite system consisting of geostationary meteorological satellites (Elektro series), polar-orbiting meteorological satellites (METEOR series), and resource/environment satellites (KANOPUS-V and Resurs-P series) by 2020. The Japan Aerospace Exploration Agency (JAXA) proposed the GOSAT program for greenhouse gas monitoring and the GCOM program for global change monitoring in addition to its ongoing efforts to build the ALOS program of high spatial resolution satellites carrying L-band SAR and hyperspectral sensors. Additionally, JAXA has plans to continue with its navigation experiment satellite program (QZS). The Indian Space Research Organization (ISRO) and the Indian National Remote Sensing Agency (NRSA) aim to improve the spatial resolution of the Resourcesat series and develop SAR-carrying satellites and environment satellites (Environment Sat) of their own (RISAT series).

In addition, some companies such as DigitalGlobe are planning to deploy new high-resolution satellites and trying to enter the microsatellite field. The planned satellites have also been extended from optical to meteorological and radar satellites. However, at present, there are few companies in the commercial satellite market; for example, DigitalGlobe provides high-resolution optical images, and the European

Airbus Defence and Space division can provide high-resolution optical and radar data. China is also planning a series of microsatellites for commercial service. Shenzhen-1 is its first microsatellite constellation and will realize 0.5 m resolution with a revisit period of less than 1 day. Furthermore, the Zhuhai-1, Beijing-1 and Beijing-2 microsatellites will be launched successively and networked. These commercial microsatellites aim to provide real time information for Digital Earth.

Future Earth satellite observation programs will focus on program continuity, development potential, and the capacity for comprehensive and coordinated applications. Therefore, long-term observation programs will be proposed and the development of aircraft-carried and satellite-carried sensors will continue with improved coordination. Relevant Earth observation programs will emphasize the coordinated use of Earth observation platforms and data to better meet the requirements of various fields that may benefit from observation efforts, as well as the nuanced strategic goals of countries and regions (Guo 2018).

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Wenxue Fu received the Ph.D. degree in SAR remote sensing from Nanjing University, Nanjing, China, in 2007. He is currently an Associate Professor with the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China. His research interests include radar interferometry for ground deformation retrieval and polarimetric SAR interferometry for forest parameter inversion.

Pei Chen received his Ph.D. degree in aerospace engineering from Beihang University, Beijing, China, in 2007. He is currently an associate professor at the school of astronautics, Beihang University. His current research activities comprise spacecraft navigation, GNSS application, and orbit determination.

Fang Chen is a professor at the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences (CAS). Dr. Chen conducts interdisciplinary work combining, remote sensing, ecology, and other fields of study to assess spatial patterns of disaster risk.

Chapter 4
Satellite Navigation for Digital Earth

Chuang Shi and Na Wei

Abstract Global navigation satellite systems (GNSSs) have been widely used in navigation, positioning, and timing. China's BeiDou Navigation Satellite System (BDS) would reach full operational capability with 24 Medium Earth Orbit (MEO), 3 Geosynchronous Equatorial Orbit (GEO) and 3 Inclined Geosynchronous Satellite Orbit (IGSO) satellites by 2020 and would be an important technology for the construction of Digital Earth. This chapter overviews the system structure, signals and service performance of BDS, Global Positioning System (GPS), Navigatsionnaya Sputnikovaya Sistema (GLONASS) and Galileo Navigation Satellite System (Galileo) system. Using a single GNSS, positions with an error of ~ 10 m can be obtained. To enhance the positioning accuracy, various differential techniques have been developed, and GNSS augmentation systems have been established. The typical augmentation systems, e.g., the Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay Service (EGNOS), the global differential GPS (GDGPS) system, are introduced in detail. The applications of GNSS technology and augmentation systems for space-time geodetic datum, high-precision positioning and location-based services (LBS) are summarized, providing a reference for GNSS engineers and users.

Keywords BDS · GNSS augmentation systems · High-precision positioning · Real-time · LBS

C. Shi (✉)
School of Electronic and Information Engineering, Beihang University, Beijing, China
e-mail: shichuang@buaa.edu.cn

C. Shi · N. Wei
GNSS Research Center, Wuhan University, Wuhan, China

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4.1 Introduction

The concept of Digital Earth was proposed by former US vice president Al Gore in 1998. At the 6th International Symposium on Digital Earth in Beijing, Digital Earth was defined as an integral part of other advanced technologies, including earth observation, geo-information systems, global positioning systems, communication networks, sensor webs, electromagnetic identifiers, virtual reality, and grid computation. Satellite navigation and positioning technology can provide precise position and time information, which are key elements of the Digital Earth.

In satellite navigation and positioning technology, the radio signals transmitted by navigation satellites are received by the user terminal. By measuring the time delay of the signal propagated from the navigation satellite to the receiver, navigation, positioning and timing services can be realized. Compared with conventional navigation and positioning techniques, satellite navigation and positioning technology can provide precise three-dimensional positions, velocity and time for users. It is an all-weather, all-time and globally available technology. Great progress has been made in recent decades, and many countries and consortia have established their own global navigation satellite systems. Global satellite navigation and positioning technology has been widely applied in navigation for vehicles, offshore ships, aero craft and aerospace vehicles and in the fields of geodesy, oil exploration, precision agriculture, precise time transfer, and earth and atmospheric sciences.

4.2 Global Navigation Satellite System

Before the advent of man-made satellites, navigation and positioning mainly depended on ground-based radio navigation systems that were developed during the Second World War such as LORAN and Decca Navigator, shown in Fig. 4.1. On October 4th 1957, the former Soviet Union (Union of Soviet Socialist Republics, or USSR) launched the first man-made satellite. Based on the Doppler shift of the radio signal, Dr. Guier and Dr. Wiffenbach from Johns Hopkins University successfully calculated the orbit of the satellite. This laid the foundation for the scientific idea of navigation and positioning with the use of man-made satellites. In 1958, the US military began to develop the first (generation) satellite navigation and positioning system in the world—the Transit navigation satellite system (TRANSIT), which was formally put into military use in 1964. The USSR also began to establish the CICADA system in 1965, and the first CICADA satellite was launched in 1967. Using the Doppler shift method, the first-generation satellite positioning system needed long-term observations to realize navigation and positioning, and the positioning accuracy was also unsatisfactory. To overcome these limitations, the joint development of a new generation satellite navigation system—the Global Positioning System (GPS)—by the US army, navy and air force was formally approved

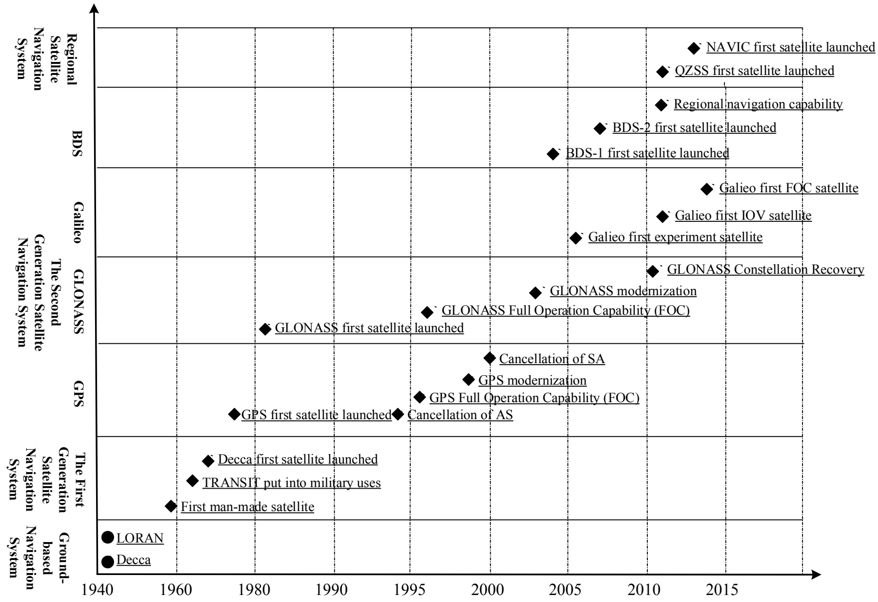

Fig. 4.1 Overview of the development of satellite navigation systems from the 20th century

by the United States Department of Defense (DoD), opening a new chapter for the development of satellite navigation systems.

The satellite navigation system was initially designed for military requirements. With the end of the Cold War, the growing demand for civil and commercial navigation became increasingly strong. Many countries in the world began to develop independent global navigation satellite systems (GNSSs), including the GPS developed by the US, the Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS) developed by Russia, the Galileo Navigation Satellite System (Galileo) established by the European Union (EU), and the BeiDou Navigation Satellite System (BDS) developed by China. Since the technical reserve and capital investment required for the GNSS development is rather large, some countries began to develop regional navigation satellite systems (RNSS) to meet the navigation and positioning demands in their own territory and the surrounding areas, for example, the Quasi-Zenith Satellite System (QZSS) of Japan and the Navigation with Indian Constellation (NAVIC) of India.

GNSSs have evolved from a single GPS constellation to multiple GNSS constellations. In the coming decades, the number of navigation satellites in orbit may increase to several hundreds. Therefore, the integration of multifrequency and multisystem GNSS data, compatibility of GNSS signals and interoperability between different GNSSs are the most important development directions.

Satellite navigation systems consist of three components: the space segment, the control segment (CS) and the user segment. The space segment comprises a constellation of navigation satellites that continuously broadcast ranging code and navigation message to users, and receive various information and commands from a ground monitoring system. The design of the navigation satellite constellation should ensure that four satellites are visible by any user at any time for positioning. The CS includes master control stations (MCSs), uplink stations and monitoring stations. The ground monitoring stations track navigation satellites and the MCSs collect observation data and calculate satellite orbit and clock errors, which are forecasted and formatted into navigation messages and uploaded to the navigation satellites through the uplink stations. The ground CS can also send various commands to the satellites through uplink stations for satellite orbit maneuver, atomic clock adjustment, fault recovery, or initiation of spare parts. The geometric distance between the navigation satellite and the receiver can be measured by the user with a GNSS receiver, and parameters such as the three-dimensional position, velocity and receiver clock errors can be obtained according to the satellite's location in space described by the ephemeris. As the main functions of these segments are similar for different satellite navigation systems, we ignore the common details in the following sections and introduce the unique features of each GNSS.

4.2.1 BDS

BDS, formerly known as COMPASS, is an independent global satellite navigation system developed and operated by China. As the third mature satellite navigation system after GPS and GLONASS, BDS provides high-quality positioning, velocity measurement, timing and short message services for global users. BDS has evolved from active positioning to passive positioning. A global passive positioning system will be established by 2020 (http://www.beidou.gov.cn).

Development of the BeiDou Navigation Satellite Demonstration System (BDS-1) was initiated in 1994. Two geosynchronous equatorial orbit (GEO) satellites were launched in 2000, and the regional double-satellite positioning system was established and put into operation. Based on the active-positioning scheme, positioning, timing, wide-area differential and short message communication services were provided for users in China. With the third GEO satellite launch in 2003, the system performance was further enhanced.

Development of the regional BeiDou Navigation Satellite System (BDS-2) began in 2004. As a passive-positioning system, BDS-2 can provide positioning, timing, wide-area differential and short message communication services for users in the Asia-Pacific region. By the end of 2012, the deployment goal of a regional satellite navigation system was accomplished, with a constellation of 5 GEO satellites, 5 inclined geosynchronous satellite orbit (IGSO) satellites and 4 medium earth orbit (MEO) satellites. On December 27th, 2012, it was officially declared that the BDS could provide regional positioning and navigation services with positioning accuracy of 10 m. China became the third country in the world with an independent satellite navigation system.

In a third step, the global BeiDou Navigation Satellite System (BDS-3) should be completed in 2020, with a constellation of 30 satellites (3GEO + 3IGSO + 24MEO). Both the GEO and IGSO satellites operate in orbits at an altitude of 35,786 km (BDS-ICD 2013). The inclination of the IGSO orbital plane is 55°. The altitude of the MEO satellites is 21,528 km, and the inclination is 55°, with a satellite orbit period of 12 h and 53 min.

BDS-3 has entered into a new era of global deployment with the introduction of new functions such as intersatellite links, and global search and rescue. The technical scheme of BDS-3 is fully forward compatible with that of BDS-2 and realizes performance improvement and service extension. By the end of 2018, the BDS-3 ‘basic system’ comprising of 18 MEO and one GEO satellites was completed to provide services for users in China and neighboring countries along the Belt and Road. In-orbit validation has shown that the positioning accuracy is 10 m globally and 5 m in the Asia-Pacific area. By 2020, BDS-3 will be fully completed to provide global services and an integrated positioning navigation and timing (PNT) system should be set up by 2035.

The code division multiple access (CDMA) signal system is used by the BDS and the carrier signal is broadcasted at B1, B2 and B3 frequencies in L band. B1I and B3I were maintained and inherited from BDS-2, and a new open signal B1C was added and the B2 signal was also upgraded into the newly designed B2a signal, which replaces the original B2I signal and greatly improves the signal performance of BDS-3. The compatibility and interoperability with other GNSSs were also taken into account. A domestically developed high-precision rubidium and hydrogen atomic clock with better stability and smaller drift rate was equipped on the BDS-3 satellites, leading to significant improvement in the performance of the onboard time and frequency standards.

The intersatellite links in the Ka frequency band are equipped for the BDS-3 constellation, and two-way intersatellite precise ranging and communication is realized through use of phased-array antenna and other intersatellite link equipment. Mutual ranging and timing through intersatellite links allow for obtaining more measurements from multiple satellites to improve the observation geometry for autonomous orbit determination. The intersatellite measurement information can also be used to calculate and correct satellite orbit and clock errors for satellite-satellite-ground integrated precise orbit determination, improving the accuracy of satellite orbit determination and time synchronization. Both open and authorized services are provided by BDS-3. The open service provides free services for global users with a positioning accuracy of 10 m, velocity measurement accuracy of 0.2 m/s and timing accuracy of 10 ns. The authorized service provides authorized users with high-precision and reliable measurement of position, velocity and time, communication services, and system integrity information.

The basic BDS observations include pseudorange and carrier phase measurements. The pseudorange measurement is calculated by multiplying the speed of light with the transmission time of the GNSS ranging code from the satellite to the receiver, which comes from the correlation operation of the ranging code generated by the receiver clock with that generated by the satellite clock. The pseudorange reflects the distance between the satellite antenna phase center at the time when the GNSS signal is transmitted by the satellite and the receiver antenna phase center when the signal arrives. Its accuracy therefore depends on the code correlation accuracy. Currently, the noise of the pseudorange measurement is approximately 1%–1‰ of the code width.

The carrier phase measurement refers to the measurement of the navigation signal received from the satellite relative to the carrier phase generated by the receiver (the beat frequency phase) at the time of reception. Once the receiver is powered on, the fractional part of the beat frequency phase is measured and the changes in the integer number of carriers are counted. However, the initial integer number of carriers between the receiver and the satellite cannot be measured. Taking a complete carrier as one cycle, the unknown number of integer cycles is called the ambiguity. The initial measurements of the carrier phase include the correct fractional part and an arbitrary integer number of cycles at the starting epoch. At present, the accuracy of the carrier phase measurement recorded by electronic devices is better than 1% of the wavelength; that is, the carrier phase measurement accuracy is millimeter level.

Compared with the other existing GNSSs, the BDS has the following features: first, the space segment of the BDS is a hybrid constellation comprised of satellites in three kinds of orbits, and the anti-jamming and anti-spoofing capability is better due to more satellites in higher orbits, especially for the low latitude regions; second, the BDS is the first GNSS with signals broadcasted at three frequencies in the full constellation, which could improve service accuracy with a multifrequency combination signals; third, navigation and communication are innovatively integrated in the BDS, so that it can implement five major functions including providing real-time navigation and positioning, precise timing and short message communication services. The service performance of BDS are summarized in Table 4.1.

Table 4.1 Overview of BDS service performance

	BDS-1	BDS-2 (regional)	BDS-3 (global)
Service coverage	China and neighboring areas	Longitude: 84°–160° E, Latitude: 55° S–55° N	Global
Positioning accuracy	<20 m	Horizontal 25 m, Elevation 30 m	<10 m (three-dimensional)
Velocity accuracy	/	0.2 m/s	<0.2 m/s
Timing accuracy	100 ns for one-way, 20 ns for two-way	50 ns	20 ns

4.2.2 GPS

The GPS space segment consists of a constellation of 24 satellites, 21 operational satellites and 3 spare satellites, shown in Fig. 4.2. Four satellites are equally spaced in each of the six orbital planes with an orbit inclination of 55°. The difference between the ascending nodes of each orbital plane is 60° and the difference in the argument of latitude for satellites in the same orbital planes is 30°. This ensures that at least four GPS satellites can be visible at any time and any location around the world. The average orbital altitude of the GPS satellites is approximately 20,200 km, and their orbital period is approximately 11 h 58 min 2 s. For more information about GPS, please refer to http://www.gps.gov/.

The first GPS satellite was launched in 1978, and the constellation of 24 MEO satellites was completed in 1994. Based on the launch time, the GPS satellites can be divided into six different types, namely, BLOCK I, BLOCK II/IIA, BLOCK IIR, BLOCK IIR-M, BLOCK IIF and GPS III satellites. The CDMA modulation is also adopted for GPS satellites to broadcast carrier signal in the L1 band (1575.42 MHz) and L2 band (1227.60 MHz). The open civil C/A code is modulated on carrier L1, and the encrypted P(Y) code for military uses is modulated on carrier L2 (ICD-GPS-200J 2018).

To further expand the GPS civil market and better serve military demands, the GPS modernization program was promoted by the US government. As shown in Table 4.2, the modernization of the GPS navigation signal and satellite constellation includes:

(1) Broadcasting a new civil navigation signal and new military code (M code). The second civil pseudorange code L2C was introduced on BLOCK IIR-M satellites in 2005, and the third carrier frequency L5 (1176.45 MHz) was added on

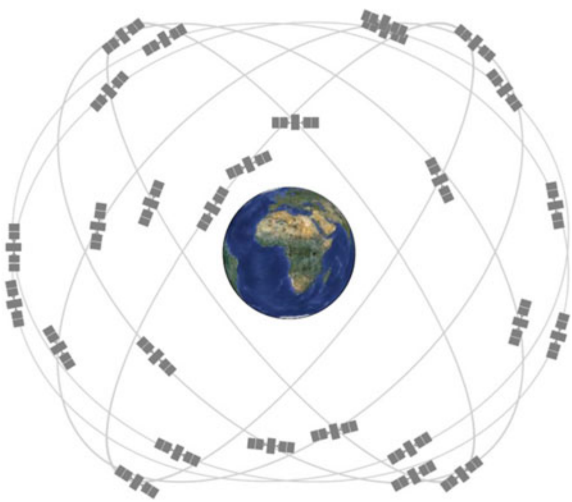

Fig. 4.2 Constellation of the GPS system (*source* http://www.gps.gov/multimedia/images/constellation.jpg)

Table 4.2 GPS satellite constellation and navigation signal modernization

	BLOCK I	BLOCK II/IIA	BLOCK IIR	BLOCK IIR-M	BLOCK IIF	GPS III
Civil code	C/A	C/A	C/A	L2C added	L5 added	L1C added
Military code	P(Y)	P(Y)	P(Y)	M code added		
Designed lifetime	4.5 years	7.5 years	7.5 years	7.5 years	12 years	15 years
Launch time	1978–1985	1990–1997	1997–2004	2005–2009	2010–2016	2016–present
	No SA ability				L5 added	No SA ability
						With laser prism reflector

(*source* http://www.gps.gov/)

BLOCK IIF satellites in 2010. In 2016, the GPS III satellites began to broadcast three GPS carrier frequencies (L1, L2 and L5) with four civil navigation codes (C/A, L2C, L5 and L1C), among which the L2C was mainly designed for commercial applications. L5 was developed to meet the demands of navigation users in the field of safety-of-life-related transportation and other high-precision applications, and L1C was designed for compatibility and interoperability between GPS and other GNSSs.

(2) Launching the new generation GPS III satellites to gradually replace the earlier satellites. The GPS III satellites were no longer able to implement the Selective Availability (SA) policy and a laser prism reflector was carried onboard to separate the satellite orbit and clock errors. The lifespan of the GPS satellites was also extended.

Until 2016, the GPS ground control segment consisted of one MCS, one backup MCS, 15 globally distributed monitoring stations, 11 uplink stations and the auxiliary communication network, shown in Fig. 4.3. Its MCS was located in Colorado, US. The ground control segment upgrade was included in the GPS modernization program and consisted of the following main aspects: (1) the Legacy Accuracy Improvement Initiative (L-AII) plan completed in 2008; ten GPS monitoring stations that belonged to the National Geospatial-Intelligence Agency (NGA) were added to the ground monitoring network to improve the forecasting accuracy of the GPS broadcast ephemeris; (2) the Architecture Evolution Plan (AEP) for MCS IT upgrade and the Launch and early orbit, Anomaly resolution, and Disposal Operations (LADO) plan for monitoring out-of-operation satellites in 2007; and (3) the Next Generation Operational Control System (OCX) plan implemented in 2010.

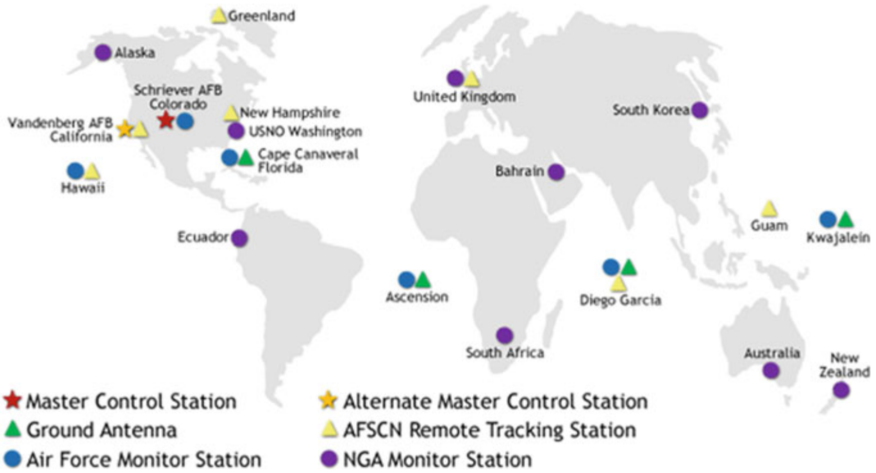

Fig. 4.3 GPS ground control segment (*source* http://www.gps.gov/multimedia/images/GPS-control-segment-map.pdf)

The major function of the GPS user segment, including GPS receivers and handheld terminals, is to track GPS satellites and compute the three-dimensional positioning, velocity and time for users. Users can receive two types of GPS positioning services: standard positioning service (SPS) and precise positioning service (PPS), shown in Table 4.3. SPS is free for all users. The positioning and timing services are obtained with C/A code on L1 and the broadcast ephemeris. PPS is aimed at serving the military and authorized users, and the positioning and timing services are obtained using the ranging code modulated on both L1 and L2 (Grimes 2007).

4.2.3 GLONASS

GLONASS was developed by the USSR in 1976 and is now operated by Russia. With the first GLONASS satellite launched on October 12, 1982, the full constellation was completed and was put into operation at the beginning of 1996. However, due to the short satellite lifespan of only 2–3 years on average and the lack of adequate funding to launch supplementary satellites after the economic recession, there were only six operational GLONASS satellites on orbit in 2011, which severely impacts the normal use of GLONASS. With the recovery of the Russian economy, the GLONASS modernization program was initiated. At the end of 2011, the full 24-satellite constellation was restored for independent navigation and positioning capability.

The space segment of GLONASS consists of 21 operational satellites and 3 backup satellites, which are evenly distributed over three orbital planes with an inclination of 64.8°. The longitude of the ascending node of each plane differs by 120° from

Table 4.3 Performance of GPS SPS and PPS

	Service performance		SPS	PPS	
	Coverage		Global (civil)	Global (authorized)	
Signal in space	Accuracy			Single frequency	Double frequency
	Ranging accuracy			5.9 m	6.3 m
	Accuracy of ranging rate			0.006 m/s	0.006 m/s
	Accuracy of ranging acceleration			0.002 m/s^2	0.002 m/s^2
	Accuracy of timing			40 ns	40 ns
	Integrity (95%) SIS URE	Alarm threshold	150 m	150 m	
		Warning threshold	8 s	8 s	
		Integrity risk	1×10^{-5}/h	1×10^{-5}/h	
	Continuity risk		SIS: 0.0002/h	SIS: 0.0002/h	
	Single slot availability		0.957	0.957	
Performance indicators	Accuracy (95%)		Horizontal: 9 m Vertical: 15 m		
	PDOP availability		Global average: PDOP $\leq$ 6 (98%) Worst case: PDOP $\leq$ 6 (88%)	Global average: PDOP $\leq$ 6 (98%) Worst case: PDOP $\leq$ 6 (88%)	
	Accuracy availability		Horizontal: 17 m Vertical: 37 m		

plane to plane. In each orbit plane, there are 8 satellites separated by 45° in argument of latitude (ICD-GLONASS 2008). At an altitude of 19,100 km, the orbital period is 11 h 15 min and 44 s. In September 2016, the number of operational satellites in orbit was increased to 27, 24 of which are GLONASS-M and GLONASS-K1 satellites with full operational capability. For more information about GLONASS, please refer to https://www.glonass-iac.ru/.

Frequency division multiple access (FDMA) modulation is used by GLONASS; thus, different satellites are distinguished by different frequencies. The frequencies of the civil signals G1 and G2 broadcasted by GLONASS satellites are as follows:

$$\begin{cases} G1: f_{K1} = 1602\,\text{MHz} + 0.5626\,\text{MHz} \times K \\ G2: f_{K2} = 1246\,\text{MHz} + 0.4375\,\text{MHz} \times K \end{cases} \tag{4.1}$$

where $K = -7, \ldots 0.6$ is the frequency number of each satellite. For any satellite, $f_{K1}/f_{K2} = 9/7$. The frequencies of carriers G1 and G2 for military use are different than those for civil use. Pseudo-random-noise code is modulated on the carrier signal and is the same for each set of frequencies. Similar to GPS, the civil code C/A was initially modulated only on carrier G1 whereas the military code P was modulated on both carriers G1 and G2. Later, the C/A code was also modulated on carrier G2 of GLONASS-M satellites. In contrast to GPS, the GLONASS P code is not encrypted.

The original intention to adopt the FDMA system in GLONASS was to enhance the anti-jamming capability. However, this strategy prevented the promotion of commercialization of GLONASS. To improve the compatibility and interoperability with other GNSSs, GLONASS began to broadcast the CDMA signal. For example, the first GLONASS-K1 satellite launched in 2011 broadcasted FDMA signals in the G1 and G2 bands and the new CDMA signal in the G3 band (1202.025 MHz), marking the first step of GLONASS signal modernization. In the future, the development of GLONASS CDMA signals will mainly focus on the G1 and G2 bands. As an improved version of GLONASS-K1, the GLONASS-K2 satellite could broadcast civil FDMA ranging code in G1 and G2 as well as the civil CDMA ranging code in G1, G2 and G3. GLONASS constellation modernization also includes stability and performance improvement of the onboard atomic clock, satellite lifespan extension, and introduction of intersatellite laser ranging (shown in Table 4.4).

The GLONASS system control center (SCC) is located in Krasnoznamensk, Moscow. The GLONASS time reference is maintained by the central clock (CC-M) in Schelkovo. Five telemetry, tracking and command (TT&C) centers are evenly

Table 4.4 GLONASS constellation modernization (*source* https://www.glonass-iac.ru/en/guide/)

		GLONASS	GLONASS-M	GLONASS-K1	GLONASS-K2
Civil signal		G1OF	G1OF/G2OF	G1OF/G2OF G3OC	G1OF/G2OF G1OC/G2OC G3OC
Military signal		G1SF/G2SF	G1SF/G2SF	G1SF/G2SF	G1SF/G2SF G1SC/G2SC
Designed lifetime		3.5 years	7 years	10 years	10 years
Launch time		1982–2005	2003–2016	2011–2018	2017~
Clock stability		5×10^{-13} ~1×10^{-13}	1×10^{-13} ~5×10^{-14}	1×10^{-13} ~5×10^{-14}	1×10^{-14} ~5×10^{-15}
Modulation mode		FDMA	FDMA	FDMA/CDMA	FDMA/CDMA
Intersatellite links:	RF	–	+	+	+
	Laser	–	–	–	+

Note 'O' is the open signal, 'S' is the precision signal, 'F' is FDMA and 'C' is CDMA

Table 4.5 Overview of GLONASS service performance

Performance indicator			Performance specification
Signal-in-space	Ranging error for any satellite		18 m
	Ranging velocity error for any satellite		0.02 m/s
	Ranging acceleration error for any satellite		0.007 m/s^2
	RMS ranging error for all satellites		6 m
Service	Coverage		From the earth's surface to an altitude of 2000 km
	Positioning accuracy (95%)	Horizontal	5 m (global average) 12 m (global average)
		Vertical	9 m (global average) 25 m (global average)
	Timing accuracy		$\leq$700 ns
	Availability (95%)	Horizontal	12 m (global average $\geq$ 99%, worst case $\geq$ 90%)
		Vertical	25 m (global average $\geq$ 99%, worst case $\geq$ 90%)
	Reliability	Fault rate	$\leq$3 times/year
		Reliability	99.97%

distributed in Saint Petersburg, Schelkovo, Yenisseisk, Komsomolsk and Ussuriysk in Russia. Although the GLONASS TT&C stations are not distributed worldwide, a high-accuracy broadcast ephemeris can be generated by the ground control segment because the longitudinal span of the Russian territory is large. In addition, some TT&C stations are also equipped with a laser station (LS) and other Monitoring and measuring stations (MS). The service performance of GLONASS system are summarized in Table 4.5.

4.2.4 *Galileo*

Galileo was developed in a collaboration between the European Union and the European Space Agency (ESA). Galileo is the first global navigation satellite system designed for civil uses. The space segment of Galileo consists of 24 operational satellites and 6 spare satellites, which will be positioned on three orbital planes with an inclination of 56°, and the ascending nodes on the equator are separated by 120°. The orbital altitude is 23,222 km, and the orbital period is approximately 14 h (ICD-Galileo 2008).

The development of Galileo can be divided into three phases: the development system testbed, in-orbit validation (IOV) and full operational capability (FOC). During the development system testbed phase, two experimental satellites, GIOVE-A and

GIOVE-B, were launched in 2005 and 2008, respectively (known as the Galileo In-Orbit Validation Element, GIOVE). Later, four Galileo-IOV satellites were launched in 2011 and 2012. In 2014, the Galileo-FOC satellites began to be launched.

The ground control segment of Galileo comprises two parts: the ground mission segment (GMS) and the ground control segment (GCS). The GMS is mainly responsible for processing observations to generate broadcast ephemeris. One ground control center (GCC) is located in Fucino, Italy, and is mainly responsible for monitoring the satellite constellation along with the GCC in Oberpfaffenhofen, Germany. These two GCCs are responsible for coordination and control of the TT&C stations, several uplink stations (ULS) and the Galileo sensor stations (GSSs) distributed worldwide, to maintain routine operation of the control segment. Galileo attaches great importance to system augmentation and integrity, which helps ensure the positioning accuracy and reliability in the fields of aviation and other safety-of-life applications.

Galileo makes use of the CDMA system to broadcast carrier signals on four frequencies: E1, E5a, E5b and E6. Five types of services are provided by Galileo for users: the free open service (OS) similar to GPS SPS, the safety-of-life service (SoLS), the commercial service (CS), the public regulated service (PRS) and the search and rescue (SAR) service. Signal E1 supports OS/CS/SoL/PRS services, E6 supports CS/PRS services, E5a supports OS services, and E5b supports OS/CS/SoL services. The service performance of Galileo system are summarized in Table 4.6.

With the modernization of GPS and GLONASS and the deployment of BDS and Galileo, the GNSS constellations has developed from approximately 30 GPS

Table 4.6 Overview of Galileo service performance

Satellite self-standing service			OS	CS	SoLS	PRS
Service	Coverage		Global	Global	Global	Global
	Positioning (95%)	Single frequency	Horizontal: 15 m Vertical: 35 m		–	Horizontal: 15 m Vertical: 35 m
		Double frequency	Horizontal: 4 m Vertical: 8 m		Horizontal: 4 m Vertical: 8 m	Horizontal: 6.5 m Vertical: 12 m
		Timing	30 ns		30 ns	30 ns
	Integrity	Alarm threshold	–		Horizontal: 12 m Vertical: 20 m	Horizontal: 20 m Vertical: 35 m
		Alarm time			6 s	10 s
		Integrity risk			3.5×10^{-7}/150 s	3.5×10^{-7}/150 s
	Continuity		–	–	1×10^{-5}/15 s	1×10^{-5}/15 s
	Availability	Available accuracy	99.8%	99.5%	99.8%	99.5%
		Available integrity	–	–	99.5%	99.5%

Table 4.7 Summary of BDS/GPS/GLONASS/Galileo system

	GPS	GLONASS	Galileo	BDS
First Launch	1978-02-22	1982-10-12	2005-12-28	2017-11-05
FOC	1995-07-17	1996-01-18	/	/
Service type	Military/civil	Military/civil	Commercial/open	Military/civil
No. of designed satellites	24	24	30	30
No. of orbital planes	6	3	3	3 (MEO)
Orbital inclination	55°	64.8°	56°	55° (MEO)
Orbital altitude	20,200	19,100	23,222	21,528 (MEO)
Orbital period	11 h 58 m	11 h 15 m	14 h 04 m	12 h 53 m (MEO)
Coordinate system	WGS84	PZ-90	GTRF	BDCS
Time system	GPST	UTC(SU)	GST	BDT
Modulation mode	CDMA	FDMA	CDMA	CDMA
Frequencies	L1:1575.42 L2:1227.60 L5:1176.45	G1:1602.00 G2:1246.00 G3:TBD	E1:1575.42 E5a:1176.45 E5b:1207.14 E6:1278.75	B1:1575.42 B2:1176.45 B3:1268.52

satellites in the early stage to more than 100 GNSS satellites in September 2016, summarized in Table 4.7. RNSSs such as QZSS and NAVIC are also under development. As shown in Fig. 4.4, the global coverage and availability of satellite navigation system signals have been improved.

In addition, the frequencies and types of GNSS satellite signals are becoming increasingly abundant (as shown in Table 4.7). For example, the second civil ranging code L2C and the third frequency L5 have been gradually provided by modernized GPS satellites. In the future, GLONASS will simultaneously broadcast FDMA, CDMA, as well as the third frequency signal G3. BDS provides signals in three frequencies of the full constellation and Galileo could broadcast carrier signals on four frequencies and 10 ranging codes. There are over 75 types of measurements (Gurtner and Estey 2013). To meet the ever-growing demand for GNSS civil applications, the third frequency signals L5 and G3 that are used for safety-of-life applications were designed by GPS and GLONASS, respectively; as a civil GNSS, Galileo gave high priority to aviation, safety-of-life and SAR applications at the beginning of its development.

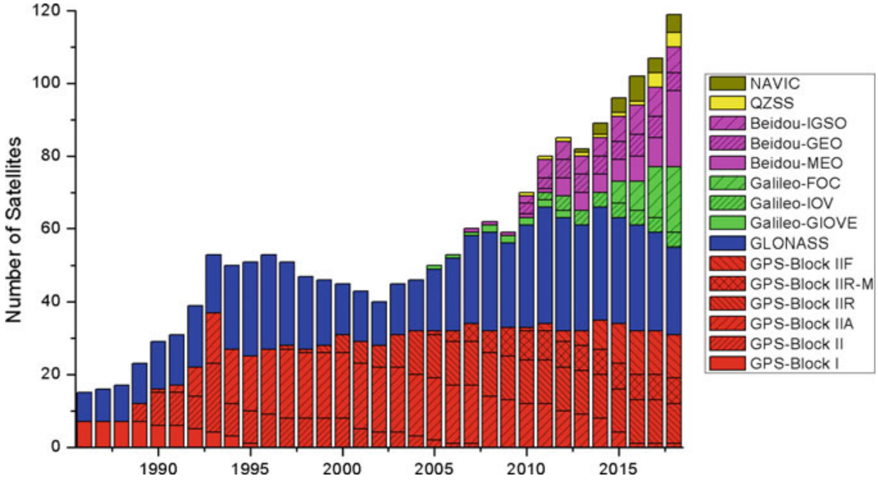

Fig. 4.4 The number of in-orbit satellites in GNSSs and RNSSs

4.3 GNSS Augmentation Systems

As described in Sect. 4.2, the accuracy of GNSS is rather limited and cannot meet the required positioning accuracy, time latency, reliability and integrity needs of higher-level users. The GNSS differential positioning technique and GNSS augmentation system strategy address this issue. In GNSS differential positioning, the observations of GNSS reference stations are used to model the error sources such as the ionospheric, tropospheric, satellite orbit and clock errors. These errors are then mitigated from the observation of users in real-time or post-processed mode to improve the accuracy and reliability of positioning. To meet the demands of different users, several different kinds of GNSS high-accuracy and real-time positioning systems have gradually been developed, including the wide-area differential augmentation system, the global/wide-area precise positioning system, the local area differential augmentation system and the local area precise positioning system (summarized in Table 4.8).

4.3.1 Wide-Area Differential Augmentation System

In the wide-area differential augmentation system, GNSS satellites are monitored with a ground tracking network and the raw observations are transferred to the master control center through communication links. The master control center models the errors of the GNSS raw observations and divides the errors into satellite orbit, clock, and ionospheric errors, which are formatted and broadcasted to users in the service region through communication links. The positioning accuracy can be improved by

Table 4.8 Overview of GNSS augmentation systems

	Reference station	Processing principle	Broadcast link	Broadcast format	Performance	Typical systems
Wide-area differential technique	Ranges of several thousand kilometers with several dozen reference stations	Differencing in the state domain, with corrections generated for orbit and clock errors, grid ionospheric VTEC values based on pseudorange measurements (assisted by the carrier phase)	GEO satellites or radio beacons	RTCA	Single-frequency pseudorange differential positioning, Precision: 3 m without initialization	WAAS EGNOS MSAS GAGAN SDCM
Global precise positioning technique	~100 globally reference stations	Differencing in the state domain, with corrections generated for orbit and clock errors based on carrier phase measurements	GEO satellites or through the Internet	SOC or User-defined protocol	Double-frequency carrier phase differential positioning, Precision: decimeter-level with initialization of approximately 20 min	GDGPS StarFire OmniStar SeaSTAR Veripos RTX
Local-area differential technique	Range of a few tens of kilometers with several reference stations	Differencing in the observation domain, with pseudorange corrections generated based on pseudorange measurements (assisted by the carrier phase)	U/VHF data link	RTCA or RTCM	Single-frequency pseudorange differential positioning Precision: submeter level without initialization	LAAS
Local-area precise positioning technique	Range of a few tens of kilometers with several reference stations and can be extended to larger regions with several thousand reference stations	Differencing in the observation domain, with regional error correction parameters generated in VRS, FKP, MAC and other processing modes based on carrier phase measurements. Users in the region can apply for such correction information	GPRS/CDMA communication link broadcasting	RTCM	Double-frequency carrier phase differential positioning Precision: centimeter level with an initialization of approximately 1–2 min	CORS

using the wide-area differential corrections. With uniform precision over broad coverage, the positioning accuracy of the wide-area differential augmentation system is independent of the distance between the user and the reference station. Several wide-area differential augmentation systems have been established worldwide, e.g., the Wide Area Augmentation System (WAAS) of the Federal Aviation Administration (FAA), the European Geostationary Navigation Overlay Service (EGNOS), the Multi-functional Satellite Augmentation System (MSAS) of Japan, the GPS-Aided Geo Augmented Navigation (GAGAN) of India and the System Differential and Correction Monitoring (SDCM) of Russia.

4.3.1.1 WAAS

The GPS SPS could not meet the higher accuracy, integrity, continuity and availability demands of users in aviation and other fields. As a result, the FAA initiated the WAAS program. As a satellite-based augmentation system (SBAS) to serve North America, WAAS is aimed at providing GPS differential correction information through GEO satellites to augment the GPS SPS. In addition to applications in the field of aviation, the WAAS has also been widely applied to support PNT services.

As illustrated in Fig. 4.5, the WAAS currently consists of 3 wide-area master stations (WMS), 38 wide-area reference stations (WRS), 4 Ground Uplink Stations and

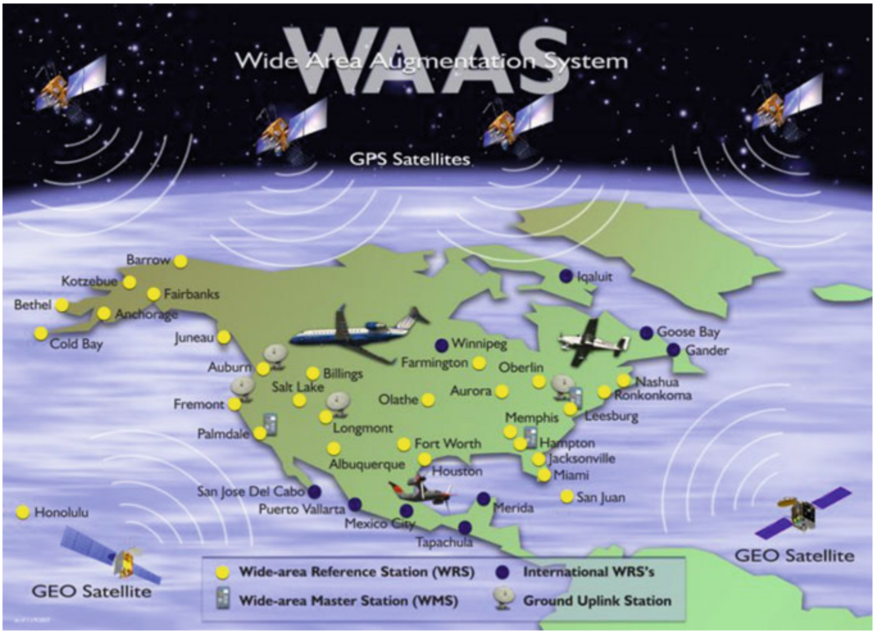

Fig. 4.5 Diagram of WAAS (*source* http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/)

GEO satellites. The WMS is responsible for calculating the differential corrections and monitoring the system integrity. The WAAS data processing center receives real-time GPS observations from the WRS and computes differential correction vectors using the RTG (Real Time GIPSY) software package developed by the JPL based on GIPSY-OASIS. The corrections include the satellite orbit error, satellite clock error and the ionospheric error. Since these differential corrections are expressed as vectors, the precision of positioning within the areas covered by the wide-area differential system is equivalent, in contrast to the local-area differential system. The corrections are uploaded to GEO satellites through uplink stations and broadcast to users in RTCA format to improve positioning accuracy. The nominal positioning accuracy of WAAS (with 95% reliability) is better than 7.6 m in the horizontal and vertical directions. The horizontal and vertical positioning accuracy of WAAS are better than 1.0 m and 1.5 m, respectively, in most regions adjacent to the US, Canada and Alaska.

4.3.1.2 EGNOS

EGNOS is a joint program of the European Space Agency (ESA), the EU and the European Aviation Safety Agency (EASA). The working principle of EGNOS is similar to that of WAAS. The difference is that EGNOS broadcasts differential corrections and integrity information for GPS as well as the differential corrections for GLONASS. The EGNOS differential correction information is calculated using software developed from BAHN, the ESA-owned precise positioning and orbit determination software, and broadcasted by GEO satellites through the L band. The EU is considering extending the broadcast coverage from the EU to other regions, including countries neighboring the EU and Africa.

The EGNOS ground network consists of 39 ranging integrity monitoring stations (RIMSs), 4 mission control centers (MCCs) and 6 navigation land earth stations (NLESs). The 4 MCCs are located in Torrejon, Spain, Gatwick, England, Langen, Germany, and Ciampino, Italy. EGNOS presently provides three types of service: (1) free open service since October 2009, with positioning accuracy of 1–2 m; (2) safety-of-life service since March 2011, with positioning accuracy of 1 m; and (3) data access service since July 2012, with positioning accuracy better than 1 m.

4.3.1.3 MSAS

MSAS was jointly developed by the Japan Civil Aviation Bureau (JCAB) and Japan's Ministry of Land, Infrastructure and Transport, mainly to provide communication and navigation services for Japanese aviation users. MSAS covers all flight service areas of Japan, and can broadcast meteorological information to mobile users in the Asia-Pacific region. The space segment of MSAS consists of two multifunctional transport satellites (MTSats), which are second generation Himawari satellites, the geostationary meteorological and environmental survey satellite developed by Japan.

The two MTSats are positioned at 140° E and 145° E. The Ku and L bands are the two frequencies; the Ku band is mainly used to broadcast high-speed communication information and meteorological data. Similar to the GPS L1 frequency, the L band is mainly used for navigation services. The working principle of MSAS is similar as those of WAAS and EGNOS, and the RTG software authorized by JPL is used for data processing. From its initial operation in September 2007, MSAS remarkably improved the navigation service performance for Japanese airports located on remote islands and met the precision demand for the nonprecision approach specified by the International Civil Aviation Organization (ICAO).

4.3.1.4 GAGAN

The GAGAN system was jointly developed by the Indian Space Research Organization (ISRO) and the Airports Authority of India (AAI). The space segment of GAGAN consists of two GEO satellites positioned over the Indian Ocean. Two bands are applied in GAGAN: the C band is used for TT&C application and the L band is used to broadcast navigation information. The frequency of the L band is identical to that of the GPS L1 (1575.42 MHz) and L5 (1176.45 MHz); thus, GAGAN is compatible and interoperable with GPS. The GAGAN signal covers the whole Indian continent, providing users with GPS signals and differential corrections to improve the GPS positioning accuracy and reliability for Indian airports and other aviation applications. The key technique and core algorithm of GAGAN is also based on technical support from the JPL. The ground segment of GAGAN consists of a master station located in Bangalore, an uplink station and eight reference stations located in Delhi, Bangalore, Ahmedabad, Calcutta, Jammu, Port Blair, Guwahati and Thiruvananthapuram.

4.3.1.5 SDCM

Serving as the GLONASS satellite navigation augmentation system, Russia began developing the SDCM system in 2002 with an aim of providing differential augmentation information for GLONASS and other GNSSs. The space segment of SDCM consists of three GEO satellites, also called the Russian civil data relay (Luch/Loutch) satellites. The three satellites are known as Luch-5A, Luch-5B and Luch-5, located at 167° E, 16° W and 16° W, respectively.

4.3.2 Global Differential Precise Positioning System

The global differential precise positioning technique was developed from the wide-area differential GNSS and the precise point positioning technique. In global differential positioning systems, the GNSS pseudorange and carrier phase observations are collected by globally distributed GNSS dual-frequency monitoring stations and transferred to data processing centers through a real-time data transmission network to calculate the real-time precise satellite orbit, clock error and ionospheric corrections. Using the corrections, a user could realize decimeter to centimeter level precise positioning around the world. The wide-area differential augmentation system mainly serves navigation users with the pseudorange observations whereas the global precise positioning system mainly targets positioning users with the carrier phase observations. Well-known established representative global differential precise positioning systems include the global differential GPS (GDGPS) system applied for satellite orbit determination, scientific research and high-end commercial services, the StarFire system developed by NavCom, OmniSTAR and SeaStar by Fugro, CenterPoint RTX by Trimble and Veripos by Subsea7.

4.3.2.1 GDGPS

GDGPS is the global precise positioning system developed by the National Aeronautics and Space Administration (NASA) of the United States. As shown in Fig. 4.6, the ground monitoring network of the GDGPS consists of more than 200 real-time monitoring stations all over the world. These monitoring stations transmit real-time data to the GDGPS processing center at 1 Hz frequency. Among the tracking stations, over 75 monitoring stations belong to the JPL. They are evenly distributed worldwide and equipped with three-frequency receivers. The time latency of the GDGPS from receiving observations to generating and broadcasting real-time differential correction products is approximately 5 s. The real-time differential correction products can be broadcasted in a variety of ways, including through the Internet, a VPN, T1, frame relay, modem and satellite broadcasting.

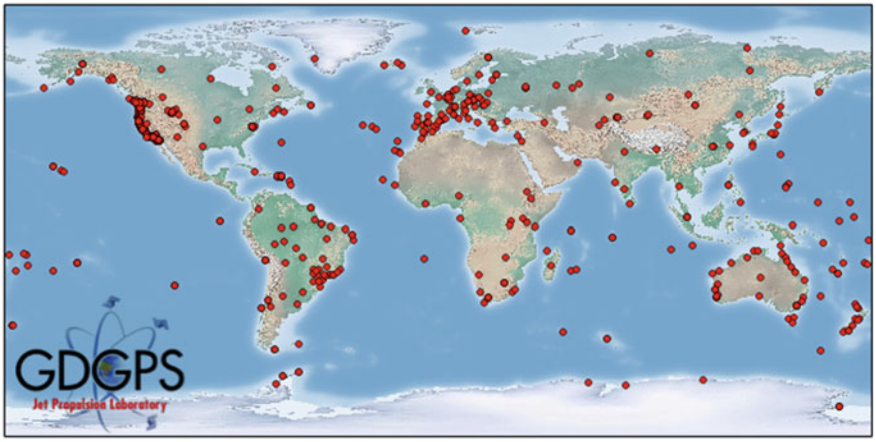

Fig. 4.6 The real-time tracking network of the GDGPS (*source* http://www.gdgps.net/)

The JPL-developed RTG software is adopted in the GDGPS, with the state-square approach proposed by the JPL as its core algorithm. Based on the real-time dual-frequency GPS observation data collected by GDGPS monitoring stations worldwide, precise satellite orbit and clock errors are determined and compared with relevant parameters in the GPS broadcast ephemeris to generate differential corrections. The corrections are broadcasted to users for precise point positioning. The GDGPS can provide decimeter-level positioning and subnanosecond-level time transfer for dual-frequency GPS receivers over the globe. Compared with traditional differential positioning services, the positioning accuracy has been improved by one order of magnitude. The single-frequency users can also use the global ionospheric TEC maps provided by the GDGPS to implement ionospheric correction and improve positioning accuracy.

4.3.2.2 StarFire

In the early stage, StarFire was designed to provide independent wide-area differential augmentation services for precision agriculture in North America, South America, Europe and Australia. The early StarFire system was similar to WAAS and EGNOS, except that StarFire users must be equipped with high-quality dual-frequency GPS receivers to eliminate ionospheric delay, and should adopt the wide area correction transform (WCT) technique that was developed on the basis of NavCom.

In 2001, an agreement was reached between NavCom and NASA/JPL to upgrade StarFire into a global dual-frequency GPS precise positioning system based on the RTG technique. Continuous real-time positioning services with subdecimeter accuracy can be accessed anywhere and anytime around the world. In addition to the RTG technique, StarFire can access observation data from the NASA/JPL global monitoring network to augment the StarFire ground monitoring network. In addition, StarFire makes use of the International Maritime Satellite (INMARSAT) to broadcast differential signals to global users through the L band. StarFire users equipped with L band communication receivers can track and observe GPS satellites and receive the differential correction signals broadcasted by INMARSAT.

RTG/RTK is a new real-time differential positioning mode recently launched by NavCom. The disadvantage of a relatively long initialization time in RTG can be overcome by using RTK. If lock-lose or communication interruption of data links occur during RTK, real-time positioning services can be continuously provided by the RTG with centimeter-level positioning accuracy. After restoring the signal tracking and data link communication in RTK, the positioning result of the RTG can be used as the initial value for rapid searching and integer ambiguity resolution. The disadvantage is that at least two RTG/RTK combined dual-frequency receivers are required on the user side for real-time positioning.

4.3.2.3 OminiSTAR/SeaStar

OmniSTAR and SeaStar are real-time global differential systems developed by the Fugro company. OmniSTAR is mainly used in land and aviation applications and SeaStar was established to meet the demands for high kinematic positioning in marine applications. OmniSTAR currently provides four types of differential GPS positioning services with different accuracies, VBS, HP, XP and G2, among which the G2 service can support both GPS and GLONASS. OmniSTAR has been widely applied in agriculture, GIS, aviation, surveying and mapping, asset tracking and monitoring and, thus, occupies a considerable market share in differential GPS services.

SeaStar primarily serves the offshore oil and gas exploitation industry to meet the demands for submeter and decimeter-level kinematic positioning with high accuracy and reliability under special circumstances. It can provide G2, XP2, SGG and standard L1 services for GPS and GLONASS, as well as XP service for GPS. The latest G4 service simultaneously supports GPS, GLONASS, BeiDou and Galileo.

4.3.2.4 CenterPoint RTX

CenterPoint RTX (Real-Time eXtended) is a global real-time differential system developed by the US company Trimble. It provides worldwide precise positioning services with a horizontal accuracy better than 4 cm for GPS, GLONASS and QZSS. Using the corrections broadcasted by the L-band satellite, the initialization time needed for positioning is less than 5 min.

4.3.2.5 Veripos

Established by the Subsea7 company, Veripos consists of more than 80 reference stations all over the world. The two control centers of Veripos are located in Aberdeen, Britain and Singapore. The Veripos Apex, Veripos Apex^2, Veripos Ultra and Veripos Ultra^2 can provide services with a positioning accuracy better than 10 cm, and Veripos Standard and Veripos Standard^2 can provide a positioning accuracy better than 1 m. The latest Veripos Apex^5 can provide augmentation services for GPS/GLONASS/Galileo/BDS/QZSS with a horizontal positioning accuracy better than 5 cm (within a 95% confidence level).

4.3.3 Local Area Differential Augmentation System

The local area augmentation system (LAAS) at airports is a typical local area differential augmentation system. Based on GPS real-time differential corrections, LAAS was established as an all-weather precision approach and landing system. It consists of reference stations, a central processing station and airborne equipment. GPS satellites are continuously tracked by several reference stations located around the airport, and the central processing station receives the GPS observations to generate pseudorange differential corrections and integrity and precision approach and landing data, which are encoded and broadcasted to the airplane through VHF data links. Based on the GPS observations, differential corrections and integrity information broadcasted by LAAS, the airborne equipment can improve the navigation accuracy, integrity, continuity and availability to realize precision approach category I (CAT I) along a specified path. The ultimate goal of an LAAS is to provide CAT II and CAT III.

4.3.4 Local Area Precise Positioning System

In the local area precise positioning system, several GNSS reference stations are established in a certain region (district, city or country) and high-accuracy positioning service is provided to users within its coverage by taking advantage of differential corrections through a wired/wireless real-time data communication link. The local area precise positioning system can be categorized into two operational modes, single reference station mode and multiple reference stations mode. In single reference station mode, a reference station directly broadcasts high-precision carrier phase measurements to users at the rover station. The rover station receives the measurements and realizes precise positioning based on the differential positioning technique. The positioning accuracy of single reference station mode is at the centimeter level, which can meet the demands of applications within a small area.

The continuously operating reference station (CORS) system is a local area precise positioning system operated in the multiple reference station mode. CORS consists of continuously operating GNSS reference stations, which are interconnected by computer, data communication and the Internet. The observation data (carrier phase and pseudorange) at CORS reference stations are transmitted to the data processing center through the communication link in real-time. The data from the reference network are then uniformly processed to calculate and model the real-time corrections for various GNSS errors within the region, such as the satellite orbit/clock error an ionospheric and tropospheric error. The corresponding observation data and GNSS error model are broadcasted by the data processing center to users at the rover station for high-accuracy positioning. Many countries have established their own CORS systems at the national level, including the US, Germany, England, Australia, Japan, and Canada. Brief introductions to the US CORS and EPN in Europe are provided as representative examples.

4.3.4.1 US CORS

The establishment of CORS in the US was led by the National Geodetic Survey (NGS). More than 200 agencies and organizations have been involved in this program. The three largest CORS networks include the national CORS network, the operational CORS network and the California CORS network. In 2015, the US CORS consisted of more than 2000 reference stations. Most of the stations are distributed in American. However, several stations are located in Canada, Mexico, Central America and North America. The US CORS provides users with coordinates under the International Terrestrial Reference Frame (ITRF) and the 1983 North American Datum (NAD83), as well as raw observations and satellite orbit products. Real-time differential positioning service is also available in some areas, e.g., the San Diego real-time network.

4.3.4.2 EPN in Europe

The EUREF permanent network (EPN) in Europe is a cooperative regional continuously operating network established by the European Commission of the IAG. The EPN was composed of 250 permanent reference stations in 2016. The workflow of the EPN is as follows: the reference stations are divided into several subnetworks with independent system operation centers. Several system operation centers constitute a regional data center, and the data from regional data centers are gathered into the European regional center, which transfers the data products to the IGS data center, regional data centers and various kinds of users. The EPN provides users with centimeter-level coordinates and velocity in ITRF and EUREF, as well as zenith tropospheric products for the reference stations. In addition, the EPN can be applied to monitor crustal deformation, sea level changes, and in numerical weather prediction (NWP).

GNSS augmentation systems have achieved significant developments in the aspects of the accuracy, integrity, coverage and differential mode. The positioning accuracy of GNSS augmentation systems has improved from meter-level, as for WAAS, EGNOS and MSAS, to real-time decimeter-level and post-processed centimeter-level, e.g. StarFire and OmniStar. The GNSS augmentation system has been extended from regional coverage to seamless global coverage. The early GNSS augmentation systems provided users with correction based on one differential approach whereas the current system can provide users with high-precision positioning with corrections derived from multiple differential approaches. As an effective supplement to GNSS, the GNSS augmentation systems have greatly improved the GNSS SPS performance to meet the ever-growing demands for integrity, continuity and availability of navigation systems. They also benefit many other applications such as navigation, aviation, maritime, industry, and precision agriculture.

4.4 Applications in Digital Earth Case Studies

GNSSs have been widely applied in navigation for vehicles, offshore ships, aero craft and aerospace vehicles, geodesy, oil exploitation, precision agriculture, precise time transfer, Earth and atmospheric sciences, and many other fields. Its applications in the establishment of space-time geodetic datum, high-precision positioning and location-based services are introduced below.

4.4.1 Terrestrial Reference System

As a result of inexpensive GNSS receivers, densely distributed tracking stations and the high accuracy performance, GNSSs have played an important role in the establishment and maintenance of geodetic datum. The location and movement of a point on the Earth's surface must be expressed in a terrestrial reference system (TRS) attached to the Earth (also called the Earth-centered Earth-fixed system). The origin of the TRS is usually defined as the center of mass of the Earth, the Z axis is aligned with the international reference pole, the X axis is coincident with the Greenwich zero meridian, and the Y axis is orthogonal to the Z and X axes in the right-handed sense. As an ideal realization of the TRS, the TRF is comprised of a set of stations distributed on the Earth's surface with precisely known coordinates. The TRF is of great importance for geodesy, geophysics and space research. GNSS is an important data source to establish and maintain the TRF.

The widely used ITRF was established based on space-geodetic observations including GNSS, very long baseline interferometry (VLBI), satellite laser ranging (SLR), and Doppler orbit determination and radio positioning integrated on satellite (DORIS). As a realization of the International Terrestrial Reference System (ITRS), the ITRF can provide datum definitions (including origin, orientation and scale) for other global and regional TRS. Since 1988, more than ten versions of the ITRF have been released by the IERS, the latest version of which is the ITRF2014 released on January 2016 (Altamimi et al. 2016).

Different TRFs are adopted by different GNSSs. They include the World Geodetic System 1984 (WGS84) for GPS, Parametry Zemli 1990 (PZ-90) for GLONASS, Galileo terrestrial reference frame (GTRF) for Galileo and the BeiDou coordinate system (BDCS) for BDS. Most of the TRFs are aligned to the ITRF. The positioning results based on GNSS broadcast ephemeris are expressed in the corresponding TRF. As the TRF for GPS broadcast ephemeris, WGS84 has been refined several times by the US DoD, resulting in WGS84 (G730), WGS84 (G873), WGS84 (G1150), WGS84 (G1674) and WGS84 (G1762). PZ-90 is the TRF for GLONASS broadcast ephemeris. Successive versions of PZ-90, PZ-90.02 and PZ-90.11, have been released (Zueva et al 2014). GTRF is the TRF for the Galileo broadcast ephemeris, and GTRF07v01, GTRF08v01, GTRF09v01 and GTRF14v01 have been released (Gendt et al. 2011).

To unify the positioning results expressed in different TRFs, a 7-parameter Helmert transformation should be applied:

$$\begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix} = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} + D \cdot R_1(\alpha_1) \cdot R_2(\alpha_2) \cdot R_3(\alpha_3) \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix} \tag{4.2}$$

where T_1, T_2, T_3 are the translation parameters for the X, Y and Z axes, respectively, D is the scale factor, and $\alpha_1, \alpha_2, \alpha_3$ denote the Euler angles of rotation for the X, Y and Z axes. $R_i(\alpha_i)$ indicates the rotation matrix constituted by the rotation angles α_i for axis i, which can be expressed as:

$$R_1(\alpha_1) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha_1) & -\sin(\alpha_1) \\ 0 & \sin(\alpha_1) & \cos(\alpha_1) \end{pmatrix}$$

$$R_2(\alpha_2) = \begin{pmatrix} \cos(\alpha_2) & 0 & \sin(\alpha_2)0 \\ 0 & 1 & 0 \\ -\sin(\alpha_2) & 0 & \cos(\alpha_2) \end{pmatrix}$$

$$R_3(\alpha_3) = \begin{pmatrix} \cos(\alpha_3) & -\sin(\alpha_3) & 0 \\ \sin(\alpha_3) & \cos(\alpha_3) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{4.3}$$

For the transformation parameters between different ITRF versions, please refer to Table 4.1 in the IERS Conventions (2010). The transformation parameters between ITRF2008 and WGS84, PZ-90, and GTRF versions are shown in Table 4.9. The definitions of the transformation parameters are the same as in Eq. (4.3).

4.4.2 Time System

Three types of time systems are commonly used. Their time scale are based on the Earth's rotation, e.g., the universal time (UT), the revolution of the Earth around the sun, and the electron transition frequency of atoms, e.g., the International Atomic Time (TAI). Coordinated Universal Time (UTC) uses the SI second of atomic time as its fundamental unit and is kept in time with the UT.

Atomic time is a time system based on the electromagnetic oscillation generated by the atomic transition inside substances. The Standard International (SI) second is defined as the time that elapses during 9,192,631,770 cycles of the radiation produced by the transition between two levels of the cesium 133 atom. The International Atomic Time (TAI) is the time system determined by the SI second, with the same origin as UT2 on 0 h 0 m 0 s, January 1, 1958. As a continuous and uniform time scale, TAI

Table 4.9 Transformation parameters between WGS84, PZ-90, GTRF and ITRF2008 (*source* http://www.unoosa.org/oosa/en/ourwork/icg/resources/Regl-ref.html)

From	To	T_1 (mm)	T_2 (mm)	T_3 (mm)	D (ppb)	R_1 (mas)	R_2 (mas)	R_3 (mas)	Epoch
WGS84 (G1674)	ITRF2008	0	0	0	0	0	0	0	2005.0
PZ-90.11	ITRF2008	−3 ±2	−1 ±2	0 ±2	0 ±0.3	0.019 ±0.072	−0.042 ±0.073	0.002 ±0.090	2010.0
WGS84 (G1150)	PZ-90.02	360 ±100	−80 ±100	−180 ±100	0	0	0	0	2002.0
GTRF09v01	ITRF2008	2.0	0.9	4.7	−0.94	0.00	0.00	0.00	2000.0
Rate		−0.3	0.0	0.0	0.00	0.00	0.00	0.00	

is maintained by the Bureau International des Poids et Mesures (BIPM) using the atomic clocks of 400 national laboratories worldwide.

Universal Time (UT) is defined as the hour angle of mean sun relative to the Greenwich meridian plus 12 h. UT can be divided into three types. UT0 is directly determined from astronomical observations. Correcting the Earth's polar motion from UT0 yields UT1 whereas UT2 is obtained by correcting the seasonal variations of the Earth's rotation from UT1. UT1 defines the orientation of the average Greenwich meridian with respect to the mean equinox and thus represents the real rotation of the Earth. Since UT1 has a tendency of long-term slowdown, the difference between UT and the atomic time will grow increasingly larger. To avoid such an inconvenience, Coordinated Universal Time (UTC) has been adopted since 1972 based on the second length of TAI. It is a uniform but discontinuous time scale, and the difference between UTC and UT1, which is known as the leap second, is maintained within 0.9 s. The leap second with respect to UT1 is released by the IERS, and the relationship between TAI, UTC and leap seconds can be described as

$$TAI = UTC + leap \tag{4.4}$$

GNSSs are also an important technology to establish and maintain time systems. The GNSS time system is atomic time, in which the TAI second length is used and maintained jointly by high-accuracy atomic clocks onboard the GNSS satellites and implemented in the ground system. With an origin at 00:00 on January 1, 1980, the GPS Time (GPST) is adopted for GPS system. To ensure uniform continuity, there is no leap second in GPST and the constant difference between TAI and GPST is maintained as 19 s.

GLONASS makes use of GLONASS Time (GLONASST), which is synchronized to the UTC (SU) of Russia but biased by 3 h to match the local time zone of Moscow: GLONASST = UTC (SU) + 3 h. Unlike GPST, there are leap seconds in GLONASST.

Galileo adopts the Galileo System Time (GST) with an origin at 00:00 on August 22, 1999 (UTC time). The difference between GST and UTC at the starting epoch is 13 s and there is no leap second to maintain the uniform continuity of GST.

BDS makes use of BeiDou Time (BDT) with an origin at 00:00 on August 22, 1999 (UTC time). The difference between BDT and TAI at the origin moment is 33 s. BDT is counted with the week number (WN) and seconds of week (SOW). Similar to GST, no leap second is adopted to maintain uniform continuity of BDT. BDT is steered to UTC (NTSC).

The transformations between GPST, GLONASST, BDT, GST and UTC are as follows:

$$\begin{cases} UTC - GPST &= 19s - leap + C_0 \\ UTC - GLONASST &= C_1 \\ UCT - BDT &= 33s - leap + C_2 \\ UTC - GST &= 19s - leap + C_3 \end{cases} \tag{4.5}$$

where *leap* is the leap second of UTC with respect to TAI, as shown in Eq. (4.4); C_0, C_1, C_2, C_3 are the daily deviation values of GPST, GLONASST, BDT and GST relative to UTC, respectively, provided by the BIPM. The accuracies of C_0 and C_1 are approximately 10 ns and several hundreds of ns, respectively (ftp://ftp2.bipm.org/pub/tai/other-products/utcgnss/utc-gnss).

High-accuracy UTC time can be obtained through GNSS data. The GNSS common-view technique has been used by the BIPM for many years as one of its main techniques for international time transfer. It has the advantages of low equipment cost, high accuracy and convenient operation. In this technique, the time difference between two clocks, A and B, is determined by simultaneous observation of a third clock on a GNSS satellite. Each station observes the time difference between its clock and the GNSS time plus a propagation delay, which can be largely removed by using one-way GNSS time transfer procedures. By exchanging data files and performing a subtraction, the time difference between the two receiving stations is obtained.

The GNSS timing technique has been widely applied to time and frequency synchronization in the communication, finance and power industries in China. In the communication field, time synchronization for the whole communication network is realized through installation of GNSS timing terminals, so the billing time can be ensured to be consistent and accurate. For the frequency synchronization networks of China mobile, China telecom and China Unicom, the first-level reference clock and part of the second-level/third-level/micro-synchronization-node clock are equipped with a built-in GNSS reception module and external GNSS receivers. The time synchronization networks are also equipped with dual-mode GNSS timing receivers.

In the power industry, time and frequency synchronization for the substation network can be provided by GNSS timing. The time systems from power transmission network to power computer network in the Chinese power industries mainly use GPS as the master clock for timing and synchronization. On December 1, 2017, the 'Technical specification of time synchronization system and equipment for smart substation' (GB/T 33591-2017) became officially effective, in which the BDS is adopted as the main technique for time synchronization. By the end of 2017, there were nearly 900 sets of dispatching automation master station systems (in 11 categories) that could receive BDS signals in the domestic power grid control network, and more than 15,000 sets of GPS timing equipment have been updated to be compatible with the BDS.

4.4.3 High-Precision Positioning

The accuracy of single-point positioning based on broadcast ephemeris is only 10 m and is influenced by the unmodeled errors and noise of the pseudo-ranges. It cannot meet the requirements of many applications and limits the use of GNSSs. Differential GNSS techniques were developed to improve the positioning accuracy to decimeter-level. DGNSS/RTK and precise point positioning (PPP) are two commonly used high-precision differential positioning methods. The basic principle uses one or more reference stations with precisely known positions to model the observation errors, including the ionospheric and tropospheric delay and satellite clock and orbit errors to improve the accuracy and reliability of positioning for users.

The high-precision GNSS positioning algorithm was developed from the single-station pseudorange differential approach and carrier phase differential approach into a real-time carrier phase differential approach based on multiple reference stations (network RTK), PPP, and PPP with fixed ambiguity resolution (PPP-AR), improving the resolution accuracy and extending the application modes. The differential algorithms can be categorized into location differential, pseudorange differential and carrier phase differential techniques according to the differential observations adopted. The differential algorithms can also be classified as single-station differential, local area differential, wide area differential, or global real-time high-precision PPP based on the effective range of the differential corrections. They can be categorized into satellite-based and ground-based differential augmentation based on the type of broadcast link. Finally, the differential algorithms can be categorized into the state space representation (SSR) differential method and the observation space representation (OSR) differential method according to the differential model algorithm and parameters.

The PPP (SSR) and the network RTK (OSR) are the two major techniques in high-precision GNSS positioning services. The network RTK method, also known as the RTK method with multiple reference stations, usually needs more than three GNSS CORS stations within a certain region. Taking one or several stations as the reference stations, the distance dependent errors are modeled as regional OSR corrections. The differential corrections are provided to the rover stations in real time for precise positioning. The network RTK method can be classified into four types, including the virtual reference station (VRS) method, the master auxiliary concept (MAC) method, the Flächen Korrektur parameter (FKP) method or the combined bias interpolation (CBI) method, according to the OSR differential corrections used.

The VRS method is the most widely used network RTK technique at present. A virtual reference station is established near the rover station. Observation of the virtual reference station is generated using the real observation of the surrounding reference stations plus the regional error corrections. By receiving the observations of the virtual reference station, users can realize high-accuracy real-time positioning with the single-station RTK method. In the MAC method, corrections from the reference network can be divided into two categories: corrections closely correlated with the carrier frequency, e.g., the ionospheric delay, and corrections independent of the carrier frequency, e.g., the orbit error, tropospheric error, and multipath effect. The integer ambiguity of the reference network is initially fixed to ensure a uniform integer ambiguity reference for all the reference stations. The correction difference between the auxiliary station and the master station is calculated and broadcasted to the rover station. The principle of the FKP method is to estimate nondifferential parameters for each reference station in real time and generate the network solution. The spatial correlation error of the ionosphere and the geometric signal inside the network is then described with regional parameters. Based on these parameters and locations, the rover station computes the error corrections and realizes precise positioning.

The FKP method has been widely applied in Germany, the Netherlands and other European countries. The CBI method does not distinguish ionospheric delay from tropospheric delay and other types of errors when calculating the corrections of the reference stations. The corrections for each reference station are not broadcasted to the users. Instead, the observation data of all the reference stations are gathered to select, calculate and broadcast the comprehensive error corrections to the user.

For specific regional users, the accuracy of network RTK can achieve centimeter-level. However, due to the spatial restriction of OSR differential correction methods, the distance between reference stations in network RTK can generally be no more than 70 km. Therefore, it would be very costly to establish a wide-area real-time service system to serve a large number of users using the network RTK method. The PPP technique based on the wide-area (global) tracking network can realize high-accuracy positioning with only a few reference stations in a wide area. It could effectively overcome the disadvantages of network RTK. However, although PPP could provide positioning service with the same accuracy all over the world, it has the disadvantages of slightly lower positioning accuracy and relatively longer initialization time than network RTK.

Based on precise satellite orbit and clock error data, the PPP method could realize decimeter-level to millimeter-level positioning accuracy using carrier phase and pseudorange observations collected by a single GNSS receiver. Only the high-precision satellite orbit and clock errors are needed to obtain high-precision positioning for any station at any location and the positioning error is homogenous worldwide. Thus, PPP has been widely used in crustal deformation monitoring, precise orbit determination, precise timing, earthquake/tsunami monitoring and warning, and many other fields. As an extension of the standard PPP technique, PPP-AR can obtain ambiguity-fixed coordinates through restoring the integer characteristics of the nondifferential ambiguity. Its accuracy is equivalent to that of RTK.

In China, the first-generation BDS augmentation system was formally approved on April 28th, 1998, with the goal of providing GPS wide-area differential and integrity service for users based on BDS-1. It aims to improve the GPS accuracy and reduce the risk of using GPS. The first-generation BDS augmentation system (the first phase of construction) was completed and began trial operation in 2003. During this period, the augmentation system operated stably and provided real-time GPS differential correction and integrity service for various users in the service region. The positioning accuracy and integrity warning capability were basically in accordance with the design indicator requirements. In recent years, research and development of a wide-area real-time precise positioning prototype system in China and the neighboring areas have been carried out with the support of the national 863 program. As a key project in the field of Earth observation and Navigation Technique under the National High-tech Research and Development Program (863 program) in 2007, the 'wide-area and real-time precise positioning technique and prototype system' was jointly undertaken by the China Satellite Communications Corporation (China Satcom), China Center for Resources Satellite Data and Application, and Wuhan

University. Based on the wide-area differential and PPP technique, the satellite navigation augmentation service is realized with a positioning accuracy of better than 1 m for land, ocean and air transport in China.

The construction of CORS around world has entered into a new era. A provincial-level CORS system in Jiangsu and Guangdong provinces has been established in China. CORS systems have also been established in various large- and medium-sized cities, e.g., Beijing, Shanghai, Tianjin, Chongqing, Nanjing, Guangzhou, Shenzhen, Wuhan, Kunming, Jinan, Qingdao, Suzhou, Changzhou, Hefei, Dongguan, and Zibo. There are more than 2200 CORS stations in China. CORS systems may be upgraded to install BDS receivers. High-precision surveying can be conducted through these CORS systems with high efficiency and less man-power than traditional technology such as a total station. The CORS system is currently a vital part of surveying and mapping activities around the world, including urban planning, land surveying and mapping, cadastral management, urban and rural construction, and mining surveying.

The differential GNSS technique can support cadastral surveying to establish property boundaries, which is of great importance for fiscal policies such as land taxation. In the different construction stages of a building or civil engineering project (such as a highway, motorway, bridge, underground tunnel, railway, reservoir or embankment), GNSS positioning can be used to automatically control the construction equipment. GNSSs are also used to define specific location points of interest for cartographic, environmental and urban planning purposes. GNSSs play an important role in measurement and calculation at each stage of mine exploitation, including safety checks. GNSSs are used to monitor critical infrastructure and the natural environment to prevent major disasters and promptly intervene in case of emergency. GNSSs can support a wide range of activities in marine surveying, such as seabed exploration, tide and current estimation and offshore surveying.

4.4.4 Location-Based Service

Location-based service (LBS) systems work independently or cooperate with mobile terminals to provide real-time and post-processed positioning and timing service for various users through different communication networks. LBS relies on GNSS and augmentation systems to provide uniform space-time datum. Other assisted navigation and positioning techniques are also incorporated to improve the anti-jamming capability and availability of LBS. Through communication networks, e.g., the internet and mobile internet, LBS can provide users with positions, attitude, velocity and time synchronization services.

The workflow of a typical LBS system can be designed as follows: the GNSS wide-area augmentation system receives a real-time data stream from various GNSS tracking networks, generates the wide-area and regional satellite navigation augmentation signals, and provides them to the authorized public users through broadcasting systems controlled by a service provider. GNSSs are 'outdoor' positioning techniques, as the GNSS signal is affected by strong attenuation and multipath caused by complex indoor environments. In severe environments, the GNSS signals cannot be captured. Thus, the location of users inside a building should be determined by an indoor positioning system using WIFI, Bluetooth, INS, magnetic fields, and virtual beacons. The information integration platform receives the satellite navigation augmentation signals and merges them with geographical data to provide users with comprehensive location-based value-added service through LBS providers. As an integration of social networks, cloud computing and the mobile internet, LBS could become the core element of a series of significant applications, e.g., intelligent transportation systems (ITS), precise agriculture, intelligence manufacturing and smart cities. GNSS-enabled LBS applications are mainly supported by smartphones.

ITS refers to efforts to add information and communications technology to transport infrastructure and vehicles in an effort to manage factors that are typically at odds with each other, such as vehicles, loads, and routes, to improve safety and reduce vehicle wear, transportation times, and fuel consumption. GNSSs play an important role in ITS applications such as traffic control and parking guidance by providing accurate and reliable positioning. The low-cost high-precision GNSS receiver has a big potential market in ITS. The low-cost GNSS receiver can also be integrated with an inertial navigation system (INS) to develop an autonomous navigation system for general aviation (GA). General aviation is the term used to describe all aviation except government and scheduled-airline use.

The accuracy of GNSS SPS is only approximately 10 m. It cannot tell users the optimal lane to get to their destination, especially in dense urban environments such as multilane roads and highways. With the aid of an LBS system, lane-level navigation and positioning with meter-level accuracy can be realized. It will become the standard configuration for passenger vehicles and freight vehicles with hazardous chemicals in the future. The consortium within the EU-funded InLane project is working on the fusion between computer vision and GNSS technologies to achieve the required level of positioning that allows for the safe operation of autonomous vehicles (https://www.gsa.europa.eu/market/market-report).

The embedment of GNSS terminals in bicycle-sharing systems can result in more accurate and reliable positioning for better user experiences, especially in complex scenarios. The positioning accuracy can be improved from 50-100 m to approximately 3 m. The GNSS terminals can also support orderly parking. Currently, approximately half of the bicycle-sharing systems in China are equipped with GPS terminals. High-precision BDS positioning has also been adopted in driver training. It can automatically record the trail of the wheel at the centimeter level. Many driving test centers in China promote this technique.

The premise of precision agriculture is to adapt field operations to local variations in crop and soil conditions using state-of-the-art technology combined with knowledge-intensive field management. The positioning system is a part of precise equipment that consists of a differential global positioning system (DGPS) receiver, a radar velocity sensor, a wheel velocity sensor and an electronic compass. Precision positioning helps complete field applications faster and more productively, accurately, safely and comfortably, with less operator fatigue. GNSS is used in agriculture in a few key areas. As crops are harvested, a GNSS receiver connected to a yield monitor sensor records a coordinate along with the yield data. This data is combined and analyzed to create a map of how well different areas of the field are producing. When spreading fertilizer or planting, equipment operators have traditionally used markers such as foam or other visual aids to mark where they've been to try to avoid overlap. The assistance of GPS and onboard guidance systems such as a light bar, can further reduce overlap.

For many years, the leading technology for precision agriculture was GPS L1 receivers providing submeter precision. That precision can meet the requirements of applications at the submeter level, such as applying chemicals, field mapping and aerial spraying. However, high-precision applications such as auto-steer need centimeter precision. Historically, Hemisphere GPS (formerly CSI), Trimble Navigation, OmniSTAR, and smaller designers and system integrators have been the GNSS technology providers for precision agriculture. The world-wide agriculture market is booming. Auto-steer and other high-precision GNSS applications in agriculture have contributed to increased production capacity.

The GNSS navigation function in smart phones can record the wheel path and personal interests as well as the behaviors of pedestrians and drivers, providing large amount of social activity information. It should be regarded as an important source of big data on human activities and interests. In the future, with the application of high-accuracy navigation based on smart phones and the implementation of integrated indoor and outdoor location services, this big data will provide more abundant information. A 2013 Nature paper noted that the owner of a cellphone can be specified (with 95% probability) by analyzing the big data of the cellphone location tracks in a city with approximately 1,500 thousand people. LBS systems could also support applications such as geomarketing and advertising, fraud management and location-based billing, which require authentication of the position to protect app users.

LBS applications for healthcare are increasing. Healthcare needs are driving the diversification of wearables. For example, a GNSS-enabled haptic shoe allows for visually impaired users to set a destination in a smartphone app. The soles guide the user to the destination by vibrating in the front, back, or sides. Visually-impaired people or wheelchair users rely on a seamless navigation experience between outdoor and indoor environments. They need more high-precision horizontal and vertical position information (https://www.gsa.europa.eu/market/market-report).

In summary, there is a huge navigation and LBS market. The navigation and LBS network will also promote the development of industries such as national security, social security, energy conservation and emission reduction, disaster relief and mitigation, traffic and transportation, the IoT, resource investigation, and precision agriculture.

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Chuang Shi is a professor at School of Electronic and Information Engineering, Beihang University. He graduated from Wuhan Institute of Surveying and Mapping (current Wuhan University) and obtained his Ph.D. in 1998. His research interests include network adjustment, precise orbit determination of GNSS satellites.

Na Wei is an associate professor at GNSS Research Center of Wuhan University. She has obtained her Ph.D. degree in 2011 from Wuhan University. Her research interests include terrestrial reference frame and surface mass loading.

Chapter 5
Geospatial Information Infrastructures

Sven Schade, Carlos Granell, Glenn Vancauwenberghe, Carsten Keßler, Danny Vandenbroucke, Ian Masser and Michael Gould

Abstract Geospatial information infrastructures (GIIs) provide the technological, semantic, organizational and legal structure that allow for the discovery, sharing, and use of geospatial information (GI). In this chapter, we introduce the overall concept and surrounding notions such as geographic information systems (GIS) and spatial data infrastructures (SDI). We outline the history of GIIs in terms of the organizational and technological developments as well as the current state-of-art, and reflect on some of the central challenges and possible future trajectories. We focus on the tension between increased needs for standardization and the ever-accelerating technological changes. We conclude that GIIs evolved as a strong underpinning contribution to implementation of the Digital Earth vision. In the future, these infrastructures are challenged to become flexible and robust enough to absorb and embrace technological transformations and the accompanying societal and organizational implications. With this contribution, we present the reader a comprehensive overview of the field and a solid basis for reflections about future developments.

Keywords Geospatial information · Infrastructure · Spatial data · Public sector · Government

S. Schade (✉)
European Commission—Joint Research Centre, Ispra, Italy
e-mail: s.schade@ec.europa.eu

C. Granell · M. Gould
Universitat Jaume I, Castellón, Spain

G. Vancauwenberghe · D. Vandenbroucke · I. Masser
Katholieke Universiteit Leuven, Louvain, Belgium

C. Keßler
Aalborg University, Copenhagen, Denmark

M. Gould
ESRI, Redlands, USA

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5.1 Introduction

Geospatial information (GI), i.e., information including a relationship to the Earth (Worboys and Duckham 2004), is a foundational ingredient for any Digital Earth application. Examples include information about land parcels, transport networks and administrative boundaries, vehicles, microplastics, fine particles, mobile devices and people. With GI, we can build digital replicas of our planet and use them to exchange knowledge, monitor the state of the Earth, simulate possible future scenarios or assess possible impacts of decision making. Although also other terms (such as 'geographic' or 'spatial') are used in scientific and other literature to refer to the same or similar concepts, we use 'geospatial' in this chapter. Furthermore, we speak of 'information' as (possibly processed) data in a context that allows for interpretation and meaningful use.

The technological, semantic, organizational and legal structure that allows for the discovery, sharing, and use of GI is called geospatial information infrastructure (GII) (Yang et al. 2010; Granell et al. 2014). With its core functionalities, a GII can be considered the backbone for Digital Earth. GIIs are essential to facilitate the information flow that is required to implement any past, present and future version of the Digital Earth vision—the knowledge sharing platform as initially envisaged by Gore (1998), a global tool for multidisciplinary research as outlined by Goodchild and colleagues (2012), or the world laboratory to support codesign, cocreation and codelivery that was suggested by Schade and Granell (2014).

Emerging from an initially highly technical concept, GIIs have a relatively long history and are well researched, including their close relationships with geographic information systems (GIS) (Worboys and Duckham 2004) and spatial data infrastructure (SDI) as enabling technologies (Masser 2005; Yang et al. 2010). Prominent examples of these enabling technologies include the spatial data infrastructure for Australia and New Zealand (ANZLIC 2019), the United States of America-US National Spatial Data Infrastructure (NSDI 2019), the Infrastructure for Spatial Information in the European Community [(INSPIRE 2019), see also Chap. 20], OpenStreetMap [(OSM 2019a), see also Chap. 18], and Google Maps (Google 2019).

By nature, GIIs undergo a continuous evolution that is primarily driven by the increasing pace of technological advancements and the inherent digital transformation of our societies (Castells and Cardoso 2005; Gimpel and Röglinger 2015). Similar to other information handling tools, GIIs face continuous challenges caused by the speed of technological progress that sometimes conflicts with the heaviness inhering in most governance structures. For example, the implementation of heavily governed GIIs bears a risk to continually run behind technological solutions (Schade and Smits 2012; Tsinaraki and Schade 2016). We have witnessed a shift from public sector (alone) to more collaborative approaches to the provision and operation of GI and related services, which increasingly involve the private sector (smeSpire 2014; Sjoukema et al. 2017). Whereas public sector information (e.g., about cadastral parcels or protected sites) continues to play an important role, increasing amounts of spatial data are produced, owned and provided by the private sector. Examples include street (navigation) data and satellite imagery, and 'standard' products such as Google Earth, Google Maps, Bing, and spatial data from GPS providers such as Here and TomTom.

In this situation, we face two opposing forces: traditional standardization processes and frequent technological disruption. Heavily standardized large infrastructures and platforms to support Digital Earth may have been a necessity a few years ago (Granell et al. 2016), when large amounts of GI were not easily accessible and data transformation used to be a process that was run on large computing machines for a long time before harmonized information could be provided to users. During that time, it was affordable to invest in traditional standard-based infrastructures and in educational programs that provided specialized training to develop, maintain and use such infrastructures (Masser 2005; Vandenbroucke and Vancauwenberghe 2016). However, is this still affordable today—in an era of fast digital transformation when disruptive technologies are about to become a new norm? Or will microservice-based architectures (Dragoni et al. 2017) to build smaller, more manageable platforms beat monolithic, big, layered architectures? How must the development of standards change to fit these new dynamics? What roles will the private sector play in this new set-up?

The question of whether Digital Earth will follow the traditional standardization approach, an alternative approach that completely embraces vivid digital transformation or anything in between has strong implications on the definition of the conceptual architecture of the GII with Digital Earth. Hence, we are at a controversial point in GII and Digital Earth history. This chapter outlines how we arrived at this point, explains the current situation in more detail, provides a critical reflection, and outlines a few future trajectories. We hope that this contribution to the Manual of Digital Earth aids in understanding the importance and evolution of GIIs and provides food for thought for those that will develop and use GIIs to implement the Digital Earth vision.

The remainder of this chapter is structured as follows. The next section introduces the history of GIIs during the different phases of organizational and technological development (Sect. 5.2). Next, we outline the current situation in respect to GII development, education and use (Sect. 5.3). We focus on the evolving relationship between GIIs and Digital Earth and important recent movements such as Open Science. In Sect. 5.4, we discuss changes and the challenges that GIIs face today. The most important implications for the Digital Earth vision are highlighted. In Sect. 5.5, we close the chapter with a brief conclusion and an outlook on the future of GIIs in support of Digital Earth. For details about GI analysis and processing, we refer the reader to Chap. 6. Matters of GI visualization are discussed in Chap. 7.

5.2 A Brief History of Geospatial Information Infrastructures

GIIs are not a new concept, and have evolved over a series of generations, each characterized by changing purposes, available technologies, and the main stakeholders involved in their design, implementation and use. Instead of describing these generations in detail, which has been done elsewhere (Rajabifard et al. 2002; Yang et al. 2010), we highlight fundamental milestones in the history of GII. We also highlight evolutions of the technical architectures used to implement GIIs over the past few decades.

5.2.1 Geospatial Information Infrastructure Milestones

In the history of GIIs worldwide, a series of milestones have been essential for the evolution of GIIs into their current form—most of which relate to actions of government, i.e., policy updates. Notably, these milestones differ in nature, for example, by administrative dimension, research purpose or geographic extent. However, they give a sensible impression of aspects that have framed the evolution of GIIs up to today.

As a first milestone, the EU initiated the CORINE program in 1985 with the aim of describing the status of the environment in Europe. This program was the first large-scale effort in Europe to collect spatial data covering the European territory according to agreed specifications in view of supporting different policies. It delivered its first pan-European land cover data set in 1990, with updates in 2000, 2006 and 2012. The second milestone dates back more than thirty years to the establishment of the Australian Land Information Council (ALIC) in January 1986. ALIC was the result of an agreement between the Australian Prime Minister and the heads of the state governments to coordinate the collection and transfer of land-related information between the different levels of government and to promote the use of that information in decision making (ANZLIC 1992). One year later, a third milestone occurred in May 1987 with the publication of the Report of the British Government Committee of Enquiry on Handling Geographic Information chaired by Lord Chorley (Coppock 1987). This report, also known as the Chorley report, set the scene for much of the subsequent discussion about GIIs in the UK and in other parts of the world. While the report reflected the committee's enthusiasm for the new technology: "the biggest step forward in the handling of geographic information since the invention of the map" (para 1.7), it also expressed their concern that information technology must be regarded as "a necessary, though not sufficient condition for the take up of geographic information systems to increase rapidly" (para 1.22). A fourth important milestone in the late 1980s was the release of the first issue of the International Journal of Geographic Information Systems, also in 1987. The journal, renamed the International Journal of Geographic Information Science in 1997, was the first scholarly journal devoted to GI.

The fifth milestone occurred in 1990 when the United States Office of Management and Budget (OMB) established an interagency Federal Geographic Data Committee (FGDC) to coordinate the "development, use, sharing, and dissemination of surveying, mapping, and related spatial data." The main objectives of a national GII were "encouraging the development and implementation of standards, exchange formats, specifications, procedures, and guidelines, promoting technology development, transfer, and exchange; and promoting interaction with other existing Federal coordinating mechanisms that have an interest in the generation, collection, use and transfer of spatial data…" (OMB 1990, pp. 6–7). These ideas were subsequently developed and extended by the United States National Research Council's Mapping Science Committee in their report 'Toward a coordinated spatial data infrastructure for the nation' (National Research Council et al. 1993). This report, which can be seen as a sixth milestone in the history of GIIs, recommended that effective national policies, strategies, and organizational structures be established at the federal level for integration of national geospatial data collection, use and distribution. A seventh milestone is the outcome of an enquiry by the Directorate-General XIII (now DG Connect) of the European Commission (EC), which found that there was a strong Europe-wide demand for an organization that would further the interests of the European GI community. As a result, the first regional level multidisciplinary SDI organization in the world was set up in 1993. The vision of the European Umbrella Organisation for Geographic Information (EUROGI) was not to "replace existing organisations but catalyse effective cooperation between existing national, international, and discipline-oriented bodies to bring added value in the areas of Strategy, Coordination, and Services" (Burrough et al. 1993).

An eighth milestone that marks a turning point in the evolution of the SDI concept came in the following year with the publication of Executive Order 12906 signed by President Bill Clinton, entitled "Coordinating Geographic Data Acquisition and Access: the National Spatial Data Infrastructure" (Executive Office of the President 1994). This described the main tasks to be carried out and defined time limits for each of the initial stages of the national spatial data infrastructure. These included the establishment of a national geospatial data clearing house and the creation of a national digital geospatial data framework. (Here, we understand data clearing houses as "internet-based components that intend to facilitate access to spatial data, by establishing a centralized site from which data from several sources can be found, and by providing complementary services, including searching, viewing, transferring, and ordering spatial data" (Davis 2009). The Executive Order gave the FGDC the task of coordinating the Federal government's development of the National Spatial Data Infrastructure. As the Executive Order also required each member agency of that committee to hold a policy-level position in their organization, it significantly raised the political visibility of geospatial data collection, management and use among US institutions and internationally. The organization of the first Global Spatial Data Infrastructure (GSDI) Conference in Bonn, Germany, in September 1996 was another—ninth—milestone in the 90s. The conference brought together representatives from the public and private sectors and academia for the first time to discuss matters relating to NSDIs at the global level. Shortly after, in 1998, the Baveno Manifesto set a fundamental milestone for European space policy. It led to the establishment of the Global Monitoring for Environmental Security (GMES) program, which was formally established in 2010 (Regulation (EU) No 911/2010), and followed by the Copernicus program in 2014 (Regulation (EU) No 377/2014).

After 2000, the evolution of GIIs worldwide continued, and several milestones can be highlighted. One was the establishment of the intergovernmental Group on Earth Observations in February 2005 to implement a global Earth observation system of systems (GEOSS) to integrate observing systems and share data by connecting existing infrastructures using common standards. In 2018, there were more than 400 million open data resources in GEOSS from more than 150 national and regional providers such as NASA and ESA, international organizations such as the World Meteorological Organization (WMO) and commercial sector groups such as Digital Globe (Nativi et al. 2013). Another—eleventh—milestone was the launch of the first scholarly journal in the GII field in 2006. The International Journal of SDI Research is a peer-reviewed journal that is operated by the Joint Research Centre of the European Commission, which aims to further the scientific endeavor underpinning the development, implementation and use of Spatial Data Infrastructures. Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 established an Infrastructure for Spatial Information in the European Community (INSPIRE, see Chap. 20 for more details) can be seen as a twelfth milestone in the evolution of GIIs. The INSPIRE Directive aimed to establish a spatial data infrastructure to improve the sharing and interoperability of geospatial data in support of environmental policies and policies that might have an impact on the environment (Directive 2007/2/EC of the European Parliament and the EU Council) and was the second multinational GII initiative that sought to make harmonized high-quality GI readily available. INSPIRE stresses the principles of data sharing and cross-border usage of the data. The year 2011 marked a key event that initiated the deep involvement of the private sector: the first Geospatial World Forum "Technology for people and Earth" (Geospatial World 2011). This global conference gathers diverse stakeholders to present and discuss the pathways of the geospatial industry. In addition, the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) was established in July 2011 (ECOSOC Resolution 2011/24) as the official United Nations consultative mechanism on global GI management. Its primary objectives are to provide a forum for coordination and dialogue among Member States of the United Nations (UN) and between member states and relevant international organizations and to propose work plans that promote global frameworks, common principles, policies, guidelines and standards for the interoperability and interchangeability of geospatial data and services. Not long ago, (23 June 2015) the first Sentinel (satellite developed for the Copernicus program delivering open Earth Observation) was launched. This milestone initiated the launch of a set of sister satellites that deliver high-resolution images and contribute strongly to a new era of GI provision worldwide.

Table 5.1 provides an overview of the fifteen milestones discussed in this section. They are mostly institutional, legal and policy-related. Notably, the milestones cover different regions (e.g., Europe, North America and Australia), administrative levels (e.g., national, regional and global) and sectors (e.g., academic and cross-sectoral initiatives). They reflect the breadth and diversity of GII initiatives since the 1980s. This demonstrates how GIIs took a leading role in promoting and enabling open data publishing, possibly as the most common theme across the globe. These developments took place in support of the Open Movement, Open Science, Open GIScience, and citizen science, which we explore in more detail later in this chapter (in Sect. 5.3).

Table 5.1 Geographical information infrastructure milestones

Year	Milestone
1985	The European Union (EU) launched the CORINE land cover program as the first large-scale effort to collect spatial data covering the European territory
1986	The Australian Land Information Council began coordinating the collection and transfer of land-related information between the different levels of government
1987	Report of the Committee of Enquiry into Handling Geographic Information, chaired by Lord Chorley
1987	Launch of the International Journal of Geographic Information Systems
1990	The US Federal Geographic Data Committee was created to coordinate the development, use, sharing and dissemination of surveying mapping and related geospatial data
1993	US Mapping Science Committee report on 'Toward a coordinated spatial data infrastructure for the nation'
1993	Establishment of the European Umbrella Organisation for Geographic Information (EUROGI) as the first regional-level multidisciplinary SDI organization
1994	Executive Order 12906 'Coordinating geographic data acquisition and access: the National Spatial Data Infrastructure'
1996	First Global Spatial Data Infrastructure conference in Bonn, Germany
2005	Establishment of the intergovernmental Group on Earth Observations in February 2005 to implement a Global Earth Observation System of Systems (GEOSS)
2006	Launch of the International Journal of Spatial Data Infrastructure Research
2007	Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE)
2011	The first Geospatial World Forum 'Technology for people and Earth' took place
2011	The United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) was established
2015	Launch of Sentinel-2, the first of a series of Copernicus satellites delivering open and high-resolution GI

5.2.2 Architectural Evolutions in Geospatial Information Infrastructure Development

Alongside these milestones, we have witnessed an evolution of GII architectures and technological solutions, following the increased sophistication of technology and growth in user requirements. We summarize the central developments, concentrating primarily on GII. Another chapter of this manual addresses the irruption of sensors, sensor networks and the Internet of Things (IoT, see also Chap. 11). For developments and implications of machine learning, deep learning, and artificial intelligence, we refer the interested reader to Chap. 10.

GI has been used for many decades in different application fields (Longley et al. 2011). In the eighties, GIS technology started to spread globally. Prior to the development of SDIs, which only expanded at a broader scale in the nineties, geospatial data assets were created, managed and used by individual organizations using standalone GIS. In 1987, Specialized software companies such as ESRI brought GIS software to the market that could run on personal computers. Others, such as Intergraph, did the same, and academic and even public sector parties developed software for using geospatial data for particular purposes. Examples include ILWIS (2019) and GRASS (2019).

However, in this period, most efforts were focused on the collection and maintenance of data, as well as its use within the organization. Big data collection efforts started taking place. For example, in Europe the need for data that are standardized, well-documented, high-quality and available for the broader community became apparent. Therefore, the Coordination of Information on the Environment—CORINE program was initiated by the EU. This and similar initiatives elsewhere in the world, e.g., in the US through the FGDC, revealed the need to work more systematically in several technical aspects: documentation (metadata), data harmonization, access mechanisms and standards (Nebert 2004). These technological developments occurred in parallel with the organizational and institutional developments described in the previous section.

Originally, the focus was on exchange formats and particularly on the transformation—where required—from one format to another. In practice, for a long time de facto standards were used a lot. One good example is the shapefile format developed by ESRI that was (and still is) used to transfer geospatial data from one organization to the other (ESRI 1998). In the nineties, data exchange between organizations, although often on an ad hoc basis, became more and more important to avoid duplication of data sets and to share resources more efficiently. With this increased exchange, good documentation became paramount (Danko 2005). From the early nineties, organizations explored ways of documenting data in a standard manner. The first standard used by many was the FGDC metadata standard, which was initiated by President Clinton by executive order 12906 (1994) and became official in 1998 (FGDC 1998). This standard was used a lot, even in Europe. Work on an international metadata standard also began in the nineties but saw only light in 2003 with the adoption and publication of the International Organization for Standardization (ISO) standard

19115 in 2003 (ISO 2003). Since then, thousands of organizations have documented their geospatial data sets according to this standard.

To make potential interested parties aware of the existence of geospatial data resources, the publish-find-bind paradigm was defined as a key concept for SDIs (van Oosterom 2005). The idea is to 'publish' geospatial data resources by documenting and putting them in a catalogue, then make them 'discoverable' by a search mechanism and 'accessible' through a binding mechanism, which means that they can be integrated in a user application (e.g., a web-viewer, a desktop GIS or other application). In addition to the metadata, access mechanisms were designed and developed and became a key component of the technical parts of an SDI (Zhao and Di 2011). The Open Geospatial Consortium (OGC), which was established in 1994, brought together different academic, private and public sector parties and soon focused on the standardization of interfaces for accessing geospatial data resources (OGC 2019). They developed several web service interfaces to perform basic jobs such as 'discovery' (CSW—Catalogue Services for the Web), 'viewing' (WMS—Web Mapping Services—a first version of the standard was released in 2000), and 'downloading' (WFS—Web Feature Services). These OGC standards were meant to adhere to Service-Oriented architecture (SOA), an architectural style aimed at designing applications based on a collection of best practices, principles, interfaces, and patterns related to the central concept of a service (Papazoglou and van den Heuvel 2007). In SOA, services are the basic computing unit to support development and composition of larger, more complex services, which can be used to create flexible, ad hoc, dynamic applications. The main design principle behind SOA is that a service is a standards-based, loosely coupled unit composed of a service interface and a service implementation. Previous examples of OGC service specifications were designed to comply with these SOA principles to publish, find and use geospatial data. Most of the commercial software companies, as well as the Free and Open Source Software for Geospatial (FOSS4G) community—with a major push in 2006 with the establishment of the Open Source Geospatial Foundation (OSGeo)—developed tools and platforms to create such services and build portals for users to find and access data (Tait 2005; Maguire and Longley 2005).

In addition to the efforts to document GI and make it more discoverable and accessible, many efforts were made to better harmonize them for use in cross-border and cross-sector settings. The ISO Technical Committee 211 (ISO/TC211) was created in 1994 to look into the standards for Geographic Information and Geomatics. There was a large effort to develop the so-called ISO 19100 series of standards that, in addition to the already mentioned metadata standard, comprise a series of standards describing how to model our world (ISO 2002). The series includes a reference model, the definition of spatial and temporal schema, rules for application schema, and a methodology for cataloguing spatial features. In 2001, preparations began to design and implement INSPIRE, the Infrastructure for Spatial Information in Europe (INSPIRE 2019). In addition to the key idea of improving GI sharing (policy challenge), another objective was to improve spatial data interoperability through the design of data specifications for 34 themes (technical and organizational challenges). The ISO 19100 series of standards served as a basis for this huge effort. The resulting portfolio of standardized data sets serves cross-border applications in the context of environmental policy making/monitoring and other sectors. The process of harmonization is still ongoing at the time of writing.

In parallel with these more formal developments, stimulated by the public sector, developments in the private sector soon influenced SDIs and were ultimately (at least partially) integrated. In 1998, US Vice President Al Gore coined the term Digital Earth in view of global challenges such as climate change (Gore 1998). In 2001, a small software company called Keyhole Inc. launched and developed the Keyhole Earth viewer for looking at our globe from a global, bird's-eye view. The technical solution, aimed primarily at the defense sector, looked at geospatial data from a 3D perspective. A few years later, in 2004, Google acquired the small company and launched the still very popular product Google Earth based on the KML standard. More SDI developments embraced these new developments and aimed to integrate data from these commercial products into SDIs and applications. This whole process ended with the adoption of KML (originally keyhole markup language) by the OGC as a community standard.

In support of the development of SDIs, specific software developments emerged. Traditional GIS desktop software such as ArcGIS from ESRI was extended with server and mobile software, and the FOSS4G communities developed specific products that became very popular, such as GeoNetwork (to create geoportals and catalogue services), GeoServer, Degree and others (to set up all kinds of web services), and open source systems for data management such as POSTGIS (Steiniger and Bocher 2009; Brovelli et al. 2017). In addition to open standards and open software, open data became a new paradigm with important initiatives that are still very popular. In 2004, there was a global effort from the geospatial community to develop and maintain a network of streets (OSM), which was a joint effort of thousands of volunteers to provide and include data into an open data product (Haklay and Weber 2008). These volunteered geographic information (VGI) efforts became also part of the maintenance procedures of commercial products such as those from TomTom (formerly Tele Atlas) and Here (formerly NavTeq). The idea of citizens contributing to data and information gathering has now become widespread and is termed crowdsourcing [(Capineri et al. 2016), see also Chap. 18 for more details]. From the SDI perspective, which often focuses on authoritative data coming from government, these initiatives and the resulting geospatial data resources are considered complementary. The concept of GIS-based (open) data portals for smart city projects has also taken hold in recent years (ESRI 2019a).

These developments (see Table 5.2) led to a vibrant geospatial community and many GIIs that are interconnected (Vandenbroucke et al. 2009) and rich in content and quality, and new developments started to influence the way of working and the methods of providing data to user communities. Although the geospatial world has always worked somewhat in isolation, the developments in the general ICT world led to increased interest in joining forces. In 2006, Tim Berners-Lee coined the concept of Linked Data to combine the huge amounts of data available on the web (Berners-Lee 2006). In the geospatial world, this led to the idea of the geosemantic web. In 2014, the OGC and W3C started several joint initiatives including the Spatial Data

Table 5.2 Timeline of relevant technological developments

Year	Technological development
1982	First release of GRASS as open source software, managed by the US Army Corps of Engineers
1985	First release of ILWIS as closed, proprietary software developed by a university, ITC in the context of a land use zoning and watershed management project in Sumatra; the release as open source software followed in 2002
1987	First release of pcARC/INFO (ESRI), available on personal computers
1992	Introduction of the shapefile format by ESRI, which became a de facto standard format for exchanging geospatial data
1994	The Open Geospatial Consortium (OGC) is established and starts work with 8 members (currently more than 500)
1994	ISO/TC 211 is created as one of the technical committees of the International Organisation for Standardisation (ISO) responsible for the field of Geographic Information
1998	The FGDC metadata standard (US) becomes official
1998	The term Digital Earth is coined by former US Vice President Al Gore, describing a virtual georeferenced representation of the Earth
1998	Publication of the specifications of the shapefile format, which became open at that stage
2000	First version of the Web Mapping Service (WMS) interface standard released by OGC
2001	Keyhole Inc., the developers of Google Earth (originally called Keyhole Earth Viewer) and the KML format, is established
2002	The development of quantum GIS (QGIS) began, released as open source in 2009
2003	ISO 19115 Geographic Information—Metadata standard is adopted by the participating countries
2004	Publication of the SDI Cookbook by the Global Spatial Data Infrastructure Association (GSDI)
2004	Keyhole Inc. is acquired by Google
2004	OSM launched
2006	Linked Data as a concept, method and technique was coined by Tim Berners-Lee within the W3C as part of the semantic web project
2006	Founding of the open source geospatial foundation OSGeo, with currently more than 30000 volunteers, and the first FOSS4G International Conference in Lausanne, Switzerland
2007	The term volunteered geographic information (VGI) was coined by Michael Goodchild
2008	INSPIRE metadata regulation adopted as Implementing Rule 2007/2/EC
2010	INSPIRE regulation regarding interoperability of spatial data sets and services adopted as Implementing Rule 1089/2010
2014	The DCAT metadata standard for data resources of W3C is released
2014	Establishment of the Spatial Data on the Web Working Group focused specifically on the intersection of issues facing OGC and W3C members
2015	OGC adopts KML as a community standard
2015	GeoDCAT-AP, an implementation allowing for data exchange between geoportals and open data portals, was adopted by the EU ISA program

on Web Working Group to examine and test new ways of publishing and linking data (W3C 2015). One of the tangible results of this closer collaboration was the effort to exchange metadata between geoportals and (open) data portals through a more generic and broadly used DCAT standard (W3C 2014). More of these developments are expected to take place—and will continue to emerge faster and faster. This poses particular challenges to standardization processes, which should keep pace with these evolutions. In the next sections, we describe ongoing and new developments, for example, the changing power relationship from the public to the private sector and challenges posed by the trending platformization of society (van Dijck et al. 2018).

5.3 Geospatial Information Infrastructures Today

Leaving the past behind, several important developments and aspects of the current situation of GIIs are important to mention. We consider the following items worth highlighting in the context of Digital Earth: the mainstreaming of GI and the proliferation of GIIs, especially on the web; the contribution of GII developments to the opening of data and science as a whole; and the growth of knowledge exchange and learning networks across the globe.

5.3.1 The Evolution of Geospatial Information on the Web

In parallel to the organizational milestones described in Sect. 5.2, the technical foundations of GIIs were developed and standardized, mostly through bodies such as the OGC and ISO (see Sect. 5.2.2). Along with this development, the proliferation of slippy web maps and map-based mobile applications has led to the establishment of a separate branch of GII that primarily addresses end-user needs by, for example, providing directions to get from one place to another or offering extensive geocoding capabilities (“where is the closest coffee shop?”). The widespread adoption of these new services that were no longer just providing GI for a group of professional users was driven by the introduction of Google Maps in 2005 as well as the introduction of touch-screen smart phones with built-in GPS through the first iPhone in 2007.

Shortly after the introduction of Google Maps, the first reverse-engineered map mashups appeared and demonstrated how Google’s JavaScript-based maps could be combined with GIs from other sources (such as crime data on ChicagoCrime.org or real estate offerings on housingmaps.com). The subsequent release of a public Application Programming Interface (API) for Google Maps that allowed for any web developer to embed a map in their web pages triggered the development of open source alternatives such as OpenLayers (OpenLayers 2019), which is still under active development today as an OSGeo project. OpenLayers is notable in this context because it bridges the worlds of consumer-oriented GI and GIIs targeted at professional use cases by allowing the combination of data from OGC-based web services with tiles and file formats such as KML. Esri released its JavaScript API to facilitate the creation of web apps from traditional GIS datasets (ESRI 2019b). Together with other, more recent examples such as Leaflet (Leaflet 2019), a 'grass-roots' standard emerged for the URL scheme of map tiles for slippy maps (OSM 2019b). This URL scheme enabled any web mapping framework to consume and display the tiles from any of the increasing number of servers that can produce them (GeoServer, MapServer and TileStache are a few examples)—a de facto standardization process that was successfully completed without the involvement of any of the abovementioned standardization bodies.

A third aspect that explains today's GII landscape is the development and widespread adoption of open data (Open Data Barometer 2015; Gurstein 2011; Kitchin 2014). This includes thematic open data sets available for direct download via web portals (ESRI 2019c) and the free provisioning of governmental data, which was previously made available for a (sometimes substantial) fee—if at all. The proliferation of open government data (OGD) has been complemented by the development of user-generated data sources, dubbed volunteered geographic information (VGI, Goodchild 2007) in the context of GI. OGD aims to make data originally produced for professional users available to a broader public, and VGI can be seen as a grass-roots movement producing its own collection of non-authoritative datasets. The VGI project with the most profound impact is OSM. OSM started as a free, bottom-up alternative to the then-prohibitively expensive data produced by the UK's Ordnance Survey, and has since become the largest collection of freely available GI. At the time of writing of this chapter, the OSM database consisted of close to 5 billion mapped nodes (points), collected by almost 5 million registered users (OSM 2019c). Its significance for development in the field today lies in the provisioning of a free, global, and in many areas extremely detailed collection of GI and in the number of innovative companies that have entered the market with products based on OSM. They continuously contribute to the OSM dataset and have developed open source tools around it for mapping, quality checking, and the use and processing of OSM data.

A notable recent development that emerged from this OSM ecosystem is the trend towards using vector tiles instead of prerendered image tiles. The improved support for rendering vector data in modern web browsers has enabled this switch. Vector tiles have several advantages over image tiles, such as adaptable styling, maps that look sharp independent of screen resolution, and opportunities for interaction with the actual individual map features (interactive labels or clickable features, for example), with smaller data volumes to transfer between the server and client.

As these examples show, the collection, distribution, and analysis of GI has evolved from a field that used to require expensive equipment and extensive professional training to activities that are carried out by users (and contributors) with highly diverse backgrounds and different levels of education. The ubiquity of devices capable of both producing and consuming GI, in combination with an ever-growing amount of free-to-use GI and powerful free and open source software solutions has led to a somewhat chaotic landscape of practices, standards and conventions for the data and processes involved. The involvement of a broader public in these processes also means that organizations such as OGC or ISO that primarily focus on the professional use of GI are addressing a decreasing share of the actual GI user base. An increasing number of users and producers of GI do not work for government agencies, conduct commercial mapping efforts, or develop software for GI web services. Instead, they may be working in data science or data visualization (Bostock et al. 2011), may be open data advocates or citizen scientists, or may do research in areas such as economics, ecology, or the humanities.

New companies that deal with GI at the core of their business that do not consider themselves GIS companies have established new ways of dealing with GI, without taking the time to go through time-consuming standardization processes. The long list of prominent examples of these companies includes Mapbox, Carto, Uber, booking.com, Trip Advisor, Google and Facebook. Many of the relatively new internet platforms contain GI and thereby initiated a shift to the traditional organizational structures (van Dijck et al. 2018).

Arguably, with this industrial production and use of GI, large companies set the de facto standards—as far as standards are relevant for their internal workings. To some extent, these developments have been acknowledged by the World Wide Web Consortium (W3C) in some efforts that have traditionally been exclusive to the OGC, most notably the Spatial Data on the Web Working (W3C 2015) and Interest Groups (W3C 2017) and the best practices documents produced in this context (W3C 2019). The formation of these groups leverages the opportunity to involve a much broader group of users in the discussion around how GI should be shared on the web, and their discussions and outputs clearly show that the integration of GI from different sources is a semantic issue at its core (Kuhn 2005). This semantic interoperability and its role for the future of GII in the context of Digital Earth is discussed in detail in Sect. 5.4.2. The following section describes how GII is a prime example of the openness that has become the new normal in many fields of science, technology, and business.

5.3.2 Geospatial Information Infrastructures Champion Openness

As presented earlier, today's GII landscape is shaped by the influence, development and widespread adoption of open data (see also above). The notion of 'openness' has long been part of GIIs, especially due to the long-term leading role of the public sector (Schade et al. 2015). A foundational role of GIIs has been, and still is, to enable the discovery and sharing of spatially referenced data. As described in Sect. 5.2, SDIs were essentially designed and developed to support the generation, management and processing of GI, as key vehicles to make data openly accessible to a broader community. However, as a social construction, the understanding and interpretation of openness is far from static; it is dynamic and changes as the tandem technology-society evolves. Thus, the interpretation of 'open' (data, tools, etc.) reflects the changes in society and necessarily adapts to the new uses and needs of people. In addition, the value of open data is under scrutiny (Craglia and Shanley 2015) and an increasing number of commercial companies produce and host GI.

To better understand how the current discussion about openness affects GIIs and to better speculate future scenarios, we provide two brief stories, paraphrasing the way Arribas-Bel and Reades (2018) examine the evolution between geography and computers. First, we take a brief historical perspective to determine what openness meant in the origins of (governmental) GIIs. Next, we look at the new 'open' trends and growing forces that are currently emerging, mostly outside of GIIs, which we argue are important for GIIs (and Digital Earth) to pay close attention to. Both stories allow for us to reflect and speculate on the need for a convergent point in the future, where GIIs can embrace and continuously adapt to evolving notions of openness and to the resulting societal changes and economic implications.

The first story goes back to the reasons that motivated the need to establish GIIs. Since the outset, GIIs in the form of hierarchical visions on SDI (Rajabifard et al. 2003) or networked visions (Tulloch and Harvey 2008; Vandenbroucke et al. 2009) contained relatively restricted themes and types of resources owned by the public sector. The underlying motto was "collected once, shared multiple times", so each GII node was managed homogeneously its own spatially referenced data. Data sharing was feasible through these infrastructure nodes because data discovery, access, and delivery were affordable through well-known standardization practices (see Sects. 5.2.2 and 5.3.1). Standardized data models and service interfaces characterized the data sharing capabilities of these government-led GIIs, although only a small group of specialized, tech-savvy users benefitted from them. At that time, the concept of openness was tightly coupled to the idea of sharing. The democratization of data sharing through GIIs was a great leap to facilitate transnational and multidisciplinary projects because the problems of discovery, access and redundancy of GI were significantly alleviated by standardized and unified mechanisms. Most recently, this led to the offerings of location enabled e-Services using web-based application programming interfaces (APIs) built upon SDIs. One example of this is the development of an application for citizens called Spotbooking to apply for, process and maintain uses of public spaces within a town or city (Spotbooking 2019).

In addition to past studies to find synergies bridging geospatial research data with public sector information and open data initiatives, other relevant open trends/movements enable knowledge/data collection, creation and dissemination and mostly operate outside GIIs (Schade et al. 2015). We do not list the multitude of open trends and their technological infrastructure here but highlight a few examples to underline the evolving meaning of openness from data sharing to dynamic processes for knowledge production and dissemination. One example is the European Open Science Cloud (EOSC 2019), a cloud for research data in Europe that supports the ongoing transitions in how research is performed and how knowledge is shared. As a second example, the IoT infrastructure generates a vast amount of spatiotemporal data streams at a finer granularity, which undoubtedly represent valuable sources of data (i.e., 'things' observe the environment by collecting data) and analytical computation (i.e., 'things' act by processing gathered data) for Digital Earth and GIIs. Granell et al. feature the promising bridges and synergies between the IoT and Digital Earth application scenarios in Chap. 11, but a true convergence of the two infrastructures is still in its infancy. As a third example, the relationship between Digital Earth and citizen science is outlined in detail in this book by Brovelli and others (Chap. 18).

Fast-forwarding to the present, openness has become a more prominent concept than ever. It has been transformed and extended to all aspects of people's daily lives (Price 2013). Contrary to the common perception of openness in the first example, which was practically restricted to 'sharing' data, today's vision of openness takes multiple and varied forms (Sui 2014). Openness permeates many facets of today's culture, society, government, science and education, leading to a series of (old and new) 'open terms' such as open culture, open cities (Domingo et al. 2013; Degbelo et al. 2016), open movement (Lee et al. 2015), open government (Lathrop and Ruma 2010; Goldsmith and Kleiman 2017), open software (Aksulu and Wade 2010), open hardware (Powell 2012), open science, open research, open laboratories (Nosek et al. 2015), open innovation (Schade and Granell 2014; Mathieu and Aubrecht 2018), and open education (Bonk et al. 2015). In contrast, as analyzed below, daily (geospatial) information still flows to platforms that are not defined as open and are owned by the above-mentioned companies. Offering services free of charge but in exchange for personal (user-generated) data has become a popular business model.

We argue that peoples' perception of openness is dramatically influenced by the irruption, rapid adoption, and new uses and appropriations of technology. Digital transformations brought changes in the proliferation of new data sources, the consolidation of novel ways of producing and consuming data, and in the demography of users. The cost of creating GI anywhere, at any time, from anyone, about anything (aka 4-A technology) drastically decreased. However, the cost for current GIIs to consume, integrate and make sense of 4A-generated data is still considerable—especially when considering the direct and indirect costs for the provision and application of 4-A-generated data for a rich portfolio of use cases and stakeholders (Johnson et al. 2017). The scale, frequency, and granularity of the data being generated and gathered today were simply unimaginable when the foundations of GIIs were designed many years ago. The motto "collected once, shared multiple times" is no longer a fundamental truth that drives GIIs because anyone can collect data on the same phenomenon, in the same place, from multiple perspectives, which was previously technically infeasible. In fact, we unconsciously create such GIs all the time. As a result, more and more data sources are available for a single phenomenon, requiring additional analytical approaches and interoperability arrangements to integrate these data sources and offer a comprehensive picture about the phenomenon in question (Huang et al. 2018). Thus, data in traditional (governmental) GIIs provide one perspective of a phenomenon (mobility, pollution, demography, etc.). Other perspectives of that phenomenon are provided by data that are collected via other infrastructures. This does not fully address the concept of openness. Openness means sharing data about a phenomenon for small groups of experts, enabling and promoting comprehensible views of phenomena taken from disparate sources, and making them accessible and understandable to various user groups. What characteristics do modern GIIs need to fully exploit 4A-generated data? What does this imply in terms of interoperability? And how does this impact current approaches to openness?

While common sense tells us that the way to solve the growing complexity of today's social challenges and underlying research problems is through multidisciplinary collaboration at all levels including technical infrastructures, access to data, and participation in the creation and dissemination of knowledge, the reality is that the diversity of 'open' trends is understandable considering the diversity of actors that have different objectives and needs and are affected differently by a constantly changing technological landscape. It appears that each actor (citizens, NGOs, scientists, private companies, government, etc.) has a different understanding of the meaning and application of the notion of openness. All of them are entirely legitimate given the contexts in which each of the different stakeholders operate.

Regardless of any controversy about the future meaning of openness, it is clear that 'open' cannot be considered a static feature of data or of GII, but should be considered under the lens of recent trends and critiques as a dynamic process for the production, creation and dissemination of knowledge, which is subject to improvements and optimizations over time. The reconceptualization of openness as a dynamic process is vital to enable convergent points and bridges among emerging movements and GIIs—which still operate rather disconnectedly—to make sense of the vast amounts of collected data to solve the pressing issues facing the Earth today. We can rephrase the previous questions: What characteristics would define such dynamic processes in GIIs to exploit 4A-generated data?

Leading GIS scientists recently reflected on the current limitations of the field and called for an entirely new brand of geospatial algorithms and techniques to analyze and process these new forms of data (Jiang 2015; Miller and Goodchild 2015; Li et al. 2016). Lü et al. (2019) magnificently summarize this perception in one sentence: "a successful past [of GII] does not guarantee a bright future" (pp 347). The historical view of GII reported in this chapter is indisputably a story of success. Nevertheless, new driving forces and trends such as open movements and open information infrastructures—along with the datafication and platformization of society—have had and will have significant impacts on the future success of GIIs, so GIIs should carefully consider them to explore alliances and actively integrate and process new forms of information sources.

5.3.3 Capacity Building and Learning for Geospatial Information Infrastructures

Although appropriate technologies and policies to enable data access and data sharing are crucial in the development of GIIs, it also requires education and capacity building to ensure the necessary knowledge, skills and competencies are available

(Craglia et al. 2008). Complementing more general frameworks on the development of digital skills (van Deursen and van Dijk 2014), the need for collaboration between government, businesses and academics in the development of an appropriate knowledge infrastructure has been reflected in national and regional GII strategies and actions (Vancauwenberghe and Vandenbroucke 2016). In the past 20 years, various education and training initiatives on GII and related topics have been developed and implemented by higher education institutions, public administrations and businesses. Throughout the years, the focus has broadly shifted from raising awareness of the potential of GI, to capacity building for the implementation of different GII components to skills and knowledge related to the use and integration of GII data and services in decision making, service delivery and product development processes. GII education and training also must be dynamic and change in response to new technological and policy-related developments. The key challenge in successful GII education and training is to ensure that it addresses the needs of GII professional developers and users. Demand-driven GII education and training requires insight in and agreement on what professionals in the domain of GII should know and be able to do (Vandenbroucke and Vancauwenberghe 2016). Studies investigating the demand for GII capacity building have been undertaken at organizational, national and cross-national levels. A European-wide study on the workforce demand in the domain of GISandT showed that, despite differences in the tasks they perform, employees and representatives from the different sectors including public administration, private sector and academia have strongly similar views on the skills and knowledge areas they consider the most relevant (Wallentin et al. 2014). The European GI community identified a shift in focus from map making and local database handling towards online and mobile technologies based on SDIs with a massive amount of—open—data to be integrated. This is a clear indication that the importance of capacity building for GII will increase in the near future.

A valuable approach in the identification of the specific knowledge and skills that professionals need to master for career success in their field is the development of a comprehensive inventory of the knowledge domain. To provide such an inventory for the GISandT domain, in 2006 the University Consortium of Geographic Information Science (UCGIS) developed the Geographic Information Science and Technology Body of Knowledge (GISandT BoK) (DiBiase et al. 2006). The main intended use of the GISandT BoK was to support the development and assessment of GISandT curricula, but the document also serves other purposes such as for professional accreditation or screening of employees. The 2006 version of the Body of Knowledge included more than 330 topics organized into seventy-three units and ten knowledge areas. Notably, the concept of ‘spatial data infrastructure’ was included twice, in two different knowledge areas: once in the knowledge area of geospatial data (as a topic under the ‘Metadata, standards and infrastructures’ unit) and once in the organizational and institutional aspects knowledge area (as a topic under the Institutional and interinstitutional aspects unit). This reflects the need for training and education on the technological and organizational (or institutional) aspects of SDI. In addition to the concept of spatial data infrastructure, the Body of Knowledge contains other concepts that are linked or relevant to the development of SDIs and

GIIs, spread across different knowledge areas and units. This demonstrates the relevance and importance of GIIs as a field and the need for an ontology-based approach to the field, where different types of relationships between concepts can be identified (Vandenbroucke and Vancauwenberghe 2016).

To reflect and address recent trends, developments and challenges in the GISandT domain, continuous revision and updating of the Body of Knowledge are required. Initiatives to revise and update the Body of Knowledge have been undertaken and are ongoing in Europe and the United States (Vandenbroucke and Vancauwenberghe 2016). In addition to the topics covered and defined learning objectives, another key aspect in the design and implementation of GII training and education is the teaching and learning activities applied to help students achieve these objectives. GII education has evolved from traditional 'teacher-centric' teaching styles to more 'learner-centric' methods and approaches. With the availability of online—open—education resources by organizations and institutions such as the EuroSDR (EduServ program), the University of Salzburg (UNIGIS program), the Geographical Information System International Group (GISIG) and recently the European Commission (Geospatial Knowledge Base (GKB) Training Platform), the GI/GII community has a strong tradition of e-learning activities. Collaboration between higher education institutions and other stakeholders to design and deliver GI and GII education has taken place for many years. In many cases, this collaboration is often organized in a rather traditional manner, through internships at public or private organizations, the provision of data and tools for educational purposes, and the organization of study visits and excursions to private or public organizations in the GISandT domain (Vancauwenberghe and Vandenbroucke 2016). Recently, several universities started experimenting with more case-based approaches in which students and teachers closely collaborate with practitioners on real-life case studies. The concept of academic SDIs for research and for education can be viewed in the context of adopting more innovative teaching and learning methods (Coetzee et al. 2017). Students could actively contribute to the development and implementation of various SDI components and use the infrastructure to share the results of their efforts with other students, teachers and researchers. In addition, GIIs play a role in the cocreation of knowledge and thereby in lifelong learning (Foresman et al. 2014), and through their fundamental contribution to the Digital Earth vision, GIIs can enable living labs, i.e., user-driven approaches to innovation (Schade and Granell 2014).

5.4 Recent Challenges and Potential for Improvement

Given the situation today—as indicated in the introduction to this chapter—we face a series of challenges. These challenges primarily emerge from the pace of technological change, including more frequent technological disruptions than in the past, and the (to some extent heavy-headed) standardization applied to GIIs. We note the challenges caused by what we call the 'big data' phenomenon (Tsinaraki and Schade 2016) and by the mainstreaming of GI, which introduced new users with new needs as well as new providers of GII. Given these current changes and challenges, we emphasize two implications for GIIs and their future evolution.

5.4.1 Strengthened Role of Semantics

The insight that semantic heterogeneity is a key factor that interferes with the effective use and analysis of GI from different sources is by no means new, nor are the solutions based on semantic web technologies to address the corresponding challenges (Kuhn 2005; Lutz and Klien 2007; Lutz et al. 2009). However, although academic research noted these issues quite early on in the establishment of SDIs, in practice, most efforts have been focused on achieving the underlying technical and syntactic interoperability. This focus is understandable, as semantic interoperability only becomes an issue when the technical and syntactical issues are largely solved. This stage in the development of GII appears to have been reached, since the role of geospatial semantics has been strengthened considerably and is now an issue that practitioners deal with in implementation of open data platforms and geospatial web services.

Arguably, this development was not solely driven by questions about the semantics of geospatial data at hand. Rather, the need for approaches that let us add information about the semantics of entities (geospatial features, in our case), particularly their types and properties, has been recognized in many other fields. These include generic examples such as the publication of structured data on the web (Schema.org is the most prominent example) or specialized application domains (such as biology or history), and closely related research fields such as the sensor web and the Internet of Things. The common need for structured data with clearly defined semantics across those domains has led to efforts in a number of different directions, including research on the theoretical underpinnings of semantic reasoning (Noy 2004; Wang et al. 2004), development of specifications [RDF(S) (Staab et al. 2002), OWL (McGuinness and Van Harmelen 2004), OWL2 (Hitzler et al. 2009; Motik et al. 2009), query languages [SPARQL (Harris et al. 2013), GeoSPARQL (Battle and Kolas 2012)], implementation of the triple stores (Rohloff et al. 2007) and query engines (Broekstra et al. 2002; Carroll et al. 2004). In combination, these efforts have led to a more widespread adoption of approaches that focus on the semantics of geospatial data (Stock et al. 2011), and semantics is now front and center in best practice recommendations for publishing spatial data (W3C 2019).

The W3C's Spatial Data on the Web Best Practices discusses how to best semantically annotate geospatial data—, i.e., using shared vocabularies—and recommends full-fledged adoption of Linked Data principles. A more widespread adoption of these best practices will imply a paradigm shift (Kuhn et al. 2014) towards a radically distributed approach to the publication of GI. Linked Data are currently treated as a byproduct in the publication of GI, e.g., when government agencies such as the UK's Ordinance Survey are starting to offer their GI as Linked Data or when universities convert OSM data to Linked Data. These are valuable efforts—a little semantics goes a long way (Hendler 2009)—but the data that is being published is still the output of an extract-transform-load (ETL) process on top of an original data source such as a relational spatial database. Furthermore, the provision of GI as Linked Data only adds another data offering with the potential use for data integration. Actual success cases remain rare.

The opportunities and challenges of making Linked Data the original data format based on which all changes are made and from which other formats can be derived can currently be observed in the Wikidata effort (Vrandečić and Krötzsch 2014). After the immense success of DBpedia (Auer et al. 2007)—a Linked Data product generated via ETL from the structured information in Wikipedia—the potential of turning this process around by making the produced structured data the actual data underlying all language editions of Wikipedia has been recognized. This approach now allows for an editor to update information in Wikidata—such as the population number for a country after a new census, or the publication of the latest book by a given author—and that information can automatically be reused across all Wikipedia.

GI still has a way to go in making a semantics-based approach its primary format for data management and publication, and thus become part of an ever-growing distributed knowledge graph. Conceived as part of the infrastructure driving Digital Earth, this goal appears attractive, particularly because of its potential to further normalize the use GI across a wider range of disciplines. However, a number of challenges must be addressed before this vision can be put into practice, including the development and implementation of standardized handling of GI in triple stores, interfaces to access geospatial Linked Data directly from GI 'front ends' such as traditional GIS, web-based and mobile mapping applications, as well as capacity building, particularly in the form of educating students in the underlying technology stack so that they can help with these developments after graduation. These challenges highlight the fact that geospatial semantics will remain an essential and dedicated research area for the foreseeable future, helping users make sensible use of GI and turn it into actionable knowledge. Finally, in the context of Linked Data, (geo)spatial information is definitely special because spatial (and particularly spatiotemporal) data can be used as an integrator to help build connections between originally disparate data sources.

5.4.2 Is Spatial Still Special?

There are several slogans related to GI, including "spatial is special". Although one might argue that GI is only more complex than many kinds of (nonspatial) information, at least in the past, geospatial informatics filled a niche role with comparably few specialists working on the topic. As far as mainstream computing was concerned, the spatial-temporal components of GI were restricted to a pair of coordinates (a point) and a date-time stamp. Today, the spatiotemporal characteristics of GI have made it popular for data integration tasks, where location is an obvious commonality between many separately collected data sources (Tsinaraki and Schade 2016). In combination with the recent trend towards platformization of society and wider use of remotely sensed images, online maps, sensors (see also Chap. 11), as well as people's location and tracks, one might argue that the time when (geo)spatial has been special has come to an end. However, although the collection of GI has become much easier (and hence gone mainstream), pitfalls in analysis (spatial autocorrelation, projections, etc.) remain. Related special challenges surface, especially when standard approaches for handling big data are directly applied to GI. Many of the common "divide and conquer" approaches applied to big data analysis tasks fail because of the spatial relationships between chunks of data. As argued in Sect. 5.4.1, semantics is highly important. Using colocation as the only element for data integration can easily lead to the senseless combined processing of data from completely different and potentially conflicting contexts.

The mainstreaming of location information has direct implications for the evolution of GII, as with the future conceptualization of GIS and SDIs. In the past, these notions were a research and application field in their own right, and they now appear to be much more integrated into the wider fields of computer science and data science (Cadell 2018). With a narrow view, this could be seen as a thread to the communities and associations that formed around these concepts (the introduction to this chapter provided some examples of these). Conversely, the mainstreaming of GI provides immense opportunities such as the increasing market for companies specializing in GI and many new job opportunities for GI experts.

From a government perspective, GIIs became more relevant—and geospatial data less special—through the use of data in this infrastructure for the provision of spatially enabled e-government services to citizens, businesses and other societal actors (Vancauwenberghe and van Loenen 2018). Geospatial data that became increasingly available were used to improve existing e-services and provide novel services. Such spatially enabled e-services now exist in many policy areas (i.e., environment, agriculture, transport) and at different levels of government (i.e., local, regional, national). They evolved from more simple information and contact services to more advanced transaction services. These spatially enabled transaction services refer to the use of geospatial data in the electronic intake and handling of requests and applications of rights, benefits and obligations. Because these transaction services demand multiple two-way interactions between governments and citizens/businesses, they are more complex than information or contact services, which are mostly one-way services. This increased complexity applies to both technological and organizational aspects, since the delivery of these e-services requires a strong alignment and possible integration of GIIs with e-government developments. Initiatives to enable this integration have been taken at organizational, national and regional levels—especially in Europe (Vancauwenberghe and van Loenen 2018).

In the private sector, we have observed manifold developments. First, the traditional partnerships with the public sector evolved into collaborations in which governmental bodies such as mapping agencies still own and provide authoritative content (such as cadaster information, protected sites, and utilities), and the industry offers solutions for data hosting, access, and cost recovery. The data and information access services (DIAS) for the European Space program Copernicus is a particularly impressive example (Copernicus 2019). In each of these five different implementations, the public-sector GII is coupled with data from commercial satellites to provide additional value. Second, there are an increasing number of companies building upon GIIs. Especially for technologies such as web-based APIs, as in the example of Spotbooking, GI has become more accessible and value-added services and applications have been created. Due to the abovementioned platformization, large internet firms create many GIs and host them in their infrastructures, and they are only occasionally linked to existing public-sector GIIs. GI has clearly moved into the mainstream information infrastructures. Lastly, many GI projects today rely on data provided by companies such as Google, DigitalGlobe, Waze, Here, and Esri. Examples include geospatial data about commercial demographics and personal mobility.

In the context of Digital Earth, these developments are all good news. In every conceptualization of the Digital Earth vision—and in any future evolution thereof—GI and GIIs will remain fundamental building blocks. As increasing related expertise becomes available and the mainstreaming trend of GI continues, GI can provide the capacity that is required for improving Digital Earth applications and enlarging implementations of the Digital Earth vision across the globe. The transition from mainstreamed GI to GIIs that are readily available to developers and implementers of the Digital Earth vision is the logical next step and an area for further research and organizational improvements. The interplay between and the changes in power relationships between society, research, industry and the public sector deserve dedicated attention.

5.5 Conclusion and Outlook

This chapter situated GIIs in the wider context of the Digital Earth vision and introduced GIIs as a major enabling element for Digital Earth implementation. The past and present of GIIs was outlined along with a subjective view of today's major challenges concerning the status of GII development and use, and possible future directions. Notably, this view might be biased towards academia and governments, but we have highlighted emerging developments from the private sector as a disruptive driving force that quickly emerged over the past decade.

This chapter demonstrates that GIIs have come a long way and evolved as a strong underpinning contribution for implementation of the Digital Earth vision. Whereas we witnessed a dispersion of efforts in the early days, we illustrated how GIIs evolved and coordinated efforts emerged in different national and international contexts. The increasing pace of technological changes poses new challenges to the continuation and further convergence of these efforts because new actors with different backgrounds and expectations enter the discussion. We see a particular need to continue and strengthen the role of semantics in GII development and implementation to ensure that the provided information can be used appropriately. We also recognize the changing power relationship from the public to the private sector, with a disrupting effect on traditional data owners (especially mapping agencies). These changes will significantly affect the role of the public sector in geospatial data management and provision.

Lastly, we underlined the needs for further evolution of GIIs so that they become flexible and robust enough to absorb and embrace technological transformations and the accompanying societal and organizational implications. These required capacities for addressing technological and organizational issues, and training of present and future generations of GII developers and GII users. As a prominent example, we highlighted the relationships to movements to open up data and the access to knowledge. GIIs—which were in the forefront of open data sharing in the past—must react to changing conditions, provide bridges to other existing infrastructures to absorb new data sources, and contribute to the development of new standards for collaboration. The next generation of GIIs should provide management and processing capacities for classical GI, and must be able to input and handle novel information sources. In this way, they will continue to fuel innovation for the future of Digital Earth. Chapters 6, 9 and 10 provide additional insight into analytical aspects and issues related to big data. For details about the economic value of Digital Earth, we refer the reader to Chap. 19.

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Sven Schade is a scientific officer at the European Commission's scientific and knowledge management service, the Joint Research Centre (JRC), with a background in geospatial information science and knowledge engineering. His interests cover knowledge extraction from heterogeneous data sources, multi-disciplinary interoperability, and public participation in science for policy.

Carlos Granell currently holds a 5 year Ramón y Cajal post-doctoral fellowship at the Universitat Jaume I of Castellón, Spain. His interests lie in multi-disciplinary application of GIS (Science/Systems), spatial analysis & visualization of streams of sensor- and/or user-generated geographic content, reproducibility research practices, and finding synergies between citizen science projects, education and dissemination of science.

Glenn Vancauwenberghe is a senior researcher at the Spatial Applications Division Leuven (SADL) of KU Leuven, with a background in sociology and public administration. His main fields of research are the governance and performance of spatial data infrastructures and the role of geospatial data in open and digital government.

Carsten Keßler is an Associate Professor for Geoinformatics in the Department of Planning at Aalborg University Copenhagen, Denmark, and an adjunct faculty member at The Graduate Center, City University of New York, USA. He is interested in data interoperability, volunteered geographic information, and geo-simulation techniques for large-scale assessments of the impacts of global warming.

Danny Vandenbroucke is research manager at KU Leuven, Belgium. His research interest relates to organizational and technical interoperability aspects and the impact geospatial standards might have on the performance of business processes. He works on several Erasmus+ projects that address the educational challenges in the geospatial domain (defining an ontology-based Body of Knowledge for GI/EO, case-based learning …).

Ian Masser has held professorial positions at the Universities of Utrecht, Sheffield and Twente as well as visiting positions in University College London, Melbourne and Leuven. His publications include twenty books and more than 300 papers. In 2016 he received the Global Citizen Award from the GSDI Association for his exemplary service to the geospatial community.

Michael Gould is a professor of GIS at Universitat Jaume I of Castellón, Spain, and ESRI's Global Education Manager working mostly in Europe, Middle East and Africa. His research interests include distributed GIS, Smart Cities, and hybrid FOSS/proprietary interoperability.

Chapter 6
Geospatial Information Processing Technologies

Zhenlong Li, Zhipeng Gui, Barbara Hofer, Yan Li, Simon Scheider and Shashi Shekhar

Abstract The increasing availability of geospatial data offers great opportunities for advancing scientific discovery and practices in society. Effective and efficient processing of geospatial data is essential for a wide range of Digital Earth applications such as climate change, natural hazard prediction and mitigation, and public health. However, the massive volume, heterogeneous, and distributed nature of global geospatial data pose challenges in geospatial information processing and computing. This chapter introduces three technologies for geospatial data processing: high-performance computing, online geoprocessing, and distributed geoprocessing, with each technology addressing one aspect of the challenges. The fundamental concepts, principles, and key techniques of the three technologies are elaborated in detail, followed by examples of applications and research directions in the context of Digital Earth. Lastly, a Digital Earth reference framework called discrete global grid system (DGGS) is discussed.

Keywords Geospatial big data · High-performance computing · Online geoprocessing · Distributed geoprocessing · Discrete global grid system

Z. Li (✉)
Geoinformation and Big Data Research Laboratory, Department of Geography, University of South Carolina, Columbia, SC, USA
e-mail: zhenlong@sc.edu

Z. Gui
School of Remote Sensing and Information Engineering, Wuhan University, Wuhan, China

B. Hofer
Interfaculty Department of Geoinformatics – Z_GIS, University of Salzburg, Salzburg, Austria

Y. Li · S. Shekhar
Department of Computer Science & Engineering, University of Minnesota-Twin Cities, Minneapolis, MN, USA

S. Scheider
Department of Human Geography and Spatial Planning, Universiteit Utrecht, Utrecht, The Netherlands

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6.1 Introduction

With the advancement of sensor and computing technologies, massive volumes of geospatial data are being produced at an increasingly faster speed from a variety of geo-sensors (e.g., in situ and remote sensors) and model simulations (e.g., climate models) with increasing spatial, temporal, and spectral resolutions. For example, satellite sensors are collecting petabytes data daily. Climate model simulations by Intergovernmental Panel on Climate Change scientists produce hundreds of petabytes of climate data (Schnase et al. 2017). In addition to these traditional data sources, geospatial data collected from ubiquitous location-based sensors and billions of human sensors (Goodchild 2007) are becoming more dynamic, heterogeneous, unstructured, and noisy.

These massive volumes of geospatial data offer great opportunities for advancing scientific discovery and practices in society, which could benefit a wide range of applications of Digital Earth such as climate change, natural hazard prediction and mitigation, and public health. In this sense, efficiently and effectively retrieving information and deriving knowledge from the massive geospatial datasets have become critical functions of Digital Earth. The questions that can be (or should be) addressed with Digital Earth include, for example, how to investigate and identify unknown and complex patterns from the large trajectory data of a city to better understand human mobility patterns (e.g., Hu et al. 2019a, b), how to rapidly collect and process heterogeneous and distributed hazard datasets during a hurricane to support decision making (e.g., Martin et al. 2017; Huang et al. 2018), how to synthesize huge datasets to quickly identify the spatial relationships between two climate variables (e.g., Li et al. 2019), and how to find spatial and temporal patterns of human activities during disasters in massive datasets that are notoriously "dirty" and biased population samples (e.g., Twitter data) in a scalable environment (e.g., Li et al. 2018).

Geospatial information computing refers to the computational tasks of making sense of geospatial data. Such tasks mainly include but are not limited to geospatial data storage, management, processing, analysis, and mining. Addressing the above questions poses great challenges for geospatial information computing. First, the volume of the geospatial data at the global scale (e.g., at the petabyte-scale) exceeds the capacity of traditional computing technologies and analytical tools designed for the desktop era. The velocity of data acquisition (e.g., terabytes of satellite images a day and tens of thousands of geotagged tweets a minute) pushes the limits of traditional data storage and computing techniques. Second, geospatial data are inherently heterogeneous. They are collected from different sources (e.g., Earth observations, social media), abstracted with different data models (e.g., raster, vector, array-based), encoded with different data formats (e.g., geodatabase, NetCDF), and have different space and time resolutions. This heterogeneity requires interoperability and standards among the data processing tools or spatial analysis functions. For example, producing timely decision support often requires combining multiple data sources with multiple tools. Moreover, with the involvement of multiple tools and datasets in the problem-solving process, data provenance, analysis transparency, and result reproducibility become increasingly important. Third, global geospatial data are often physically distributed. They are collected by distributed sensors and stored at data servers all over the world. Moving data from one location such as local server to another such as cloud for processing becomes problematic due to the high volume, high velocity, and necessity of real-time decision making.

A variety of processing and computing technologies have been developed or adapted to tackle these challenges. Figure 6.1 depicts a geospatial information computing framework of Digital Earth, highlighting three types of popular technologies in geospatial information computing: high-performance computing (HPC, Sect. 6.2), online geospatial information processing (or online geoprocessing, Sect. 6.3), and distributed geospatial information processing (or distributed geoprocessing, Sect. 6.4). HPC aims to tackle the large-volume challenge by solving data- and computing-intensive problems in parallel using multiple or many processing units (e.g., GPU, CPU, computers). Online geoprocessing comprises techniques that allow

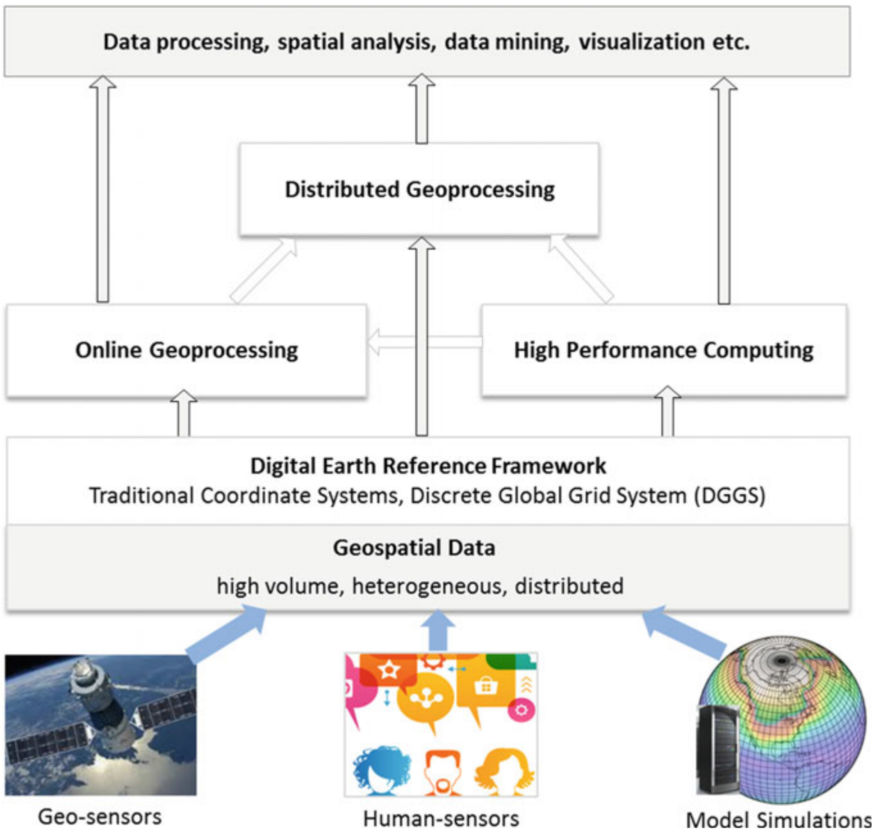

Fig. 6.1 Geospatial information computing framework of Digital Earth composed of high-performance computing, online geoprocessing, and distributed geoprocessing

for performing data processing and spatial analysis tasks on the web using geospatial web services (e.g., OGC web services) or web APIs (e.g., RESTful). Through standardization, these services and APIs are essential for addressing the heterogeneity challenges of geospatial data. Distributed geoprocessing refers to processing geospatial data and information in a distributed computing environment. By chaining a set of distributed data processing services into an executable workflow, the datasets and analysis steps involved in a task are documented, which improves the reproducibility of the analysis.

The following three sections start with a brief introduction and definition of a technology followed by its key principles, techniques, and examples of applications that support Digital Earth. Research challenges and future directions are discussed at the end of each section. A summary of the three technologies and a discussion of the discrete global grid system (DGGS) are provided in the last section. This chapter is not intended to be comprehensive or cover all aspects and technologies of geospatial information computing. The three selected technologies are described to provide the readers with a sense of geoinformation processing and how it is applied to support Digital Earth.

6.2 High-Performance Computing

6.2.1 The Concept of High-Performance Computing: What and Why

HPC aims to solve complex computational problems using supercomputers and parallel processing techniques. Since commodity clusters revolutionized HPC twenty years ago, a price-performance standard has become dominant, which includes inexpensive, high-performance x86 processors, functional accelerators (e.g., Intel Xeon Phi or NVidia Tesla), and open source Linux software and associated toolkits. It has been widely used in various applications such as weather forecasting, nuclear test simulation, and molecular dynamics simulation.

The growing availability of spatial datasets, in the form of GPS vehicle trajectories, social media check-ins, earth observation imagery, and sensor readings pose serious challenges for researchers and tool users in geo-related fields. The currently available computational technology constrains researchers and users in geo-related fields in two ways. First, the size of problems that can be addressed using the currently available methods is limited. Additionally, new problems, patterns, research, and decisions that may be discovered from geospatial big data cannot be found using existing tools. The 3 “V” s of big geospatial data (volume, variety, and velocity) impose new requirements for computational technology for geospatial information processing, for example, large, cheap, and reliable storage for large amounts of data, as well as scalable algorithms to process data in real time. Due to its computational capability, HPC is well suited for geospatial information processing of geospatial big data. A highly integrated and reliable software infrastructure ecosystem based on HPC will facilitate geo-related applications in two ways. First, it will scale up the data volume and data granularity of data management, mining, and analysis, which has not been possible in the desktop era using the currently available methods. Furthermore, it will inspire and enable new discoveries with novel big-data-oriented methods that are not implementable in the current desktop software.

In the following, we describe HPC platforms frequently used in geospatial information processing, and look at how HPC is applied in spatial database management systems and spatial data mining.

6.2.2 High-Performance Computing Platforms

Since HPC was introduced in the 1960s, parallelism has been introduced into the systems. In parallelization, a computational task is divided into several, often very similar, subtasks that can be processed in parallel and the results are combined upon completion. The direct computational time savings of HPC systems results from the execution of multiple processing elements at the same time to solve a problem. The process of dividing a computational task is called decomposition. Task interaction necessitates communication between processing elements, and thus increasing granularity does not always result in faster computation. There are three major sources of overhead in parallel systems: interprocess interaction, idling, and excess computation. Interprocess interaction is the time spent communicating data between processing elements, which is usually the most significant source. Idling occurs when processing elements stop execution due to load imbalance, synchronization, or the presence of serial components in a program. Excess computation represents the extra time cost of adopting a parallel algorithm based on a poorer but easily parallelizable algorithm rather than the fastest known sequential algorithm that is difficult or impossible to parallelize.

To facilitate the parallelism of HPC systems, the architecture of HPC systems dictates the use of special programming techniques. Commonly used HPC platforms for large-scale processing of spatial data include the Message Passing Interface (MPI), Open Multi-Processing (OpenMP), Unified Parallel C (UPC), general-purpose computing on graphics processing units (GPGPU), Apache Hadoop, and Apache Spark. These platforms can be roughly classified according to the level at which the hardware supports parallelism.

OpenMP, MPI, and UPC support parallelism on central processing units (CPUs). OpenMP is an API that supports multi-platform shared memory parallel programming in C/C++ and Fortran; MPI is the most commonly used standardized and portable message-passing standard, which is designed to function on a wide variety of parallel computing architectures. There are several well-tested and efficient implementations of MPI for users programming in C/C++ and Fortran. They can work cooperatively in a computer cluster such that OpenMP is used for parallel data processing within individual computers while MPI is used for message passing between computers. UPC extends the C programming language to present a single shared, partitioned address space to the programmer, where each variable may be directly read and written by any processor but is physically possessed by a single processor.

The GPGPU platform performs computations that are traditionally conducted by CPUs using graphic processing units (GPUs). Architecturally, a CPU is composed of a few cores that can handle complex tasks whereas a GPU is composed of hundreds of cores for simple tasks, so a GPU can dwarf the calculation rate of many CPUs if the computational task can be decomposed to simple subtasks that can be handled by a GPU's core. The GPGPU is programmed using programming models such as CUDA or OpenCL.

Due to the popularity of commodity computer clusters, the MapReduce programming model was introduced to maintain their reliability. Apache Hadoop, which is a collection of open-source software utilities based on the MapReduce programming model, can automatically handle hardware failures that are assumed to be common. Apache Spark was developed in response to limitations in the MapReduce model, which forces a linear dataflow structure to read and write from disk. Instead of a hard drive disk, Apache Spark functions on distributed shared memory. Figure 6.2 illustrates how HPC platforms support both spatial database management systems and spatial data mining.

The abovementioned HPC platforms facilitate the realization of several HPC applications such as cloud computing, newly emerging edge computing (Shi et al. 2016) and fog computing (Bonomi et al. 2012). Cloud computing is the on-demand availability of computational resources such as data storage and computing power without direct active management by the users. It emphasizes the accessibility to HPC over the Internet ("the cloud"). As the cost of computers and sensors continuously decrease and the computational power of small-footprint devices (such as

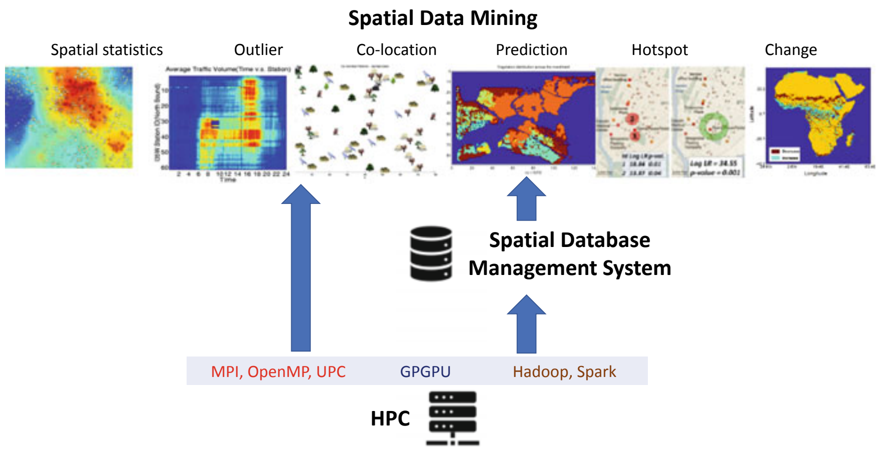

Fig. 6.2 HPC for spatial database management systems and spatial data mining

gateways and sensor hubs) increase, the concepts of edge computing and fog computing include more processing elements such as end devices in the Internet of Things in the computer clusters.

6.2.3 Spatial Database Management Systems and Spatial Data Mining

A database management system (DBMS) is a computerized system for defining, creating, querying, updating, and managing a database. It provides persistence across failures, concurrency control, and scalability to search queries of datasets that do not fit inside the main memories of computers. Spatial DBMSs are software modules that can work with an underlying DBMS; they were developed to handle spatial queries that cannot be handled by a traditional DBMS, for example, listing the names of all employees living within one kilometer of a company (Shekhar and Chawla 2003). Spatial DBMSs are an essential component of spatial data storage and management for geospatial information processing.

Spatial data mining is the process of quantifying and discovering interesting, previously unknown, potentially useful pattern families from large spatial datasets such as maps, trajectories, and remote sensing images (Shekhar et al. 2015). Compared with traditional data mining, spatial data mining has three special challenges. First, objects in space exhibit spatial dependence at nearby locations as well as distant locations. The spatial dependence at nearby locations is called the spatial autocorrelation effect. It is also known as Tobler's first law of geography: "Everything is related to everything else, but near things are more related than distant things." For example, people tend to cluster together with others that share similar characteristics, occupation, and background. Examples of long-range spatial dependence, i.e., spatial tele-coupling, include El Niño and La Niña effects on the climate system. A second challenge is that spatial data is embedded in a continuous space whereas classical datasets are often discrete. Third, spatial heterogeneity and temporal nonstationarity make it difficult to find a global law that is valid across an entire space and for all time. In other words, spatial context matters. Consequently, classical data mining algorithms often perform poorly when applied to spatial data sets and thus more powerful methods such as spatial statistics and spatial data mining are needed.

Spatial statistics (Cressie and Wikle 2015) provides theories (e.g., spatial point process, geostatistics, and lattice statistics), models (e.g., spatial autoregression model), and methods (e.g., Kriging) for spatial data mining. Spatial data mining focuses on five pattern families, namely, outliers, colocations and tele-couplings, location prediction, hotspots, and spatiotemporal change. A spatial outlier is defined as a spatially referenced object whose nonspatial attribute values are inconsistent with those of other objects in its spatial neighborhood (Shekhar et al. 2003). Contrary to global outliers, whose nonspatial attributes are compared with the remainder of the dataset, the attributes of spatial outliers are compared with a local subset of data around their footprints. For example, a road intersection where the vehicle speed is much higher than in other intersections nearby is a spatial outlier although it may not be a global outlier compared with other intersections in the city.

Spatial colocations represent subsets of spatial event types whose instances are often located in close geographic proximity (Huang et al. 2004). For example, the Nile crocodile and the Egyptian plover are frequently colocated, which indicates their symbiotic relationship. Other common colocation patterns include the colocation of the fast food restaurants McDonald's, Burger King, and KFC; the colocation of shopping malls with movie theaters; and the colocation of bars and drunk driving. Spatial tele-coupling represents interactions across distant locations. For example, the El Niño weather pattern (warming of the Pacific Ocean) affects the weather thousands of miles away in the midwestern and eastern United States.

Location prediction aims to learn a model to infer the location of a spatial phenomenon from maps of other spatial features. Examples include learning land-cover classification maps, predicting yearly crop yield, and predicting habitats for endangered species. Classical data mining techniques yield weak prediction models as they do not capture the spatial autocorrelation and heterogeneity in spatial datasets. Ignoring spatial autocorrelation often results in salt-and-pepper noise, i.e., locations whose predicted land-cover class is very different from the predicted land-cover classes of its neighboring locations. Such problems are significantly reduced by spatial autocorrelation-aware location prediction methods such as spatial autoregression, Markov random field-based Bayesian classifiers, and spatial decision trees (Jiang et al. 2015). Spatial heterogeneity, which prevents single-learner methods (e.g., neural networks and random forests) from accurately learning a global model is considered by spatial ensemble methods as well as Gaussian multiple instance learning methods (Jiang et al. 2017).

Spatial hotspots represent spatial regions where the concentration of objects inside the region is significantly higher than that outside. Hotspot analysis is widely used in public health and public safety to identify hotspots of disease and crime, respectively. False positives and true negatives carry high costs in such settings. Incorrectly labeling a neighborhood a disease or crime hotspot may lead to stigmatization and significant economic loss, and missing true hotspots of disease may lead to preventable mortalities and disease burden.

Spatiotemporal change may be defined in several ways. It may be a change in a statistical parameter, where the data are assumed to follow a distribution and the change is a shift of this distribution. It may be a change in actual value, where the change is defined as the difference between a data value and its spatiotemporal neighborhood. It may also refer to a change in models fitted to data, where the change is defined as a change in the models fitted to the data. Studies have been conducted to find more scalable algorithms for biomass monitoring using Gaussian process learning (Chandola and Vatsavai 2011).

There are many other interesting, useful and nontrivial patterns of interest in spatial data mining. For example, emerging hotspot detection aims to detect disease outbreak well before an outbreak results in a large number of cases. Interested readers are referred to papers on spatial data mining (Shekhar et al. 2011, 2015) and parallel computing algorithms for GIS (Healey et al. 1997; Shekhar et al. 1996, 1998; Zhao et al. 2016) for additional details.

6.2.4 Applications Supporting Digital Earth

Spatial database management systems using HPC have been studied extensively. Since Hadoop was introduced and its ability to handle big data in computer clusters was demonstrated, researchers and savvy tool users have taken advantage of it in various ways. Some tools and studies use Hadoop as a black box for operations on data, such as GIS tools for Hadoop, a package composed of programming libraries and an add-on toolbox of ArcGIS desktop (ESRI 2018), and Hadoop-GIS, a scalable spatial data warehousing system (Aji et al. 2013). Spatial Hadoop adds native support for spatial data by supporting a set of spatial index structures and developing spatial functions that interact directly with Hadoop base code (Yao et al. 2017). Impala, a distributed SQL query engine for Hadoop, has also been extended for spatial data (Eldawy et al. 2015). Apache Spark's core in-memory data abstraction, called a resilient distributed dataset (RDD), outperforms MapReduce-based approaches. Inefficient handling of interactive operations, the performance bottleneck of Hadoop-based tools, is addressed by GeoSpark, which adds support for spatial data and operations to Spark (Yu et al. 2015). GCMF, an end-to-end software system on GPGPU, illustrates the potential of GPGPU as a platform for geospatial information processing, as it can handle spatial joins over non-indexed polygonal datasets containing more than 600,000 polygons on a single GPU within 8 s (Aghajarian et al. 2016).

HPC is also applied in spatial data mining. Examples of HPC for spatial statistics include parallelizing the computation of statistical measures (e.g., Moran's I and Getis-Ord) using MPI and OpenMP (Wang et al. 2008; Kazar et al. 2004). Parallelization of the interpolation method has also been studied. Parallelized Kriging has been implemented on both MPI and GPGPU (Pesquer et al. 2011; de Ravé et al. 2014). Hadoop and Spark have also been leveraged as platforms to implement Kriging and inverse distance-weighted interpolation algorithms (Xu et al. 2015; Rizki et al. 2017). Parameter estimation for many spatial statistical models (e.g., spatial autoregression and space-time kernel density estimation) relies on matrix operations and may benefit from parallel formulations of linear algebra algorithms. A parallelization of wavelet transform, which can locate frequency outliers, has been implemented on MPI to scale up outlier detection algorithms (Barua and Alhajj 2007). Both GPU-based and OpenMP-based parallel algorithms have been explored for spatial prediction and classification (Gandhi et al. 2006; Rey et al. 2013). Researchers are investigating the use of GPUs as a platform for computing likelihood ratios as well as Ripley's K function (Pang et al. 2013; Tang et al. 2015). GPU-based methods have also been introduced to accelerate the computation of change detection (Prasad et al. 2013, 2015).

6.2.5 Research Challenges and Future Directions

HPC is essential for handling today's growing volumes of spatial data and the ever-increasing size and complexity of geospatial information processing problems. In addition to the existing methods and tools, further study in two focus areas is necessary to take full advantage of HPC for geospatial information processing.

The first focus of study is the parallelization of the currently available methods for HPC. The ubiquitous existence of spatial autocorrelation makes parallelization not applicable for most geo-related algorithms because the dependence between data partitions requires task interaction, which increases the difficulty of parallelizing serial algorithms in spatial database and spatial data mining functions. Additionally, the load balancing between processing elements is complicated when dealing with sparse data structures for which the pattern of interaction among data elements is data-dependent and highly irregular. Spatial networks (e.g., road networks) are an example of these data structures.

The second focus of study is utilization of geospatial big data to discover novel problems, patterns, research, and decisions. For example, most current research in spatial data mining uses Euclidean space, which often assumes isotropic properties and symmetric neighborhoods. However, the distribution of many spatial phenomena is strongly affected by the underlying network space, such as rivers and road networks. Some cutting-edge research has been conducted to generalize spatial analysis and data mining methods to the network space, such as network spatial interpolation (Kriging), network point density estimation, and linear hotspot detection (Okabe and Sugihara 2012). However, more research is needed in the network space. For example, in addition to the shortest paths, simple paths or irregular subgraphs are potential candidates for study in linear hotspot detection problems to discover interesting patterns.

In addition to the network space, the curved surface of the Earth is rarely considered in the currently available spatial database and data mining functions. For example, Chap. 2 discusses extending spatial indexing based on a space-filling curve and coordinate system to the curved surface. However, another family of spatial indexing, R-tree, which is the default spatial indexing supported by major DBMSs such as Oracle, MySQL, and PostGIS, only works in Euclidean space. Additionally, the definition of distance on the curved surface of the Earth is different from that in the Euclidean space, which affects the discovery of spatial patterns such as outliers, hotspots, and colocation.

Spatial heterogeneity is another topic to be explored. Spatial heterogeneity refers to the uneven distribution of spatial phenomena within an area. Most of the existing methods focus on the discovery rules or patterns valid for the whole dataset. However, the belief that spatial context matters is a major theme in geographic thought (Miller and Goodchild 2015). Different rules or patterns may exist in various places. If a pattern is infrequent relative to the size of the whole dataset, it may be missed if the entire dataset is analyzed. Such localized patterns are easier to find in smaller subsets of the data, around their spatial footprints. Identifying these patterns is challenging due to the need to enumerate all relevant footprints that may include an exponential number of data partitions (e.g., subgraphs of a road network). Examples of research on this topic include the spatial ensemble classification method (Jiang et al. 2017) and study of local colocation pattern detection (Li and Shekhar 2018).

Both the abovementioned future research directions pose new challenges for the computational capacity of currently available systems and tools. A highly integrated and reliable infrastructure ecosystem of HPC is required for geospatial information processing because most existing approaches focus on parallelization of specific tasks. Such an infrastructure can be utilized to speed up data management, mining, and analysis projects with scale and data granularity that were previously not possible, and enable new discoveries and ways of planning and decision making with novel big-data-oriented tools that are unavailable in the standard software.

6.3 Online Geospatial Information Processing

6.3.1 Web Service-Based Online Geoprocessing

Online geoprocessing refers to the use of spatial analysis functionality (such as buffer, interpolation and filtering operations) on the web to generate the desired output by applying a requested operation or chains of operations on input data. For the client-server interaction to work, clients and servers must be able to exchange requests and responses, for example, in the form of standardized web services. The standardization body in the geoinformatics sector is the Open Geospatial Consortium (OGC) (http://www.opengeospatial.org/standards/owc). OGC standards are aimed to provide syntactically interoperable services to facilitate integration, exchange and reuse of observations, data and geocomputational functions. Current applications of online geocomputation in the context of Digital Earth demonstrate the benefits of this standards-based technology. Some examples of such applications as well as challenges for advancing online geoprocessing for Digital Earth applications are discussed in Sect. 6.3.3. The alternative to standardized web services is application programming interfaces (API) and data formats such as JSON—the JavaScript Object Notation, which are increasingly popular (Scheider and Ballatore 2018). However, the plethora of available APIs limits the reusability of services that is with standardized approaches.

OGC service specifications cover services for raster or vector data, sensor observations, processing services, catalog services, and mapping services. The principle behind these services is that the interfaces are standardized, which means that resources can be requested following a set of defined parameters via the hypertext transfer protocol (HTTP). The requests are processed by a server and a response is sent back to the requesting user or service; the responses are generally encoded in XML (eXtensible Markup Language). Providers of web services can register their services in catalogs such that clients can discover and use these services. This publish-find-bind principle is fundamental in service-oriented architectures (SOAs) that realize the principle of integrating resources from distributed sources. Service-oriented architectures are commonly used in the context of spatial data infrastructures and (open) data initiatives, for example, GEOSS (http://www.geoportal.org).

According to Yue et al. (2015) such web services have the potential to become *intelligent,* i.e., easing the *automated* discovery and composition of data and processing services to generate the required information at the right time. To realize this vision, a move from the currently supported syntactic interoperability towards *semantic interoperability* is a core requirement (Yue et al. 2015). This section discusses the state-of-the-art of online geoprocessing in the context of Digital Earth as well as current lines of research related to semantics of geocomputational functions and spatial data. The objectives of this section are reflected in its structure: Sect. 6.3.2 introduces the principles of two geoprocessing services—the web processing service (WPS) and the web coverage processing service (WCPS). Section 6.3.3 discusses the state-of-the-art by reviewing successful applications of geoprocessing technology. Some current research trends and future directions to realize intelligent online geoprocessing are discussed in Sect. 6.3.4.

6.3.2 Web (Coverage) Processing Services

The key technologies for web service-based online processing are web processing services (WPSs) and web coverage processing services (WCPSs). As their names suggest, WCPSs provide processing functionality for coverages and is related to the web coverage service (WCS) standard; WPS provide general processing functionality for geospatial data. Both of these services follow the overall design principle of interoperable OGC web services and are briefly introduced below.

WPSs are currently available in version 2.0. A WPS must support the GetCapabilities, DescribeProcess and Execute requests, which are sent to the server using the HTTP GET or POST methods or the simple object access protocol (SOAP) (http://cite.opengeospatial.org/pub/cite/files/edu/processing/basic-index.html). The responses of the GetCapabilities and DescribeProcess requests contain information on parameter values required for an Execute request. These pieces of information cover the input, parameters and output of processes. Input and output data, which are either complex or literal data, are specified with a description and information on mimeType (e.g., "text/xml"), encoding (e.g., "UTF-8") and schema (e.g., "http://schemas.opengis.net/gml/3.2.1/feature.xsd"). It is possible to specify the data types of literal data as well as allowed values. WPS can be executed in synchronous or asynchronous modes; asynchronous execution is preferred for calculations that take longer.

The nature of WPS is generic as the kind of calculation a processing service provides is not specified. The generic nature of WPS is said to be one reason for its slow uptake, as it is difficult for clients to deal with the variety of outputs generated by different WPSs (Jones et al. 2012). The process implementations are hidden from the users; the information provided on the processes includes their input, output and parameters as well as a title, description, identifier and additional optional metadata. To reuse processes, it is essential to have information on what a process does and the datasets it can be applied to. Thus, process profiles have been revised and modified to describe the meaning of operations and their inputs and outputs in the WPS 2.0 standard (Müller 2015).

The web coverage processing service is an extension of the WCS standard with an explicit focus on the processing of coverages, i.e., multidimensional raster data; it has been available since 2008. The current WCS 2.1 version supports the GetCapabilities, DescribeCoverage and GetCoverage requests. These requests are extended for the ProcessCoverage request in WCPS. Filter mechanisms that restrict the spatial or temporal extent of the processed data are a core requirement for interaction with multidimensional coverages. The WCPS provides a specific syntax, which is somewhat similar to the structured query language SQL, for formulating queries of temporal and spatial subsets of data (Baumann 2010). WCS and WCPS can handle a multitude of different formats of data encodings that are relevant in the context of image data; these include NetCDF, GeoTiff, JPEG, and GRIB2. A tutorial on WCS and its extensions is available on Zenodo (Wagemann 2016).

Although WCPS was specifically designed for coverage data, its reuse across applications is hindered by diverging definitions of data models and the heterogeneity of data formats (Wagemann et al. 2018).

6.3.3 Online Geoprocessing Applications in the Context of Digital Earth

This section presents three recent examples of application of online geoprocessing. These applications were published in a related special issue aimed at promoting online geoprocessing technology for Digital Earth applications (Hofer et al. 2018). The applications demonstrate the use of web processing services and web coverage processing services as extensions of existing infrastructures in a variety of contexts. They derive relevant and timely information from (big) data in efficient and reusable manner, which serves the objectives of Digital Earth.

Wiemann et al. (2018) focus on the assessment of water body quality based on the integration of data available in SDIs to date; the data types considered are feature objects and raster data. Their work introduced a new concept of geoprocessing patterns that suggest the application of processing functionality based on input data selected by the user of the application. The motivation behind this development is to assist users in deriving information from data. Their information system supports determination of river sinuosity as an indicator of the ecological quality of rivers, assessment of real estate values potentially affected by floods, and the discovery of observations made along rivers.

Stasch et al. (2018) present the semiautomatic processing of sensor observations in the context of water dam monitoring. An existing infrastructure makes sensor observations such as water levels and GPS measurements of dam structure available and the objective of their work is to statistically analyze the observations and use them as model inputs. Their motivation to use WPS is related to the possible reuse of services and flexibility regarding the integration of sensor observations from other sources in the final decision making. The coupling of sensor observation services (SOSs) with WPS is not a standard use case. Therefore, Stasch et al. (2018) discuss various approaches of coupling SOSs and WPS and selected a tight coupling approach in which a processing service can directly request observations from an SOS, which reduces overhead in communication. The authors also developed a REST API for WPS to reduce the required parsing of extensive XML files and ease client development; they provided the specification of a REST binding, which is lacking in the current WPS 2.0 standard.

Wagemann et al. (2018) present examples of the application of web coverage processing services in the context of big Earth data. They show how online geoprocessing supports the derivation of value-added products from data collections and how this technology transforms workflows. They state that server-side data processing can overcome issues using different solutions for data access and can minimize the amount of data transported on the web (Wagemann et al. 2018). They described examples of the application of WCPS in the domains of ocean science, Earth observation, climate science and planetary science; all of the examples use the rasdaman server technology. One of the presented applications for marine sciences provides a visual interface where a coverage of interest such as monthly values of chlorophyll concentration that were derived from ocean color satellite data can be specified (http://earthserver.pml.ac.uk/www). The provided coverage data can be compared with in situ measurements via a match-up tool. The match-up is calculated on the server and the users are presented with the results without having to download the chlorophyll data to their machines. The provider of this service must offer the required computing resources and the limitation of requests to a certain data volume is a known issue (Wagemann et al. 2018).

6.3.4 Research Challenges and Future Directions

Online geoprocessing technology has been improved over the last decade and the applications demonstrate its usability in real-world use cases. The potential of standardized web services lies in the flexible integration and reuse of services and computational power from different providers. However, in addition to the costs of service provision to potential clients, the *complexity* and *opacity* of geoprocessing workflows seem to hinder their mass usage. This is indicated by the fact that mapping services and data services are much more widely spread than processing services (Lopez-Pellicer et al. 2012). The reasons for this are manifold and relate to the variety of data models and formats, which limits the applicability of existing processing services (Wagemann et al. 2018), lacking descriptions of processing services such as those approached with WPS process profiles (Müller 2015) and the required transfer of potentially large data from a data provider to a service provider.

Assuming that geoprocessing services are available for reuse across applications, the most relevant current challenges concern the *opacity* of service, data and tool interfaces, and the corresponding lack of clarity about when a geocomputational service is potentially useful. Applying a geocomputational function is a matter of analytic purpose as well as of the properties of the data sources used. The latter goes well beyond data types and necessarily involves background knowledge about the semantics of spatial data (Hofer et al. 2017; Scheider et al. 2016). Thus, it was recognized early in the field of geocomputation that, in addition to syntactic interoperability (i.e., the matching of formats and data types), *semantic interoperability* must be taken into account (Ouksel and Sheth 1999; Bishr 1998). Since then, many attempts have been made to incorporate semantics into service descriptions, e.g., in the form of Datalog rules and types that restrict the application of geocomputational functions (Fitzner et al. 2011; Klien et al. 2006). The technology evolved as a particular (service-oriented) strand of the semantic web, starting in 2000 (Lara et al. 2004) and resulting in standards such as the semantic markup for web services (OWL-S) (https://www.w3.org/Submission/OWL-S/) and web service modeling language (WSML) (http://www.wsmo.org/).

Researchers of semantic web services have shown that service descriptions and Semantic Web technology can be effectively combined and that abstracting from particular implementations of geocomputational functions remains very difficult (Treiblmayr et al. 2012). Which aspects of such a function are mere technicalities? Which aspects are essential and thus should be represented on the semantic level of the service and data? More generally, what does a reusable representation that is valid across implementation specific details look like (Hofer et al. 2017)? The lack of a good answer to these questions in semantic web service research, e.g., in terms of a *reusable service ontology,* may be the reason why semantic web processing services have become less of a focus in research today. Drawing a line between semantic and syntactic interoperability is not straightforward, and different and incompatible "ontological" views on the world must be acknowledged (Scheider and Kuhn 2015). The need to infuse and reuse such flexible semantics in the age of big data has not lessened and is more urgent than ever (Janowicz et al. 2014; Scheider et al. 2017).

We currently lack *reusable representations* of the different views that make geoprocessing operations and data sources useful for a specific purpose. We also lack *neat theories* that tell us which concepts and aspects should be retained to describe data and geocomputational functions from the practical viewpoint of data analysis. Ontology design patterns have been proposed as a means to create such representations (Gangemi and Presutti 2009) and have recently gained popularity. Furthermore, it is an open question how geocomputational functions relate to the *purposes of analysis*. Finally, we need *computational methods* that allow for us to *infuse* the needed background knowledge into service and data descriptions to enable *publishing* and *exploiting* it.

Current research on semantic issues in geoprocessing tackles these challenges to support spatial analyses. We summarize three main lines of research that have evolved in recent years that may be promising for progress on a *semantically interoperable* Digital Earth:

6.3.4.1 Service Metadata, Computational Core Concepts, Linked Data and Automated Typing

In the current web processing service standards, to reuse a service it is necessary to describe the capabilities of the service and the service parameters (including data sources) in terms of metadata. However, the current metadata standards do not specify how to do this. It remains unclear which language and concepts should be used in these descriptions; it is also unclear how these concepts can be shared across communities of practice and how they can be automatically added without manual intervention. Regarding the first problem, several recent investigations attempted to identify a necessary and sufficient set of "core" concepts of spatial information (Kuhn 2012; Kuhn and Ballatore 2015; Scheider et al. 2016), which remain to be tested in diverse practical analytical settings. Regarding the second problem, linked open data (LOD) provides a way to remove the distinction between metadata and data, enabling us to publish, share and query data and its descriptions at the same time (Kuhn et al. 2014). Similarly, Brauner (2015) investigated the possibilities of describing and reusing geooperators with linked data tags on the web, and Hofer et al. (2017) discussed how such geooperator descriptions can be used for workflow development. Regarding the third problem, it has long been recognized that semantic labeling is a central automation task for the semantic web, as users tend to avoid the extra manual work involved. For this purpose, it has been suggested that the provenance information contained in workflows can be used to add semantic labels to the nodes in such a workflow (Alper et al. 2014). For the geospatial domain, it was demonstrated that the information contained in GIS workflows can be used to enrich geodata as well as GIS tools with important semantic types by traversing such a workflow, and share this information as linked data (Scheider and Ballatore 2018). Furthermore, certain semantic concepts such as the distinction between extensive and intensive attributes, which is central for geocomputation and cartography, can be automatically added as labels using machine learning classifiers (Scheider and Huisjes 2019).

6.3.4.2 From Service Chaining to Automated Workflow Composition

Automated service chaining has been a scientific goal and research topic since the start of the development of semantic web services (Rao and Su 2005). Ontologies are used to describe the restrictions on input and output types, which can be exploited by service chaining algorithms to suggest syntactically valid workflows. This idea has also been adopted for the geospatial domain (Yue et al. 2007), where the ontological concepts were mainly based on geodata types. However, in the wider area of workflow composition (Gil 2007; Naujokat et al. 2012), finding efficient composition algorithms is not the issue, finding the relevant semantic constraints that render the problem tractable is. Once such constraints are found, it is much easier to devise an algorithm that makes service composition computable for practical purpose, and it becomes possible to filter out syntactically valid but *nonmeaningful* workflows that are currently clogging the workflow composition flows (Lamprecht 2013). Thus, similar to the metadata challenge discussed above, scientific progress largely depends on whether we will be able to devise a set of reusable valid semantic concepts for both geocomputation and geodata. In the future, it would be valuable to measure the effectiveness of spatial semantic concepts in reducing computational time and increasing accuracy in automated GIS workflow composition.

6.3.4.3 From Geocomputation to (Indirect) Question Answering

Since the application of geocomputational tools and the chaining of services require lots of background knowledge and GIS skills, their usage is currently restricted to GIS experts. However, those with little or no technical expertise in this area would benefit most, as well as those with a *relevant spatial question* about Digital Earth. How can Digital Earth technology help such users answer their questions? Question-based spatial computation was proposed as a research topic by Vahedi et al. (2016) and Gao and Goodchild (2013). The question-answering (QA) computational technique has been investigated during the last two decades from the information retrieval perspective (Lin 2002). Standard QA technology parses a natural language question and matches it with answers available in a database or the web. Recently, linked data-based data cubes were proposed as a way to realize question answering on a web scale (Höffner et al. 2016). However, question answering for geocomputation and analysis requires handling questions that *do not yet have an answer* but could be answered using appropriate tools and data. The latter problem was therefore termed *indirect question answering* by Scheider et al. (2017). A semantically informed retrieval portal that can answer such questions should be able expand a data query in a way that encompasses data sets that do not directly answer a given query but can be made to do so via appropriate analysis steps. For this purpose, geocomputational tools and datasets need to be described by the questions they answer, so that they can match the questions posed by a user. A recent first step in developing such a system for a set of common GIS tools was made based on SPARQL query matching (Scheider et al. 2019), following the idea of query matching for service descriptions proposed by Fitzner et al. (2011). However, similar to the previous two computational challenges, the kinds of questions and the matching language and technology are dependent on our theories of spatial (interrogative) concepts used to formulate these questions. In the future, we should investigate what kinds of spatial questions are relevant and how they can be formally captured in terms of core concepts. For related work, refer to the ERC-funded project QuAnGIS: Question-based analysis of geographic information with semantic queries (https://questionbasedanalysis.com).

6.4 Distributed Geospatial Information Processing

6.4.1 The Concept of Distributed Geospatial Information Processing: What and Why

Distributed geospatial information processing (DGIP) (Yang et al. 2008; Friis-Christensen et al. 2009) refers to geospatial information processing (geoprocessing for short) in a distributed computing environment (DCE). With the development of the Internet and world wide web, architecture modes of software have changed dramatically. Decentralization and cross-domain collaboration under a loosely coupled and dynamically changed DCE has become an emerging trend. Adoption of service-oriented architecture (SOA) and cloud computing is a promising and prevalent solution for modern enterprises to enhance and rebuild their cyberinfrastructure. Using these technologies, it is more agile and much easier to build cooperation networks and adjust cross-enterprise business workflows dynamically.

Following this trend, geographical information systems (GISystems) are also experiencing an evolution from traditional stand-alone toolkits to web service-based ecosystems (Gong et al. 2012), e.g., the geospatial service web (GSW). The GSW is a conceptual framework for a loosely coupled geospatial collaboration network through which the end users can share and exchange geospatial resources and conduct geoprocessing online by using distributed geographical information services (GIServices). In the GSW, everything is encapsulated as a service (XaaS), as shown in Fig. 6.3, including computing resources (CPU, memory, storage and network, etc.), geospatial data, models, algorithms and knowledge. The wide adoption of the enabling technologies such as web services, SOA and cloud computing make such a distributed geospatial collaboration network possible but there are also challenges. One of the major challenges is how to guarantee the reliability of geoprocessing in a mutable DCE (Gong et al. 2012; Wu et al. 2015). Traditionally, geoprocessing is conducted on a single machine with a stand-alone GISystem toolkit installed. Since the functional components of a GISystem are tightly coupled, it is relatively easy to capture and handle geoprocessing exceptions and ensure the whole geoprocessing process, e.g., a workflow synthesized with coordinate transformation, buffering and overlay operations. In comparison, in a DCE, it is complicated to define, coordinate and guarantee such a process due to the complexities in data transmission, workflow control and exception handling.

Therefore, DGIP has become a research hotspot as well as an application trend (Yang et al. 2008; Wu et al. 2014; Jiang et al. 2017). In this section, we introduce the basic concept and key techniques of DGIP, and demonstrate its applications in Digital Earth. Finally, we discuss the technical challenges and future directions.

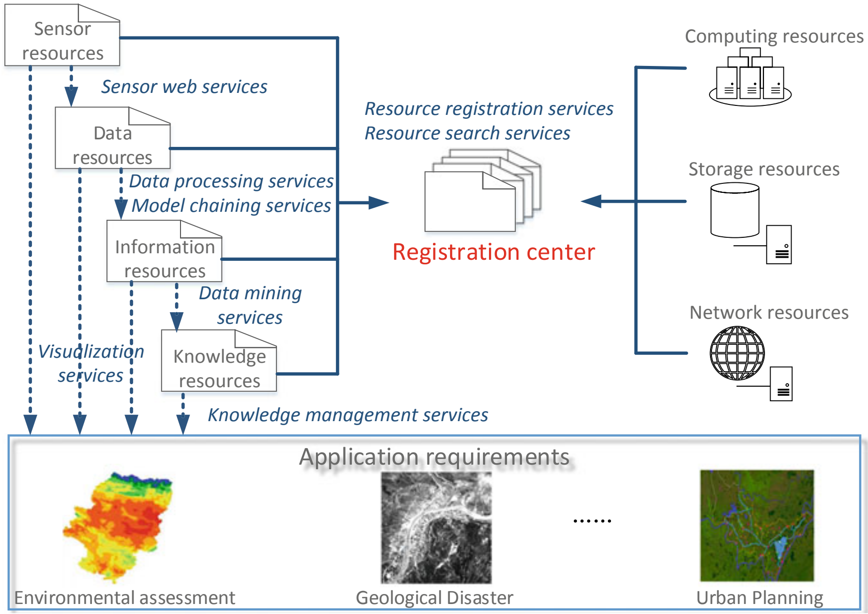

Fig. 6.3 The Conceptual framework of the geospatial service web (Gong et al. 2012)

6.4.2 Fundamental Concepts and Techniques

6.4.2.1 Collaboration Mode (Orchestration vs. Choreography)

For a distributed workflow to operate appropriately, the coordination and controlling mechanism is critical. In an SOA context, there are two basic collaboration modes (Peltz 2003), choreography and orchestration, based on the control flow patterns and how messages are exchanged, as illustrated in Fig. 6.4.

Web service orchestration (WSO) employs a centralized approach for service composition. A workflow is represented by a centralized coordinator that coordinates the interaction among different services. The coordinator or so-called composite service is responsible for invoking service partners, manipulating and dispatch messages. The relationships between the participating services are maintained by the coordinator. Since WSO adopts a hierarchical requester and responder model, it is process-centralized and the cooperation among participating services is weakened. The participating services do not need to know about each other in collaboration. In WSO, the status maintenance and error handling are relatively easier since it can be monitored and controlled by the coordinator. When an exception occurs, the coordinator can trigger exception handling or a compensation mechanism before the workflow progresses into the next step.

In comparison, web service choreography (WSC) adopts a decentralized peer-to-peer model. There is no a centralized compose service acting as the coordinator to

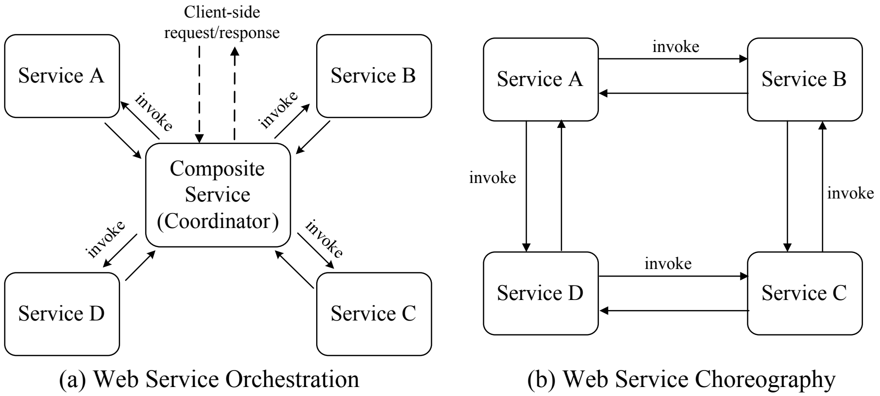

Fig. 6.4 Architectures of web service orchestration and web service choreography

control participating services, which makes it much more loosely coupled. The whole workflow is defined by exchanging messages, rules of interaction and agreements between services. Each participating service knows when and how to interact with each other, as well as whom to interact with, i.e., it is self-described and highly autonomous. One side effect is that it is difficult to detect errors in a timely manner and conduct exception handling from the workflow perspective. However, it can avoid the performance bottleneck problem for the coordinator in message exchange and data transmission.

In summary, the WSC describes the interactions between multiple services from a global view whereas WSO defines control from one party's perspective, and the control logic of the interactions between services is explicitly modeled in the composite service (Peltz 2003). Therefore, WSO is generally an intraorganization workflow modeling solution whereas WSC is more suitable for interorganizational or cross-domain workflow modeling when it is difficult to set up a centralized coordinator across the boundary of management.

Learning from service composition in the IT domain, the geospatial domain proposed the concept of a geospatial service chain, which is defined as a model for combining services in a dependent series to achieve larger tasks for supporting DGIP. According to the definition of international standard ISO 19119 (2002), there are three types of architecture patterns to implement a service chain, as illustrated in Fig. 6.5, by giving different controlling authorities to clients (Alameh 2003; ISO 19119 2002), i.e., user-defined chaining, workflow-managed chaining and aggregated chaining.

- In user-defined (transparent) chaining, the client defines and controls the entire workflow. In this case, the client discovers and evaluates the fitness of available services by querying a catalog service, which gives most freedom to the client to make the control decision and ask for workflow modeling knowledge.
- In workflow-managed (translucent) chaining, the workflow management service controls the service chain and the client is aware of the participating services. In

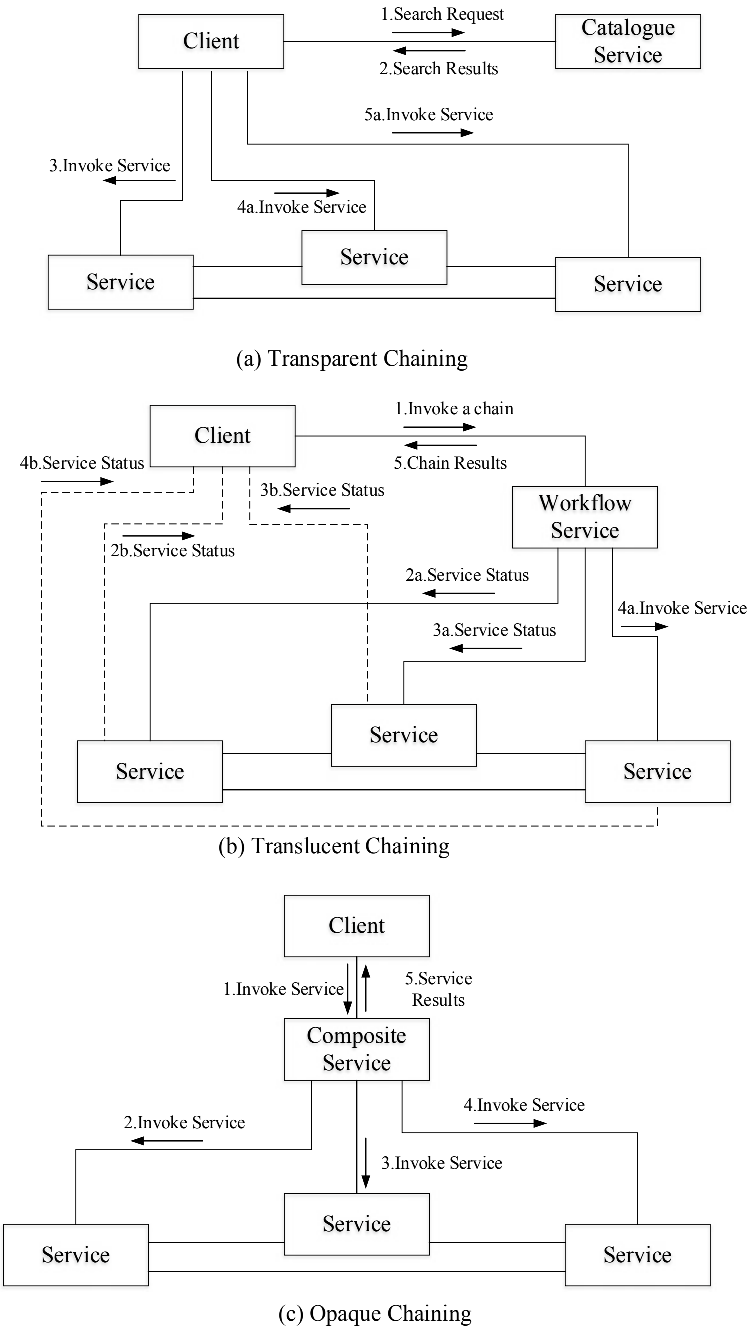

Fig. 6.5 Three architecture patterns for geospatial service chains defined in ISO 19119

this mode, the client can check the execution status of individual participating services, and the workload on workflow control is reduced.

- In aggregated service (opaque) chaining, the client invokes a compose service without awareness of the individual participating services. The compose service manages all the details of chain execution.

Although ISO 19119 gives the architecture patterns of service chaining, there is no de facto domain-specific standard on modeling language. The modeling languages of web service composition introduced in the next section use service chain modeling as a reference.

6.4.2.2 Workflow Modeling Language

A formalized model description language is desired to allow for a service chain be understood and shared among heterogeneous systems. Computer-aided business process management (BPM) has been widely used in modern enterprises for decades. Due to the variety of the backend IT enabling technologies and application scenarios, there are hundreds of workflow languages developed by different communities. These languages have different capabilities for flow rule expression (Aalst et al. 2003). In general, the languages can be classified into industrial specifications and academic models (Beek et al. 2007).

Industrial workflow specifications are model languages that target a certain technique implementation, and are widely supported by companies and standardization organizations. Web services business process execution language (WS-BPEL) and web service choreography description language (WSCDL) are two workflow standards specialized for web service composition. There are many open-source and commercial toolkits for reliable workflow modeling and execution management based on these specifications. However, these specifications are usually mixed with lower-level techniques such as XML encoding, XQuery, SOAP, WSDL and WS-addressing. These technical details increase the learning curve for users that lack or have little background knowledge of programming and web service standards. Workflow Management Coalition (WfMC) created an XML-based process definition language (XPDL) to store and exchange workflow models defined by different modeling language that is independent of concrete implementation techniques. XPDL is considered one of the best solutions to formally describe workflow diagrams defined using business process modeling notation (BPMN).

Academic workflow models express abstract process structures and rules that are not bound by a concrete runtime environment, lower-level implementation details and protocols (Beek et al. 2007; Gui et al. 2008), e.g., automata and process algebras. Directed graph and mathematical notations are widely used for workflow description, e.g., Petri nets (Hamadi and Benatallah 2003). Academic workflow models can express abstract process knowledge and have strict mathematical logics for process validation. However, these models are less used in industrial environments, and software to support workflow modeling and runtime management is lacking.

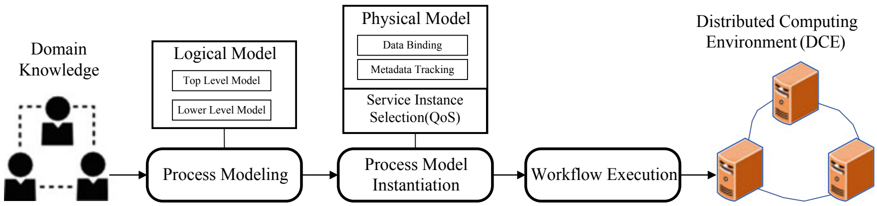

Fig. 6.6 A multistage geospatial service chaining process

In terms of geospatial service chaining, there is no well-accepted model language and domain-specific modeling methods should be developed. The European Space Agency (ESA) adopted WS-BEPL and established a service partner network to support global collaboration on earth observation. WS-BPEL is a de facto and widely used standard of the Organization for the Advancement of Structured Information Standards (OASIS) derived from the combination of IBM's Web Services Flow Language (WSFL) and Microsoft's notation language for business process design (XLANG). However, the lower-level technique details in WS-BPEL may be beyond the expertise of domain experts without web service knowledge. WS-BPEL adopts static binding to specify service partners and communication rules in advance and makes it difficult to adopt a dynamic and mutable environment. Therefore, a multistage geospatial service chaining method is highly desired to separate abstract geoprocessing workflow knowledge and lower-level implementation details, and make service partner binding dynamic, as illustrated in Fig. 6.6.

As shown in Fig. 6.6, Di et al. (2006) divided geospatial service chaining process into three steps, geoprocessing modeling, geoprocessing model instantiation and workflow execution. In the processing modeling stage, geoscience domain experts use a logical model language to depict abstract geoprocessing workflows based on process knowledge. In the process model instantiation stage, the logical model is mapped into a physical model that binds with implementation details. The data sources of the input data and service instances of participating services are specified during instantiation. Then, the physical model can be deployed into a workflow engine for workflow execution and runtime management.

6.4.3 Application Supporting Digital Earth

6.4.3.1 Development of Geospatial Workflow Modeling Languages and Tools

Based on the concept of multistage geospatial service chaining, various model languages have been proposed and modeling platforms have been developed. Chen et al. (2009) defined a geospatial abstract information model (AIM) language to describe logical models, which can be considered a new virtual geospatial product for process knowledge sharing and reuse. A logical model has a directed graph expression as well as an XML presentation that can be instantiated and translated into an executable WS-BPEL model for reliable execution management. By adopting such technologies, Di (2004) developed GeoBrain, a geospatial knowledge building system based on web service technologies, to automate data discovery and facilitate geoprocessing workflow modeling. Gui et al. (2008) also proposed an abstract geospatial service chain model language, DDBASCM, by combining data-dependency directed graph and block structures. In DDBASCM, the data flow is represented using a directed graph structure, and the control flow and aggregated service are depicted as block structures by learning from the concept of a transition-bordered set in Petri Net. Based on DDBASCM and WS-BPEL, a geospatial web service chain visual modeling and execution platform called GeoChaining was developed, which integrates catalog-based geospatial resource searching, service chain visual modeling, execution status monitoring and data visualization (Wu et al. 2011, 2014). Sun et al. (2012) developed a task-oriented geoprocessing system called GeoPWTManager to design, execute, monitor and visualize the workflow. In GeoPWTManager, the entire modeling and execution process is ensured by the collaboration of three components, i.e., a task designer, a task executor and a task monitor. Based on GeoPWTManager, GeoJModelBuilder, an open source geoprocessing workflow tool, was developed by leveraging open standard, sensor web, geoprocessing service and OpenMI-compliant models (Jiang et al. 2017).

Although implementation technologies are continuously evolving and new tools will be developed, the demand for development of a domain-specific workflow modeling language that can explicitly describe the terminologies and geoprocessing knowledge in the geospatial domain is still high. Cloud-based services that integrate online resource discovery, visualization, automatic/semiautomatic modeling, model sharing and reuse will be a trend to facilitate DGIP workflow modeling and execution management.

6.4.3.2 Digital Earth Applications

Geospatial service chaining provides an agile and loosely coupled approach to arrange the cooperation of dispersed GIServices to achieve DGIP. Based on the aforementioned technologies and platforms, DGIP-supported earth science applications have been developed. For example, the ESA created a net primary productivity (NPP) workflow in its online collaboration platform, Service Support Environment (SSE), for repeatable estimates of the net flux of carbon over user-specified AOI areas using SPOT vegetation S10 data. There are also more than 30 DGIP workflow-based applications provided by 23 service partners from 10 countries, including for oil spill detection, fire risk, Kyoto protocol verification, desert locusts, land use, snow cover, tidal currents, and multiple catalog access. In GeoBrain, many DGIP workflow models have been developed based on the proposed logical modeling language. A landslide susceptibility model (Chen et al. 2009) that integrates terrain slope and aspect analysis services as well as landslide susceptibility analysis services has been used to analyze landslide susceptibility in California, USA. GeoChaining (Wu et al. 2014) also provides workflow models by integrating third-party developed GIServices such as OpenRS (Guo et al. 2010) and GIServices developed by encapsulating the open-source GIS tool GRASS (https://grass.osgeo.org). A flood analysis model was developed to analyze flooding in the Boyang Lake area using remote sensing data before a flood, during flooding and after flooding. By developing web-based human-computer interaction interfaces using Rich Internet Application (RIA) technologies, workflow models involving human participation have also been developed in GeoSquare for educational and research purposes (Wu et al. 2015; Yang et al. 2016), including remote sensing image geometrical rectification and classification. Through integration with NASA world wind, GeoJModelBuilder (Jiang et al. 2017) also provides many hydrological models such as for water turbidity, watershed runoff, and drainage extraction.

In addition to applications comprised of geospatial service chaining, there are other forms of DGIP. For example, volunteer computing (VC) is a type of distributed computing that incorporates volunteered computing resources from individual persons and organizations. The VC usually adopts middleware architecture containing a client program that is installed and running on volunteer computers. VC has been successfully applied to many scientific research projects such as SETI@home (https://setiathome.berkeley.edu) and Folding@home(https://foldingathome.org). In the earth science domain, NASA launched a VC project named Climate@home to create a virtual supercomputer to model global climate research. This project utilizes worldwide computing resources to establish accuracy models for climate change prediction (Li et al. 2013).

Various applications have been developed, and the potential application scenarios are unlimited. As more GIServices for geoprocessing and big data analysis are developed using cloud computing and VC technologies, more interdisciplinary applications in earth science and social science will be developed.

6.4.4 Research Challenges and Future Directions

6.4.4.1 Communication Mechanism and Code Migration

Optimized network communication is critical for efficient and reliable DGIP because it relies on network communication for data transmission and service collaboration. The simple object access protocol (SOAP) is a widely used messaging protocol for exchanging information and conducting remote procedure calls (RPCs) in DCE using multiple lower-level transportation protocols such as HTTP, SMTP and TCP. SOAP is extensible to support functions such as security, message routing and reliability by compositing with web service specifications. SOAP supports multiple message exchange patterns (MEPs) such as one-way messages, request/respond mode and asynchronous messages. However, SOAP is not efficient in encoding due to its XML-based hierarchical envelope structure, for example, when transmitting vector data represented in GML or a raster image formatted using base64 binary encoding. As a result, SOAP message transmission optimization technologies have been developed. Binary data code can be sent as multipart MIME documents in SOAP attachments, and XML-binary Optimized Packages (XOP) provide a reliable approach to refer external data in the SOAP messaging, as proposed in SOAP standard version 1.2.

The development of HTTP Representational State Transfer (RESTful) (Fielding 2000) brings new challenges for DGIP. The RESTful architecture style has been widely adopted in web application development (Pautasso et al. 2008). OGC GIService standards use RESTful APIs as the major interoperating approach. Considering this trend, service composition technologies and tools should support RESTful services. Compared with SOAP, RESTful is lightweight and stateless, but the security, routing and reliable message transmission are weakened. Therefore, making DGIP reliable and secure has become critically important. Robust flow control, exception handling and compensation mechanisms must be developed for both the workflow engine and the participating services.

Communication issues have also inspired new ideas and research directions. Geoprocessing usually involves a large data volume and intensive geo-computation. The intensive data transmission increases the workload of the network infrastructure, as well as those of the participating services and workflow coordinator, and makes time efficiency a troublesome issue. To improve the user experience for DGIP, an asynchronous execution status-tracking method has been developed (Wu et al. 2014). Version 2.0 of the OGC web processing service (WPS) standard officially supports asynchronous execution of geoprocessing by the conjunction of *GetStatus* and *GetResult* operations. The *GetStatus* operation provides status information of a processing job for query, and *GetResult* allows for the client to query the result of a processing job. Through an asynchronous mechanism, a geoprocessing workflow engine can actively and instantly push the latest execution status of dispersed services to clients. Data transmission may also introduce data security risks, especially for classified or sensitive data. As the volume of software programs may be much smaller than the data volume, researchers proposed the idea of code migration. However, it is not easy to migrate code in heterogeneous systems due to the complex dependency of software packages. VC provides an alternative solution by installing a specified client to set up a unified runtime environment, e.g., BOINC (https://boinc.berkeley.edu). This problem is eliminated in a clustered computing environment because the computing nodes are equipped with the same operating system and distributed computing framework and thus the code can be migrated smoothly. For example, the high-performance frameworks introduced in Sect. 6.2, e.g., Apache Hadoop and Spark, migrate codes to computing nodes according to the locality of the dataset in the distributed file system to avoid IO overhead and optimize computing performance.

6.4.4.2 Quality-Aware Service Chain Instantiation

As global providers deliver more GIServices with similar functions but diverse quality, it has become challenging to select appropriate service instances from similar service candidates. To enable quality-aware service chain instantiation, quality evaluation methods and mathematical planning methods must be developed (Hu et al. 2019b). Quality evaluation assesses the fitness of individual participating services or aggregated services according to user quality requirements, and mathematical planning assists the service instance selection for each individual participating service by considering the overall quality of the service chain.

Multiple quality dimensions such as time efficiency and reliability must be leveraged to evaluate the quality of a participating service. Operations research methods such as multiple attribute decision making (MADM) and the analytic hierarchy process (AHP) provide solutions for quality dimension integration (Zeng et al. 2003). However, the control-flow and data-flow structures must be considered to determine the aggregated quality of a service chain (Jaeger et al. 2004).

In terms of service chaining, quality metrics have different aggregation behaviors under different flow structures (Aalst et al. 2003). For example, the total response time of a service chain with a sequential control-flow structure is the sum of the response times of all the participating services, and the total reliability is calculated by multiplying the availability of all the participating services. Quality computation can be more complicated in service chains with nested flow structures. If only the quality status of participating services is considered and the workflow structure is ignored, then the overall optimization of a service chain cannot be guaranteed (Jaeger et al. 2004; Gui et al. 2009; Hu et al. 2019a, b), especially when multiple quality metrics must be balanced.

To support quality-aware geospatial service chain instantiation, sophisticated GIService selection methods must be developed. Mathematical programming approaches such as Linear Programming (LP) can be used in service chains (Zeng et al. 2003; Gui et al. 2009) with a limited number of participating services. When the scale of the service chain increases, these methods become less efficient due the computing complexity. Furthermore, LP can only provide one optimized solution in the planning stage, which may not be optimal when one of the quality metrics slightly changes, since service runtime and network environments are typically mutable. Evolutionary methods (Canfora et al. 2005) such as genetic algorithms and swarm intelligent algorithms provide strong search capabilities and robustness in dynamic situations (Jula et al. 2014) and can be applied for geospatial service chain optimization. Considering the nature of complex flow structures and high dimensions of the quality metrics of a geospatial service chain, more research on quality evaluation and GIService selection must be conducted.

6.4.4.3 Semantic-Aided Automatic Service Chaining

With the development of artificial intelligence (AI) and semantic web technologies, automatic service chaining has been a research hotspot for many years and is still evolving. The goal of automatic service chaining is to make the computer capable of discovering web service resources and automatically building the service chain according to the requirements and constraints of the end user. In contrast to quality-aware service chain instantiation, there is no logical model available in advance for automatic service chaining. Thus, the computer must build the logical chain and instantiate it upon domain knowledge and the timeliness of the service resources, i.e., whether the service instance or data provider is available or not. To achieve this goal, a formal description of knowledge is required. The development of semantic web, ontology web language (OWL) and domain ontologies facilitates GIService semantic markups. For example, ontology-based description languages and rule languages are used for semantic discovery and geospatial service chaining (Lutz and Klien 2006; Yue et al. 2009), including semantic markup for web services (OWL-S), web service modeling ontology (WSMO), description logics (DL) and first-order logic (FOL). GeoBrain provides a web-based semiautomatic chaining environment by allowing for end-users to participate in human-computer interaction during the backwards reasoning (Di 2004; Han et al. 2011). The degree of suitability for candidate workflows is calculated by using the semantic similarity to support semiautomatic chaining (Hobona et al. 2007).

Semantic-aided chaining approaches have been developed and verified in laboratory environments; however, more research must be conducted to make them feasible in real-world applications. Currently, semantic markups for describing content, functions or prerequisites lack in most online-accessible geospatial resources. In addition, spatial data infrastructures (SDIs) and geoportals such as GEOSS clearinghouse, Data.gov, and INSPIRE do not provide semantic-aware discovery functions. The challenges include determining how to provide a semantic-enabled metadata Registry Information Model (RIM) for GIService semantic description, retrieval and validation (Qi et al. 2016; Zhang et al. 2017). W3C semantic standards such as the resource description framework (RDF) and OWL-S provide promising solutions for describing domain knowledge, enabling intelligent and efficient service discovery. However, these semantic languages must be linked with existing metadata standards in global SDIs (Gui et al. 2013). From the chain modeling perspective, AI reasoning technologies require further development to enable automatic and intelligent chaining. The rapid development of knowledge graph and mining technologies may provide a potential solution, which has been widely adopted in domain knowledge modeling and reasoning (Lin et al. 2015). Furthermore, to conduct DGIP-supported geoscience data analysis using heterogeneous Earth observation and socioeconomic data, we need to establish and advocate for standardization of the Discrete Global Grid System (DGGS) (Mahdavi-Amiri et al. 2015). It is critically important to promote heterogeneous earth science data fusion and interoperability, and the related standards and data models should be integrated into global SDIs (Purss et al. 2017).

6.5 Discussion and Conclusion

Geospatial information processing and computing technologies are essential for Digital Earth, as they enable various Digital Earth applications by turning geospatial data into information and knowledge. By identifying the challenges of geospatial data manipulation in the big data era, including massive *volume*, *heterogeneous*, and *distributed*, this chapter introduced three population technologies for geospatial data processing: high-performance computing, online geoprocessing, and distributed geoprocessing. Each of the three technologies focuses on addressing a specific challenge, though there are some overlaps. High-performance computing primarily deals with the *volume* challenge by solving data- and computing-intensive problems in parallel. Online geoprocessing tackles the *heterogeneous* challenge through standardized and interoperable geospatial web services and web APIs. Distributed geoprocessing addresses the *distributed* challenge by processing geospatial data and information in a distributed computing environment. The fundamental concepts, principles, and key techniques of the three technologies were elaborated in detail. Application examples in the context of Digital Earth were also provided to demonstrate how each technology has been used to support geospatial information processing. Although the three technologies are relatively mature and have a broad range of applications, research challenges have been identified and future research directions are envisioned for each technology to better support Digital Earth.

For high-performance computing (Sect. 6.2), one research challenge and direction is to continue the efforts to parallelize existing serial algorithms in spatial database and spatial data mining functions considering the dependence and interactions between data and problem partitions. Another direction is to develop new parallel algorithms to mine geospatial big data in the network space instead of in Euclidean space, as many spatial processes and interactions often occur in the network space. The third direction is to explore new and efficient computing methods to identify patterns from massive volumes of geospatial data considering the spatial heterogeneity. For online geoprocessing (Sect. 6.3), the main challenge is the lack of opacity in the services, data, and tool interfaces. This hinders the interoperability among the diverse services and creates a challenge when a problem needs to be solved by processing multi-sourced data using different services and tools. One promising solution is to incorporate semantics into web services to increase the interoperability among heterogeneous resources. In semantic web service research, three research directions are envisioned to achieve a semantically interoperable and intelligent Digital Earth: linked data and automated typing, automated workflow composition, and question answering. For distributed geoprocessing (Sect. 6.4), one challenge arises from reliability and security concerns. More efforts are needed to ensure a reliable and secure distributed computing environment considering aspects of the flow control, exception handling, compensation mechanism, and quality-aware service chains. The large volumes of geospatial data also lead to challenges in moving distributed data to the processing tools/services. Although moving code to data (code migration) is a promising solution, further research is needed to migrate code among the heterogeneous systems due to the complex dependency of software packages. In addition, more efforts are needed to move semantic-aided automatic service chaining techniques from the laboratory environment to real-world applications.

Lastly, the Digital Earth reference framework (Fig. 6.1) aims to integrate heterogeneous data sources with a harmonious high-level data model of the Earth so that data can be handled seamlessly with different tools, protocols, technologies. Currently, most of the tools use the framework of traditional coordinate systems such as the geographic coordinate system based on the continuous latitude and longitude or the projected coordinate system that projects the curved Earth surface to a flat surface. Although the traditional coordinate systems have been successful, another reference framework called the discrete global grid system (DGGS, see Chap. 2 *Digital Earth Platforms* for more details) is considered better for data associated with the curved heterogeneous surface of the Earth (Sabeur et al. 2019). We believe that the DGGS will play an increasingly important role in geospatial information processing in the big data era because (1) the DGGS provides a single and relatively simple framework for the seamless integration of heterogeneous distributed global geospatial data from different sources and domains; (2) the DGGS works with high-performance computing to handle big data extremely well because data managed with the DGGS is already decomposed into discrete domains and can be processed in parallel; and (3) by providing a single framework, the DGGS benefits interoperability among different tools and geoprocessing technologies and is a promising solution to build a semantically interoperable Digital Earth. However, most available analysis tools are designed to work with the traditional reference framework. Thus, more efforts are needed to design and develop storage mechanisms, spatiotemporal indexes, computing algorithms, and big data computing platforms that are compatible with the DGGS framework.

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Zhenlong Li is an Assistant Professor with the Department of Geography at the University of South Carolina, where he leads the Geoinformation and Big Data Research Laboratory. His primary research focuses on geospatial big data analytics, high performance computing, and CyberGIS with applications to disaster management, climate analysis, and human mobility. He serves as the Chair of the Association of American Geographers CyberInfrastructure Specialty Group.

Zhipeng Gui is Associate Professor of Geographic Information Science at School of Remote Sensing and Information Engineering, Wuhan University. His research interest is geospatial service chaining, high-performance spatiotemporal data mining and geovisual analytics. He serves as the Co-chair of International Society for Photogrammetry and Remote Sensing (ISPRS) Working Group V/4—Web-based Resource Sharing for Education and Research.

Barbara Hofer is GIScientist and works as Associate Professor at the Interfaculty Department of Geoinformatics—Z_GIS at the University of Salzburg, Austria. She is co-leader of the research group "geographic information infrastructure", which relates to her interest in the field of spatial data infrastructures, Digital Earth, online geoprocessing and reproducible research. Currently, Barbara also serves as councillor for AGILE—the Association of Geographic Information Laboratories in Europe.

Yan Li is a Ph.D. student in Computer Science at the University of Minnesota. His research interest includes spatial computing, data mining, and machine learning. He got his bachelor's degree in Remote Sensing at Wuhan University, China, and master's degree in Geography at the University of Tennessee.

Simon Scheider is an Assistant Professor in Geographic Information Science at the Department of Human Geography and Spatial Planning, University Utrecht. His research focuses on understanding the concepts underlying spatio-temporal data, including reference systems, fields, places, objects, events, trajectories and their relationship to human activities. He uses linked data and Semantic Web technology to support GIS analysts and to automate analytic workflows.

Shashi Shekhar is a Professor in Computer Science at the University of Minnesota. He is a spatial database and data mining researcher and a GeoInformatica co-Editor-In-Chief, co-authored a textbook Spatial Database, and co-edited an Encyclopedia of GIS. Honors include IEEE-CS Technical Achievement Award, AAAS Fellow, and IEEE Fellow.

Chapter 7
Geospatial Information Visualization and Extended Reality Displays

Arzu Çöltekin, Amy L. Griffin, Aidan Slingsby, Anthony C. Robinson, Sidonie Christophe, Victoria Rautenbach, Min Chen, Christopher Pettit and Alexander Klippel

Abstract In this chapter, we review and summarize the current state of the art in geovisualization and extended reality (i.e., virtual, augmented and mixed reality), covering a wide range of approaches to these subjects in domains that are related to geographic information science. We introduce the relationship between geovisualization, extended reality and Digital Earth, provide some fundamental definitions of related terms, and discuss the introduced topics from a human-centric perspective. We describe related research areas including geovisual analytics and movement visualization, both of which have attracted wide interest from multidisciplinary communities in recent years. The last few sections describe the current progress in the

A. Çöltekin (✉)
Institute for Interactive Technologies, FHNW University of Applied Sciences and Arts Northwestern Switzerland, Brugg-Windisch, Switzerland
e-mail: arzu.coltekin@fhnw.ch

A. L. Griffin
School of Science, RMIT University, Melbourne, Australia

A. Slingsby
Department of Computer Science, City University of London, London, UK

A. C. Robinson
Department of Geography, GeoVISTA Center, The Pennsylvania State University, University Park, USA

S. Christophe
University of Paris-Est, LASTIG GEOVIS, IGN, ENSG, 94160 Saint-Mandé, France

V. Rautenbach
Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Pretoria, South Africa

M. Chen
Key Laboratory of Virtual Geographic Environment, Ministry of Education of the People's Republic of China, Nanjing Normal University, Nanjing, China

C. Pettit
Cities Analytics Lab, UNSW, Sydney, Australia

A. Klippel
Department of Geography, The Pennsylvania State University, University Park, USA

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use of immersive technologies and introduce the spectrum of terminology on virtual, augmented and mixed reality, as well as proposed research concepts in geographic information science and beyond. We finish with an overview of "dashboards", which are used in visual analytics as well as in various immersive technologies. We believe the chapter covers important aspects of visualizing and interacting with current and future Digital Earth applications.

Keywords Visualization · Geovisualization · User-centric design · Cognition · Perception · Visual analytics · Maps · Temporal visualization · Immersive technologies · Virtual reality · Augmented reality · Mixed reality · Extended reality

7.1 Introduction

A future, fully functional Digital Earth is essentially what we understand as a (geo)virtual reality environment today: A multisensory simulation of the Earth *as-is* and how it *could be*, so we can explore it holistically, with its past, present, and future made available to us in any simulated form we wish (Gore 1998; Grossner et al. 2008). The concept of Digital Earth can be associated with the emergence of the (recently popularized) concept of a 'digital twin', conceptualized as a digital replica of a physical entity. Although several researchers have expressed skepticism about the appropriateness and precision of the term 'digital twin' in recent publications (Batty 2018; Tomko and Winter 2019), it appears that the broad usage of the term refers to a reasonably rigorous *attempt* to digitally replicate real-world objects and phenomena with the highest fidelity possible. Such efforts currently exist for objects at microscales, such as a wind turbines, engines, and bridges; but they are also envisioned for humans and other living beings. A digital twin for an entire city is more ambitious and requires information on the interoperability and connectivity of every object. A true 'all containing' Digital Earth is still unrealized and is more challenging to construct. However, as Al Gore (1998) noted in his original proposal for a Digital Earth in 1998, **making sense** of the information a Digital Earth contains is even more difficult than its construction. A key capability that supports sensemaking is the ability to **visualize geospatial information**. There are countless ways to visualize geospatial information. For thousands of years, humankind has used maps to understand the environment and find our way home. Today, there are many visual methods for depicting real, simulated, or fictional geospatial 'worlds'.

This chapter provides an overview of key aspects of visualizing geospatial information, including the basic definitions and organization of visualization-related knowledge in the context of a future Digital Earth. As understanding related human factors is necessary for any successful implementation of a visualization within the Digital Earth framework, we include a section on cognition, perception, and user-centered approaches to (geo)visualization. Because we also typically pose and answer analytical questions when we visualize information, we provide an overview of visual analytics; paying special attention to visualizing and analyzing temporal phenomena including movement because a Digital Earth would be clearly incomplete if it only comprises static snapshots of phenomena. After this examination of broader visualization-related concepts, because we conceptualize Digital Earth as a virtual environment, we pay special attention to how augmented (AR), mixed (MR), and virtual reality (VR) environments can be used to enable a Digital Earth in the section titled "Immersive Technologies—From Augmented to Virtual Reality". The Digital Earth framework is relevant to many application areas, and one of the foremost uses of the framework is in the domain of urban science. This is unsurprising given that 55 percent of the population now live in urban areas, with the proportion expected to increase to two-thirds of the population by 2050 (United Nations Population Division 2018). Urban environments are complex, and their management requires many decisions whose effects can cause changes in other parts of the urban environment, making it important for decision makers to consider these potential consequences. One way of providing decision makers with an overview of urban environments is through dashboards. Therefore, we feature "dashboards" and discuss the current efforts to understand how they fit within the construct of Digital Earth. We finish the chapter with a few concluding remarks and future directions.

7.2 Visualizing Geospatial Information: An Overview

Cartography is the process by which geospatial information has been typically visualized (especially in the pre-computer era), and the science and art of cartography remain relevant in the digital era. Cartographic visualizations are (traditionally) designed to facilitate **communication** between the mapmaker and map users. As a new approach to making sense of geospatial information in the digital era, specifically in the development of digital tools that help map readers interact with this information, the concept of **geovisualization** emerged (MacEachren 1994; Çöltekin et al. 2017, 2018) and widened our understanding of how maps could help make sense of a Digital Earth when used in an **exploratory** manner in addition to their role in communication. Thus, geovisualization is conceived as a process rather than a product, although the term is also commonly used to refer to any visual display that features geospatial information (maps, images, 3D models, etc.). In the geovisualization process, the emphasis is on information exploration and sensemaking, where scientists and other experts design and use "visual geospatial displays to explore data, and through that exploration to generate hypotheses, develop problem solutions and construct knowledge" (Kraak 2003a, p. 390) about a geographic location or geographic phenomenon. How these displays (and associated analytical tools) could be designed and used became a focus of scientific research within the International Cartographic Association's (ICA) *Commission on Visualization and Virtual Environments*, whose leaders described the term geovisualization as the "theory, methods and tools for visual exploration, analysis, synthesis, and presentation of geospatial data" (MacEachren and Kraak 2001, p. 3). Designing tools to support visualizing the geospatial information contained in a Digital Earth requires thinking about the data, representation of those data, and how users interact with those representations. Importantly, it requires the design of visual displays of geospatial information that can combine heterogeneous data from any source at a range of spatiotemporal scales (Nöllenburg 2007). To facilitate the ability to think spatially and infer spatiotemporal knowledge from a visualization, the visualization must also be usable, support users' tasks and needs, and enable users to interact with the data (Fuhrmann et al. 2005). Visualizations of geospatial data connect people, maps, and processes, "leading to enlightenment, thought, decision making and information satisfaction" (Dykes et al. 2005a, p. 4). Below, we describe three key areas of knowledge that support the design of visualizations with the goal of helping users make sense of the information that a Digital Earth contains. The **data** that are available for incorporation in a Digital Earth are increasingly heterogeneous and more massive than before. These complex, large datasets include both spatial and aspatial data, all of which must be combined, 'hybridized' (i.e., synthesized in meaningful ways), and **represented** within a visualization environment. Users expect to be able to visualize complex spatiotemporal phenomena to analyze and understand spatiotemporal dynamics and systems. To support them in this, considering **user interaction** and interfaces is necessary to develop and incorporate intuitive and innovative ways to explore visual displays. This is especially relevant to virtual and augmented reality, to facilitate exploration of data and experiencing spaces 'without hassle'.

Data A key goal of geovisualization is "to support and advance the individual and collective knowledge of locations, distribution and interactions in space and time" (Dykes et al. 2005b, p. 702). This remains a challenge due to increases in the diversity and quantity of data, users, and available visualization techniques and technologies (Griffin and Fabrikant 2012). The age of the data deluge (Bell et al. 2009) resulted in the generation of large quantities of spatial data (vector databases, maps, imagery, 3D models, numeric models, point clouds, etc.), as well as aspatial data (texts, stories, web data, photographs, etc.) that can be spatialized (Skupin and Buttenfield 1997). The 'covisualization' of those data together, such as in *multiple coordinated views* (or *linked* views, see Roberts 2007), is difficult due to their heterogeneity. This heterogeneity can be in the data's source, scale, content, precision, dimension, and/or temporality. The *visual integration* of such heterogeneous data requires the careful design of graphical representations to preserve the legibility of the data (Hoarau and Christophe 2017).

7.2.1 Representation

Bertin's seminal work (1967/1983) provides a conceptual framework, the visual variables, that allows for us to consider the graphical representation of geospatial information at a fundamental level (although it is important to note that Bertin's propositions were not evidence-based, it was rather based on intuition and qualitative reasoning). Originally, Bertin proposed seven variables: position, size, shape, color value, color hue, orientation, and texture. Later work extended Bertin's framework to include dynamic variables such as movement, duration, frequency, order, rate of change, synchronization, (Carpendale 2003; DiBiase et al. 1992; MacEachren 1995) and variables for 3D displays such as perspective height (Slocum et al. 2008), camera position, and camera orientation (Rautenbach et al. 2015). Visual variables remain relevant as a core concept of visualization research and have generated renewed interest in digital-era research questions, including in fields beyond geovisualization (e.g., Mellado et al. 2017). Notably, the information visualization community has also embraced Bertin's visual variables (e.g., Spence 2007). Visual complexity is a major challenge in designing representations of geospatial data, and innovative measures and analysis methods have been proposed to address this problem (Fairbairn 2006; Li and Huang 2002; MacEachren 1982; Schnur et al. 2010, 2018; Touya et al. 2016). Digital Earth's 'big data' challenges these efforts, stretching the capacity of existing tools to handle and process such datasets as well as the capacity of visualization users to read, understand, and analyze them (Li et al. 2016). One application area that is particularly afflicted by visual complexity is research on the urban and social dynamics that drive spatiotemporal dynamics in cities (Brasebin et al. 2018; Ruas et al. 2011). Developing approaches to represent spatiotemporal phenomena has been a long-standing challenge and many options have been investigated over the years (Andrienko and Andrienko 2006). Despite some progress, many questions remain (see the "Visualizing Movement" section). Some potential solutions such as using abstraction and schematization when visualizing urban datasets in Digital Earth can be found in the fields of data and information visualization (Hurter et al. 2018).

Another key aspect of visual representation design for geospatial data in Digital Earth applications involves how to deal with uncertainty. Uncertainty, such as that related to data of past or present states of a location or models of potential future states, remains difficult to represent in visual displays, and this is a major challenge for geovisualization designers. Which visual variables might aid in representing uncertainty? This question has been explored and tested to some degree (e.g., MacEachren et al. 2012; Slocum et al. 2003; Viard et al. 2011), although the majority of research has focused on developing new visualization methods rather than testing their efficacy (Kinkeldey et al. 2014). There are still no commonly accepted strategies for visualizing uncertainty that are widely applied. MacEachren (2015) suggests that this is because data uncertainty is only one source of uncertainty that affects reasoning and decision making and argues that taking a visual analytics approach (see the "Geovisual Analytics" section) might be more productive than a communication approach. Hullman (2016) notes the difficulty of evaluating the role of uncertainty in decision making as a major barrier to developing empirically validated techniques to represent uncertainty.

7.2.2 User Interaction and Interfaces

Since geovisualization environments are expected to provide tools and interaction modalities that support data exploration, user interaction and interface design are important topics for geovisualization. The visual display is an interface for the information, so users need effective ways to interact with geovisualization environments. Interaction modalities in geovisualization environments are ideally optimized or customizable for the amount of data, display modes, complexity of spaces or phenomena, and diversity of users (e.g., Hoarau and Christophe 2017). Interaction tools and modalities are a core interest in human-computer interaction (e.g., Çöltekin et al. 2017) and, in connection with visualization, they are often investigated with concepts explored in the information visualization domain (Hurter 2015; van Wijk and Nuij 2003), among others. Interaction and how it is designed are especially relevant for virtual and augmented reality approaches to visualization (see the "Immersive Technologies—From Augmented to Virtual Reality" section). Some form of interaction is required for most modern 2D displays, and it has a very important role in supporting exploration tasks, but seamless interaction is a necessity in a virtual or augmented world. Without it, the immersiveness of the visualization—a critical aspect of both VR and AR—is negatively affected. One approach that is notably at the intersection of representation design and user interaction design is a set of methods that are (interactively) nonuniform or space-variant. An example is displays in which the resolution or level of detail varies across the display in real time according to a predefined criterion. The best known among these nonuniform display types are the focus + context and fisheye displays (dating back to the early 1990s, e.g., see Robertson and Mackinlay 1993). Both the focus + context and fisheye displays combine an overview at the periphery with detail at the center, varying the level of detail and/or scale across a single display. A variation on the focus + context display has been named "context-adaptive lenses" (Pindat et al. 2012). Conceptually related to these approaches, in gaze-contingent displays (GCDs), the level of detail (and other selected visual variables) is adapted across the display space based on where the user is looking. This approach draws on perceptual models of the visual field, mimicking the human visual system. GCDs were proposed as early as the 1970s (see, e.g., Just and Carpenter 1976) and have continued to attract research interest over time as the technology developed (e.g., Bektas et al. 2015; Duchowski and Çöltekin 2007; Duchowski and McCormick 1995). For more discussion of "interactive lenses" in visualization, see the recent review by Tominski et al. (2017). Various other space-variant visualization approaches have been proposed in which, rather than varying the scale or level of detail, the levels of realism or generalization are varied across the display to support focus + context interactions with the data. These approaches aim to smoothly navigate between data and its representation at one scale (e.g., Hoarau and Christophe 2017), between different levels of generalization across scales (e.g., Dumont et al. 2018), or between different rendering styles (Boér et al. 2013; Semmo and Döllner 2014; Semmo et al. 2012). Mixed levels of realism have been proposed for regular maps used for data exploration purposes (Jenny et al. 2012) as well as for VR. In VR, egocentric-view-VR representations with selective photorealism (a mix of abstract and photorealistic representations) have been tested in the context of route learning, memory, and aging and have been shown to benefit users (Lokka et al. 2018; Lokka and Çöltekin 2019).

Decisions on how to combine data to design representations and user interactions should be informed by our understanding of how visualization users process visual information and combine it with their existing knowledge about the location or phenomenon to make sense of what they see. Thus, building effective visualizations of geospatial information for a Digital Earth requires an understanding of its **users**, their capabilities and their constraints, which we describe in the next section.

7.3 Understanding Users: Cognition, Perception, and User-Centered Design Approaches for Visualization

A primary way that humans make sense of the world—the real world, an "augmented world" with additional information overlaid, or a virtual word (such as a simulation)—is by making sense of what we see. Because vision is so important to human sense-making, visualizations are major facilitators of that process and provide important support for cognition. When effectively designed, visualizations enable us to externalize some of the cognitive burden to something we can (re)utilize through our visual perception (Hegarty 2011; Scaife and Rogers 1996). However, our ability to *see* something—in the sense of *understanding* it—is bounded by our perceptual and cognitive limits. Thus, any visualizations we design to help work with and understand geospatial information must be developed with the end user in mind, taking a **user-centered design (UCD)** approach (Gabbard et al. 1999; Huang et al. 2012; Jerald 2015; Lloyd and Dykes 2011; Robinson et al. 2005). A UCD approach is useful for understanding perceptual and cognitive limits and for adapting the displays to these limits. It also helps to evaluate the strengths of new methods of interacting with visualizations (Roth et al. 2017). For example, a user-centered approach has been used to demonstrate that an embodied data axis aids in making sense of multivariate data (Cordeil et al. 2017). Similarly, UCD was useful in determining which simulated city environments lead to the greatest sense of immersion to support participatory design processes for smart cities (Dupont et al. 2016), assuming that immersion has a positive effect in this context.

7.3.1 Making Visualizations Work for Digital Earth Users

7.3.1.1 Managing Information

As briefly noted earlier, a key benefit—and a key challenge—for visualization in the Digital Earth era is related to the amount of data that is at our fingertips (Çöltekin and Keith 2011). With so much available data, how can we make sense of it all? What we need is the right information in the right place at the right time for the decisions we are trying to make or the activities we are trying to support. Thus, understanding the context in which information and visualizations of information are going to be used (Griffin et al. 2017)—what data, by whom, for what purpose, on what device—is fundamental to designing appropriate and effective visualizations. For example, ubiquitous sensor networks and continuous imaging of the Earth's surface allow for us to collect real-time or near real-time spatial information on fires and resources available to fight fires, and firefighters would benefit from improved situation awareness (Weichelt et al. 2018). However, which information should we show them, and how should it be shown? Are there environmental factors that affect what information they can perceive and understand from an AR system that visualizes important fire-related attributes (locations of active burns, wind speed and direction) and firefighting parameters (locations of teammates and equipment, locations of members of the public at risk)? How much information is too much to process and use effectively at a potentially chaotic scene?

A great strength of visualization is its ability to abstract: to remove detail and to reveal the essence. In that vein, realism as a display principle has been called "naive realism" because realistic displays sometimes impair user performance but users still prefer them (e.g., Lokka et al. 2018; Smallman and John 2005). The questions of how much abstraction is needed (Boér et al. 2013; Çöltekin et al. 2015) and what level of realism should be employed (Brasebin et al. 2018; Ruas et al. 2011) do not have clear-cut answers. In some cases, we need to follow the "Goldilocks principle" because too much or too little realism is suboptimal. As Lokka and Çöltekin (2019) demonstrated, if there is too much realism, we may miss important details because we cannot hold all the details in our memory whereas if there is too little, we may find it difficult to learn environments because there are too few 'anchors' for the human memory to link new knowledge of the environment. These issues of how to abstract data and how it can be effectively visualized for end users are growing in the era of big data and Digital Earth.

7.3.1.2 Individual and Group Differences

Nearly two decades ago, Slocum et al. (2001) identified individual and group differences as a research priority among the many "cognitive and usability issues in geovisualization" (as the paper was also titled). There was evidence prior to their

2001 paper and has been additional evidence since then that humans process information in a range of ways. Such differences are often based on expertise or experience (e.g., Griffin 2004; Çöltekin et al. 2010; Ooms et al. 2015) or spatial abilities (e.g., Liben and Downs 1993; Hegarty and Waller 2005), and are sometimes based on age (Liben and Downs 1993; Lokka et al. 2018), gender (Newcombe et al. 1983); culture (Perkins 2008), confidence and attitudes (e.g., Biland and Çöltekin 2017), or anxiety (Thoresen et al. 2016), among other factors. For brevity, we do not expand on the root causes of these differences, as this would require a careful treatment of the "nature vs. nurture" debate. We know that many of the shortcomings people experience can be remedied to different degrees based on interventions and/or training. For example, spatial abilities, as measured in standardized tests, can be enhanced by training (Uttal et al. 2013), and expertise/experience and education affect the ways that people process information (usually in improved ways, but these forms of knowledge can also introduce biases). Many of the above factors could be considered cognitive factors and might be correlated in several ways. A key principle arising from the awareness that individuals process information differently and that their capacities to do so can vary (whatever the reason) is that the "*designer is not the user*" (Richter et al. 2015, p. 4). A student of geovisualization (we include experts in this definition) is a self-selected individual who was likely interested in visual information. With the addition of education to this interest, it is very likely that a design that a geovisualization expert finds easy-to-use (or "user friendly", a term that is used liberally by many in the technology sector) will not be easy-to-use or user friendly for an inexperienced user or a younger/older user.

7.3.1.3 Accessibility

Related to the individual and group differences as described above, another key consideration is populations with special needs. As in any information display, visualization and interaction in a geovisualization software environment should ideally be designed with accessibility in mind. For example, visually impaired people can benefit from multimedia augmentation on maps and other types of visuospatial displays (Brock et al. 2015; Albouys-Perrois et al. 2018). Another accessibility issue linked to (partial) visual impairment that is widely studied in geovisualization is color vision impairment. This is because color is (very) often used to encode important information and color deficiency is relatively common, with up to eight percent of the world's population experiencing some degree of impairment (e.g., Brychtová and Çöltekin 2017a). Because it is one of the more dominant visual variables (Garlandini and Fabrikant 2009), cartography and geovisualization research has contributed to color research for many decades (Brewer 1994; Brychtová and Çöltekin 2015; Christophe 2011; Harrower and Brewer 2003). Two of the most popular color-related applications in use by software designers were developed by cartography/geovisualization researchers: ColorBrewer (Harrower and Brewer 2003) for designing/selecting color palettes and ColorOracle (Jenny and Kelso 2007) for simulating color blindness. Color is a complex and multifaceted phenomenon even for those who are not affected by color vision impairment. For example, there are perceptual thresholds for color discrimination that affect everyone (e.g., Brychtová and Çöltekin 2015, 2017b), and how colors are used and organized contributes to the complexity of maps (e.g., Çöltekin et al. 2016a, b). Color-related research in geographic information science also includes examination of the efficacy of color palettes to represent geophysical phenomena (Spekat and Kreienkamp 2007; Thyng et al. 2016) or natural color maps (Patterson and Kelso 2004). We include color in the above discussion because it is one of the strongest visual variables. However, color is not the only visual variable of interest to geovisualization researchers. Many other visual variables have been examined and assessed in user studies. For example, the effects of size (Garlandini and Fabrikant 2009), position, line thickness, directionality, color coding (Monmonier 2018; Brügger et al. 2017), shading, and texture (Biland and Çöltekin 2017; Çöltekin and Biland 2018) on map reading efficiency have been examined.

It is not possible to provide an in-depth review of all the user studies in the geovisualization domain within the scope of this chapter. However, it is worth noting that if a design maximizes accessibility, the users benefit and the (consequently) improved usability of visuospatial displays enables other professionally diverse groups to access and create their own visualizations: for example, city planners, meteorologists (e.g., Helbig et al. 2014) and ecoinformatics experts (e.g., Pettit et al. 2010), all of which are support systems of a 'full' future Digital Earth.

7.4 Geovisual Analytics

The science of analytical reasoning with spatial information using interactive visual interfaces is referred to as **geovisual analytics** (Andrienko et al. 2007; Robinson 2017). This area of GIScience emerged alongside the development of **visual analytics**, which grew out of the computer science and information visualization communities (Thomas and Cook 2005). A key distinction of geovisual analytics from its predecessor field of geovisualization is its focus on support for analytical reasoning and the application of computational methods to discover interesting patterns from massive spatial datasets. A primary aim of geovisualization is to support data exploration. Geovisual analytics aims to go beyond data exploration to support complex reasoning processes and pursues this aim by coupling computational methods with interactive visualization techniques. In addition to the development of new technical approaches and analytical methods, the science of geovisual analytics also includes research aimed at understanding how people reason with, synthesize, and interact with geographic information to inform the design of future systems. Progress in this field has been demonstrated on each of these fronts, and future work is needed to address the new opportunities and challenges presented by the big data era and meeting the vision proposed for Digital Earth.

7.4.1 Progress in Geovisual Analytics

Early progress in geovisual analytics included work to define the key research challenges for the field. Andrienko et al. (2007) called for decision making support using space-time data, computational pattern analysis, and interactive visualizations. This work embodied a shift from the simpler goal of supporting data exploration in geovisualization toward new approaches in geovisual analytics that could influence or direct decision making in complex problem domains. Whereas the goal in geovisualization may have been to prompt the development of new hypotheses, the goal in geovisual analytics has become to prompt decisions and actions. To accomplish this goal, GIScience researchers began to leverage knowledge from intelligence analysis and related domains in which reasoning with uncertain information is required to make decisions (Heuer 1999; Pirolli and Card 2005). Simultaneously, there were efforts to modify and create new computational methods to identify patterns in large, complex data sources. These methods were coupled to visual interfaces to support interactive engagement with users. For example, Chen et al. (2008) combined the SaTScan space-time cluster detection method with an interactive map interface to help epidemiologists understand the sensitivity of the SaTScan approach to model parameter changes and make better decisions about when to act on clusters that have been detected. Geovisual analytics have been applied in a wide range of domain contexts, usually targeting data sources and problem areas that are difficult to approach without leveraging a combination of computational, visual, and interactive techniques. Domains of interest have included social media analytics (Chae et al. 2012; Kisilevich et al. 2010), crisis management (MacEachren et al. 2011; Tomaszewski and MacEachren 2012), and movement data analysis (Andrienko et al. 2011; Demšar and Virrantaus 2010). The following section on "Visualizing Movement" includes a deeper treatment of the approaches to (and challenges of) using visual analytics for dynamic phenomena.

A concurrent thread of geovisual analytics research has focused on the design and evaluation of geovisual analytics tools. In addition to the development of new computational and visual techniques, progress must also be made in understanding how geovisual analytics systems aid (or hinder) the analytical reasoning process in real-world decision making contexts (Çöltekin et al. 2015). Approaches to evaluating geovisual analytics include perceptual studies (Çöltekin et al. 2010), usability research (Kveladze et al. 2015), and in-depth case study evaluations of expert use (Lloyd and Dykes 2011). Additionally, new geovisual analytics approaches have been developed to support such evaluations (Andrienko et al. 2012; Demšar and Çöltekin 2017), as methods such as eye tracking are capable of creating very large space-time datasets that require combined computational and interactive visual analysis to be made sense of.

7.4.2 *Big Data, Digital Earth, and Geovisual Analytics*

The next frontier for geovisual analytics is to address the challenges posed by the rise of big spatial data. **Big data** are often characterized by a set of so-called *V's*, corresponding to the challenges associated with volume, velocity, variety, and veracity, among others (Gandomi and Haider 2015; Laney 2001). Broadly, geovisual analytics approaches to handling big spatial data need to address problems associated with analysis, representation, and interaction (Robinson et al. 2017), similar to the challenges faced by geovisualization designers. New computational methods are needed to support real-time analysis of big spatial data sources. Representations must be developed to render the components and characteristics of big spatial data through visual interfaces (Çöltekin et al. 2017). We also need to know more about how to design interactive tools that make sense to end users to manipulate and learn from big spatial data (Griffin et al. 2017; Roth et al. 2017).

The core elements behind the vision for Digital Earth assume that big spatial data will exist for every corner of our planet, in ways that support interconnected problem solving (Goodchild et al. 2012). Even if this vision is achieved (challenging as that may seem), supporting the analytical goals of Digital Earth will require the development of new geovisual analytics tools and techniques. Major issues facing humanity today regarding sustainable global development and mitigating the impacts of climate change necessarily involve the fusion of many different spatiotemporal data sources, the integration of predictive models and pattern recognition techniques, and the translation of as much complexity as is possible into visual, interactive interfaces to support sensemaking and communication.

7.5 Visualizing Movement

One of the most complex design issues in visualization is how to deal with dynamic phenomena. Movement is an inherent part of most natural and human processes, including weather, geomorphological processes, human and animal mobility, transport, and trade. We may also be interested in the movement of more abstract phenomena such as ideas or language. Although movement is a complex spatiotemporal phenomenon, it is often depicted on static maps, emphasizing *geographical* aspects of movement. In the context of visualization, "Digital Earth" implies use of a globe metaphor, where movement data is displayed on a globe that can be spun and zoomed (see Fig. 7.1). In this section, we review *map-based* representations of movement that can be used within a 3D globe-based immersive environment. Visual representations that do not emphasize geographical location (e.g., origin-destination matrices and various timeline-based representations) are less amenable to being used within a global immersive environment, though they may have a supporting role as multiple coordinated views.

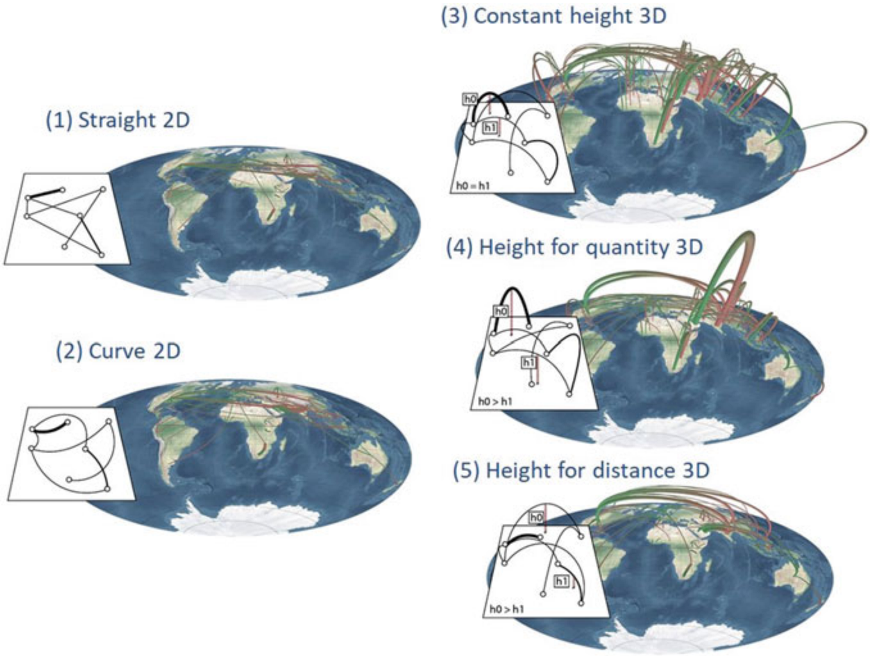

Fig. 7.1 Approaches to visualizing flows in a 3D immersive environment that were investigated by Yang et al. (2019). Figure is modified based on Yang et al. (2019) with permission from the original authors

Note that most techniques for visualizing movement on the Earth's surface were developed as *2D* representations. However, many of these representations can be placed on the surface of a 3D globe and we can identify where the 3D environment may offer benefits and disadvantages. Notably, one disadvantage is that 3D environments often result in occlusion, and this occlusion is only partially addressed through interaction (Borkin et al. 2011; Dall'Acqua et al. 2013). Below, we begin by visually depicting *individual* journeys and progressively review *aggregated* movement data representations, which are more scalable and can synthesize and reveal general movement patterns (the individual trajectories cannot).

7.5.1 Trajectory Maps: The Individual Journey

Individual journeys can be expressed as **trajectories** that represent the geometrical paths (routes) of objects through time as a set of timestamped positions. For example, if we were interested in migrating birds, GPS loggers attached to individual birds could produce trajectories (see Fig. 7.2 for an example). These may help understand the route taken, stop-overs, timing, and interactions between individuals. The detail

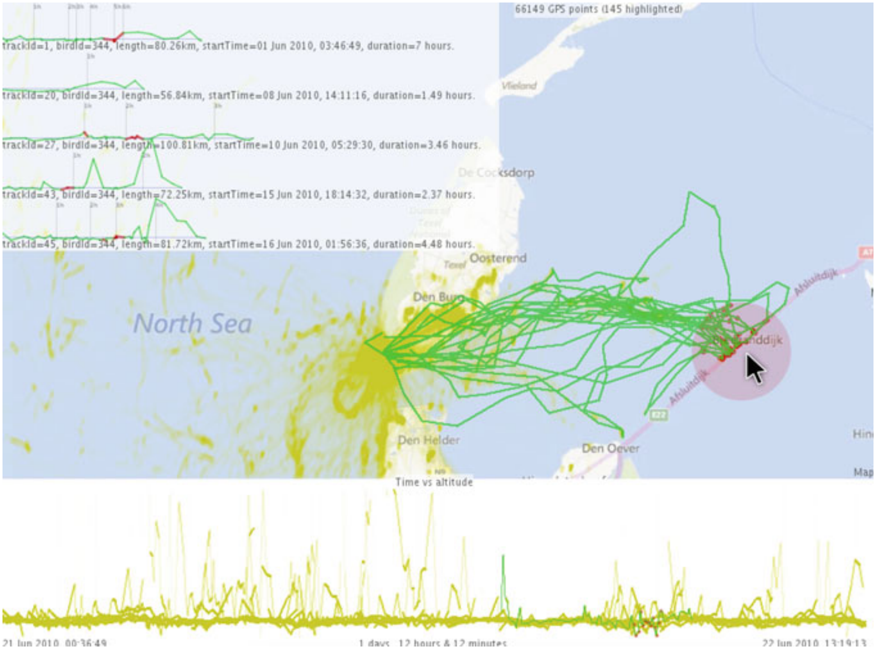

Fig. 7.2 A (green) subset of bird tracked trajectories filtered on the spatial region on the map indicated by the red circle linked to the mouse pointer. These trajectories are identified in green on the timeline below (time vs altitude), indicating when the journeys occurred, with five of the journeys shown at the top left (time vs distance, with hourly isochrones). Figure is modified, based on Slingsby and van Loon (2016) with permission from the original authors

with which the geometrical path is captured depends on the temporal resolution of the sampled locations. Trajectories can also be reconstructed by stringing together locations from other sensors, for example, from multiple cameras with automatic license plate recognition or from a set of georeferenced tweets from a single user. One aspect of trajectories that is often overlooked is how they are **segmented**, that is, where they start and stop over the course of the journey. For tracked animals, algorithms that segment trajectories based on position or time intervals during which where there is little movement are common (e.g., Buchin et al. 2011). In the example above (Fig. 7.2), the nest location was used to segment trajectories into foraging trips.

Trajectory maps depict individual movement by showing the geometrical traces of individual journeys on a map. Where there are few trajectories, trajectory maps can clearly illustrate specific journeys and facilitate visual comparison within an individual's journeys or between journeys undertaken by different individuals. An excellent book by Cheshire and Umberti (2017) uses a whole range of static visualization methods to illustrate the movements of various types of animals, including trajectory maps. As well as presenting movement traces, trajectory maps can be a useful precursor to more substantial and directed analyses (Borkin et al. 2011; Dall'Acqua et al. 2013).

Map-based representations emphasize the **geometry** of the path, and it can be difficult to use maps to determine **temporal** aspects of the trajectory, including direction and speed. One option is to use **animation**, which only displays the parts of trajectories that are within a moving temporal window. Although animation may be effective when presented as part of an existing narrative, it can be difficult to detect trends as it is hard to remember what came before (Robertson et al. 2008). Various user studies have investigated animation and its efficiency and effectiveness for spatiotemporal tasks, with mixed results. The current understanding is that animations can introduce too much cognitive load if the task requires comparisons, thus, animations must be used cautiously (Robertson et al. 2008; Russo et al. 2013; Tversky et al. 2002). So-called **small multiples** (a series of snapshots, see Tufte 1983) can be better than animations for some tasks. Another option that is similar to small multiples in the sense that all of the presented information is visible at all times or is easily on demand is the use of **multiple coordinated views** (briefly introduced above). With multiple coordinated views, a temporal representation of the movement is interactively linked to the map. When the mouse is "brushed" over parts of the trajectory on the map, corresponding parts on the timeline are identified and vice versa (as shown in Fig. 7.2). **Brushing** along the timeline has a similar effect as animation but is more flexible. Although trajectory maps can be good to represent relevant individual instances of journeys, they **do not scale well** to situations where there are more than a few trajectories. The effect of over plotting with multiple crossing lines often obscures patterns. Making trajectories **semitransparent** can help to some degree, as it emphasizes common sections of routes by de-emphasizing those that are less commonly used. Modifying the color hue—and/or other visual variables or symbols—can help **identify individuals** or **categories of journeys** (which might include the purpose of the journey or mode of transport). Hue typically does not facilitate distinguishing more than approximately ten individuals or categories, but **labels** and **tooltips** can provide such context. Sequential color schemes can indicate continuous numerical data along trajectories such as **speed** or **height** above the ground. Arrows or tapered lines can help show the direction of movement. To simplify displays, one can also attempt to simplify the underlying data rather than tweak the display design. Common approaches include **filtering trajectories** by various criteria, **considering only origin-destination pairs**, or **spatiotemporal aggregation** (we elaborate on these approaches below). Trajectory maps can also be shown in a **3D environment**. **Space-time cubes** (Hägerstrand 1970) are a form of 3D trajectory map (Andrienko et al. 2003; Kapler and Wright 2004; Kraak 2003b) where the *x*- and *y*-axes represent geographical coordinates and the ***z*-axis represents the progression of time** (see Fig. 7.3 for an example). As with trajectory maps, space-time cubes can indicate spatiotemporal aspects of small numbers of journeys. However, when more trajectories are added, the occluding effects can be even more severe than in 2D. Interactive rotation and zooming of the cube, highlighting trajectories, and interactive filtering can address the problematic effects of such occlusion but do not scale well to many trajectories.

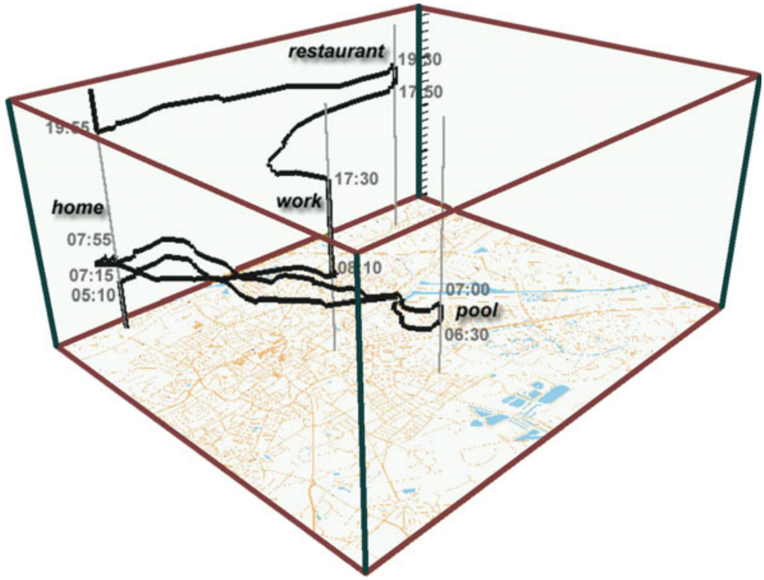

Fig. 7.3 A Space-Time Cube, showing a journey in which a person visits a pool, home, work, a restaurant and home. Figure based on Kraak (2008) with permission from the original author

In 3D representations, the ***z*-axis can also be used for nontemporal data**, which may create a conflict. Where trajectories define movement in 3D space, the z-axis can be used to represent a third spatial dimension, that is, it can be used to depict the **height above the ground**. There are also many opportunities to depict other characteristics of trajectories along the z-axis, as illustrated by the "trajectory wall" (Tominski et al. 2012) shown in Fig. 7.4.

Because the above approaches do not scale well when there are many trajectories, we must consider simplifying the data and display, such as by **filtering** the data. Notably, filtering serves *two* purposes. The first addresses the fact that trajectory maps do not scale well in situations in which there are more than a few trajectories. The second is to **identify multiple trajectories or groups of trajectories for comparison**. Tobler (1987) suggested **subsetting** and **thresholding** to reduce the number of trajectories on a single map. This involves filtering on the basis of characteristics of trajectories, such as using geographical (see Fig. 7.5 below) and temporal windows (see Fig. 7.7) through which trajectories can pass or filtering the trajectory's length, importance, or category. These are now routinely facilitated using interactive methods that support visual exploratory data analysis. Identifying multiple trajectories or groups of trajectories for comparison includes choosing representative trajectories for a set of people or different times of the day or different days of the week. This identification of trajectories may be manually achieved as part of an exploratory analysis or geovisualization approach and can be assisted by

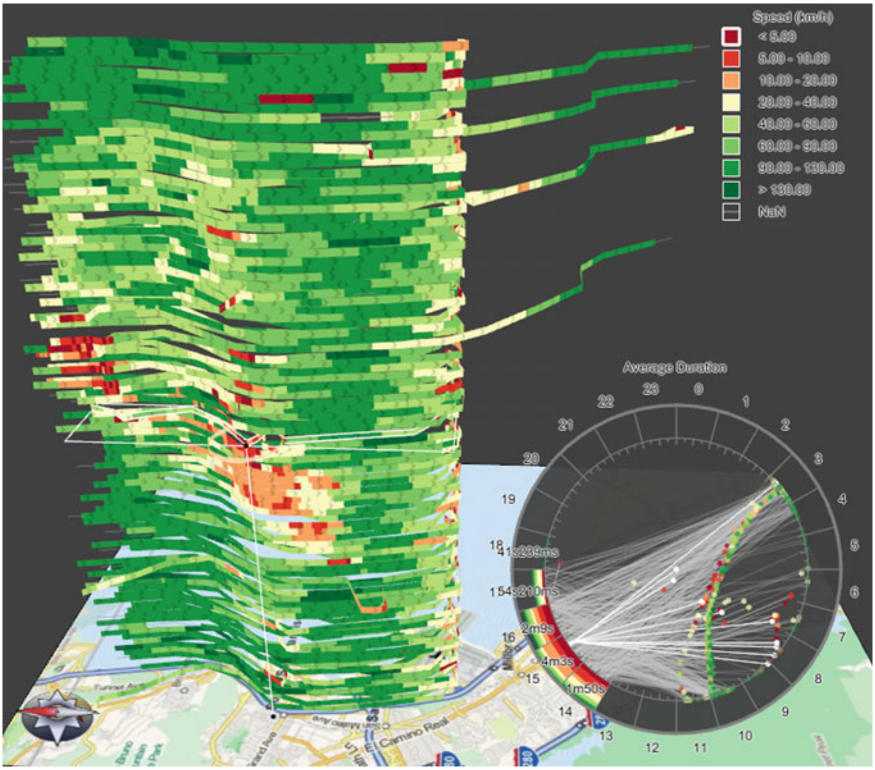

Fig. 7.4 “Trajectory wall” in which multiple (and sometimes time-varying) attributes are displayed vertically along a trajectory, based on Tominski et al. (2012), with permission from the original authors

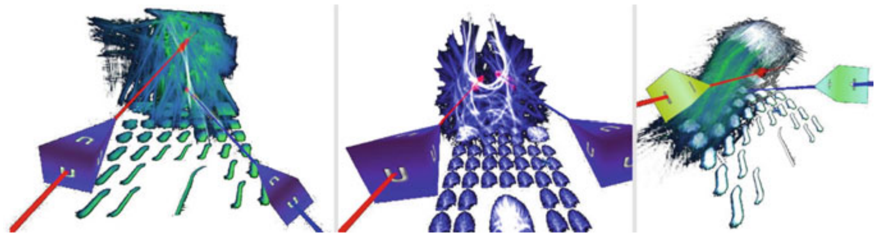

Fig. 7.5 Hurter et al.’s (2018) interactions in a 3D immersive environment to explore and filter a huge set of trajectories. Figure based on Hurter et al. (2018), with permission from the original authors

statistical and data mining techniques in a geovisual analytics approach. For example, "K-means" clustering can be used to group trajectories into "clusters" (based on a chosen metric of trajectory similarity) and representative trajectories can be compared (Andrienko and Andrienko 2011). Visualization techniques that facilitate such comparisons are simply **switching between** displaying trajectories or groups of trajectories by using interactive brushing, **superpositioning** (where trajectories are displayed on the same map), or **juxtaposition**, where maps of groups of trajectories are displayed side-by-side using small multiples (Tufte 1983).

In summary, trajectory maps are good for showing detailed examples of journeys but do not scale well to more than a few trajectories. Characteristics of these individual trajectories can be explored through multiple coordinated views with brushing. Trajectories are often displayed in maps in 2D, but 3D space-time cubes are also common. Overplotting many trajectories with semitransparent lines can help indicate parts of routes that are commonly taken, and a selected trajectory can be highlighted using a visual variable if there is a reason to emphasize a particular trajectory. In addition, trajectories can be filtered, grouped, and visually compared. For higher-level pattern identification, it is helpful to perform some aggregation, as discussed in the next section.

7.5.2 Flow Maps: Aggregated Flows Between Places

Flow maps depict movement between locations or regions. Unlike trajectory maps, they typically do not represent the route or path taken. This is suitable for cases in which there are **origin-destination pairs**; for example, county-country migrations (Fig. 7.6) and public bike hire journeys taken between pairs of bike docking stations (Fig. 7.7).

Tobler's (1987) early flow maps connected locations with **straight lines**. However, **curved lines** help reduce the undesirable occluding effects of line crossings. Jenny et al. (2018) provide a comprehensive set of guidelines for designing flow maps. Wood et al. (2011) also used curved lines to distinguish and visually separate flow in either direction, using asymmetry in the curve to indicate direction (Fig. 7.7). Yang et al. (2019) provide specific guidance for designing flow maps on (**3D**) digital **globes**. They recommend taking advantage of the *z*-axis to design flows with **3D curvature** to help reduce clutter and make the maps more readable and provide evidence-based advice for displaying flows on 3D globes.

A characteristic of flow data is that it is usually **aggregated**, with the number of flows between origin-destination pairs reported. This is facilitated by the fact that there are often a finite number of spatial units (origins and destinations), as is the case for bike docking stations or country-country migration data. This makes them more scalable but, as shown in Fig. 7.6 (Wood et al. 2011), flow maps can have clutter and occlusion issues similar to those observed in trajectory maps. These can be partially addressed by filtering as in trajectory maps, but because flows are usually already aggregated, filtering by geographical area is likely to reduce such

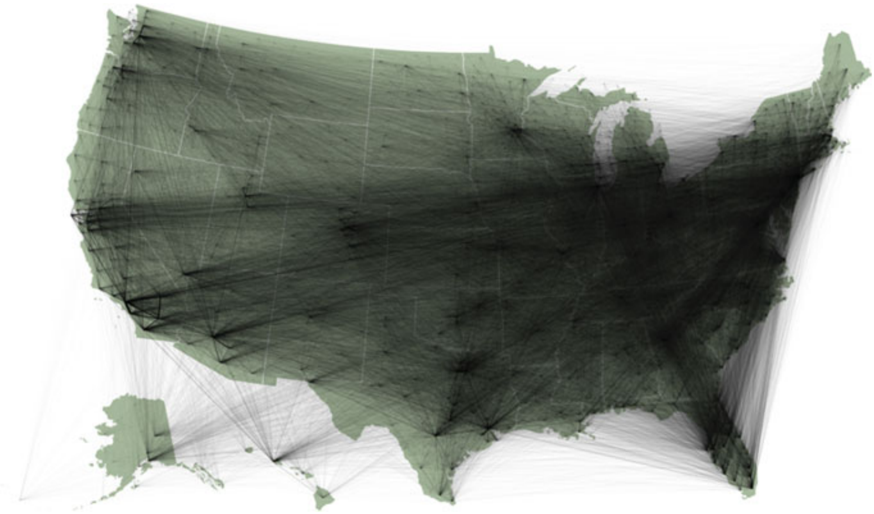

Fig. 7.6 20,000 county-county US migration vectors (3% random sample) between 2012 and 2016, rendered with transparency and anti-aliasing to show 'occlusion density'. Figure based on Wood et al. (2011), redrawn by Jo Wood using data from https://vega.github.io/vega-lite/data/us-10m.json and https://gicentre.github.io/data/usCountyMigration2012_16.csv

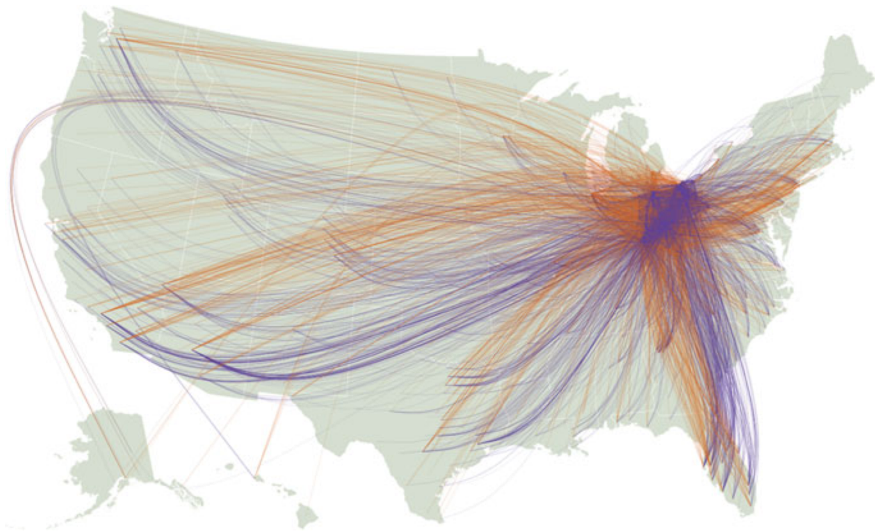

Fig. 7.7 As in Fig. 7.6, but clutter is reduced by filtering county-county flows to and from Ohio (orange and purple, respectively), where line thickness is proportional to volume and curved lines allow directions to be distinguished and reduce occlusion. Produced by Jo Wood using data from https://vega.github.io/vega-lite/data/us-10m.json and https://gicentre.github.io/data/usCountyMigration2012_16.csv

clutter more effectively to make patterns visible and interpretable (Andrienko and Andrienko 2011) [see the geographical filtering in the green trajectories shown in Fig. 7.2]. There are other ways to reduce clutter and provide more interpretable visual representations of movements, for example, by employing **spatial aggregation** or applying **edge bundling.**

7.5.2.1 Spatial Aggregation of Flows

Spatial aggregation reduces the geographical precision of movement but benefits visualization. In Fig. 7.6, although the US county-county migration data is already aggregated by county pair, further aggregating the state-state migration would produce a more interpretable graphic. However, this additional aggregation is at the expense of being able to resolve differences within states. In this example, we suggested aggregating the input data by pairs of **existing defined regions** (counties and states), but the data can also be aggregated into pairs of **data-driven irregular tessellations** (e.g., Voronoi polygons, Fig. 7.8) or **regular tessellations** (e.g., grid cells). **Flows can also be generated from full trajectory data** (see the above section) by aggregating the start and end points to spatial units, provided they have meaningful start and end points. When performing spatial aggregation, it is typical to disaggregate by temporal unit (e.g., year) and/or by categorical attribute (e.g., gender). This enables comparison of temporal and other attributes, for example, using small multiples as described in the previous section (e.g., Fig. 7.7 could be arranged in small multiples by the hour of the day).

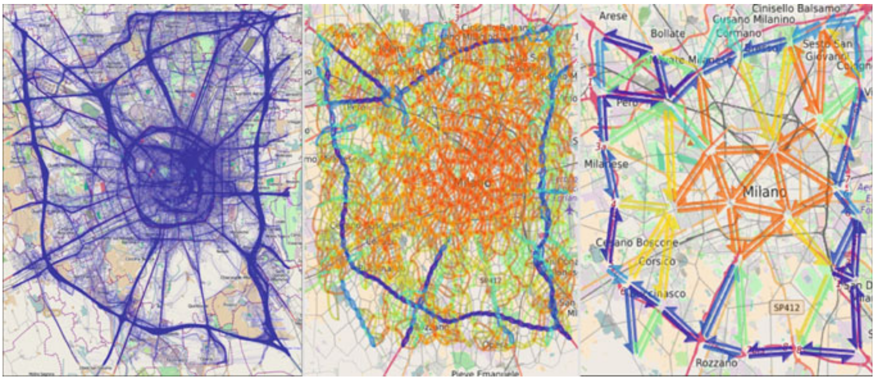

Fig. 7.8 Aggregating flows into data-driven Voronoi polygons. **Left**: Car journey trajectory data, using transparency to reduce clutter and occlusion. **Middle and right**: Aggregated flows into data-driven Voronoi polygons of different scales. Figure based on Andrienko and Andrienko (2011) with permission from the original authors

7.5.2.2 Edge Bundling of Flows

Edge bundling is a class of techniques designed to layout flows in interpretable ways, by 'bundling' parts of different flows that go in different directions (see the example in Fig. 7.9). Bundling techniques are used to reduce occlusion and convey the underlying movement structure (Holten and van Wijk 2009; Fig. 7.10). Jenny et al. (2017) provide an algorithm to facilitate this. For cases with a specific origin or destination of interest, Buchin et al. (2011) suggest an algorithm that aggregates flows into a tree-like representation that clarifies the flow structure (Fig. 7.11).

7.5.3 Origin-Destination (OD) Maps

OD maps (Wood et al. 2011) are also an important tool. They aggregate flows into a relatively small number of spatial units based on existing units (e.g., states) or those that result from a Voronoi- or grid-based tessellation. OD maps are effectively small

Fig. 7.9 Examples of origin-destination maps that are subsetted on a single origin and where an aggregated tree layout simplifies the visual complex complexity of flows to multiple destinations (Buchin et al. 2011). Figure based on Buchin et al. (2011), with permission from the original authors

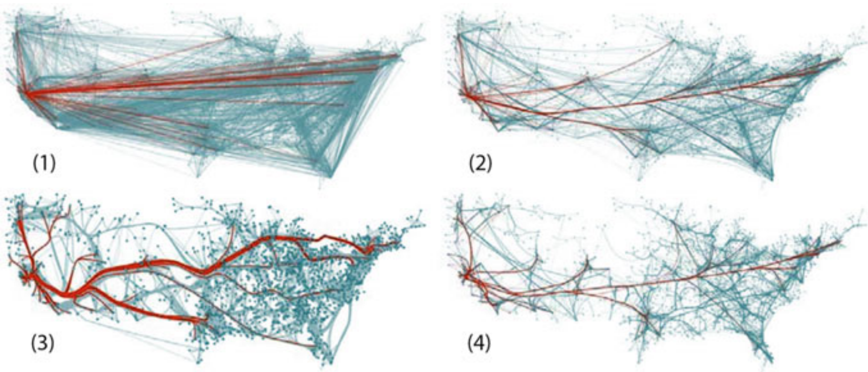

Fig. 7.10 US migration graph (9780 aggregated origin-destination pairs), in which (a) simply uses straight lines and the others are *bundled* using various algorithms (Holten and Van Wijk 2009). Figure based on Holten and Van Wijk (2009) with permission from the original authors

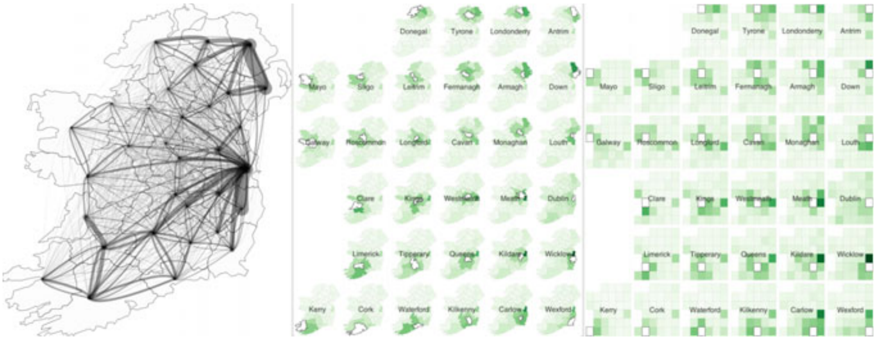

Fig. 7.11 Internal migration in Ireland. **Left**: a flow map, where line thickness indicates flow. **Middle**: spatially-arranged small-multiples of destination maps. **Right**: OD maps with the same grid-based layouts at both levels of the hierarchy. Based on Kelly et al. (2013) with permission from the original authors

multiple destination maps. Cases with irregular spatial units should be organized in a grid layout that preserves as much of the geographical 'truth' as possible. The center of the labels typically indicates the origin (e.g., of migrants or another phenomenon), and the maps show the destinations from each origin (Fig. 7.9). Flow maps aid in visually understanding the structure of movement between places (Jenny et al. 2017). Below, we disregard the connection between the origin and destination and simply consider the density of movement.

7.5.4 In-Flow, Out-Flow and Density of Moving Objects

This section concerns movement for which we **do not have the connection between origin and destination**. This includes situations in which we only have data on the **outflow** (but do not know where the flow goes), **inflow** (but do not know where the flow originates from), or the **density of moving objects**. This can be expressed as a single value describing the movement for each spatial unit, for example, the out-migration flow from each county. As described above, the spatial units used may be derived from existing units (e.g., states) or Voronoi/grid-based tessellations. These values can be displayed as **choropleth maps**, in which regions are represented as tessellating polygons on a map and a suitable color scale is used to indicate in- or out-movement or the density of moving objects.

When performing spatial aggregation, the data in each spatial unit can be disaggregated by temporal unit or by category. Figure 7.12 provides a visual representation of this, where the density of delivery vehicles is aggregated to 1-km grid squares and the vehicles in each grid square are disaggregated into densities for five vehicle types, the days of the week, and 24 h of the day. Many environmental datasets that describe

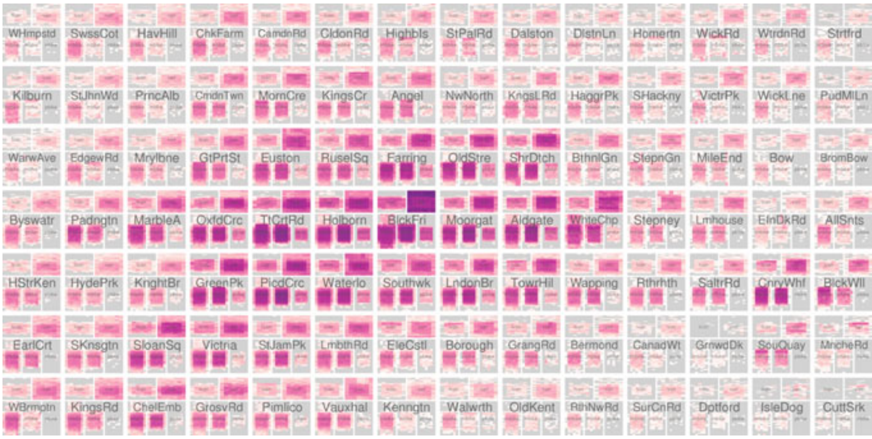

Fig. 7.12 Represents the density of moving vehicles in London, by grid square, day of week, hour of day and vehicle type, using a logarithmic colour scale. Figure based on Slingsby et al. (2010) with permission from the original authors

the movement of water or air masses do not have a meaningful concept of individual journeys. These datasets usually summarize movement as **vectors depicting the flow magnitude and direction** within grid cells. Visual representations of these movements usually take the form of **regular arrays of arrows on maps** (Fig. 7.13). Here, vectors represent a summary of 'movement' within grid cells. These can be explored using some of the methods described above, including filtering, temporal animation, and small multiples. Doing so may result in multiple vectors per grid cell, which provides an opportunity to symbolize multiple variables as glyphs (Slingsby 2018), for example, for climatic data (Wickham et al. 2012) or a rose diagram at origin or destination locations. In spatial tessellations, the problem of overlapping places is not as common. However, the on-screen size of spatial units must be large enough for the symbolization to be interpreted.

In summary, movement data exists in different forms and can often be transformed. This section provided an overview of map-based representations for three different levels of precision for movement data. The reviewed approaches can be used with digital globes, or a future Digital Earth with virtual dashboards through which one can integrate analytical operations within an AR or VR system. Hurter et al. (2018) show how interactions in a 3D immersive environment (see the "Immersive Technologies—From Augmented to Virtual Reality" section) can enable the exploration of large numbers of individual 3D trajectories. Next, we review the current state of the art in immersive technologies.

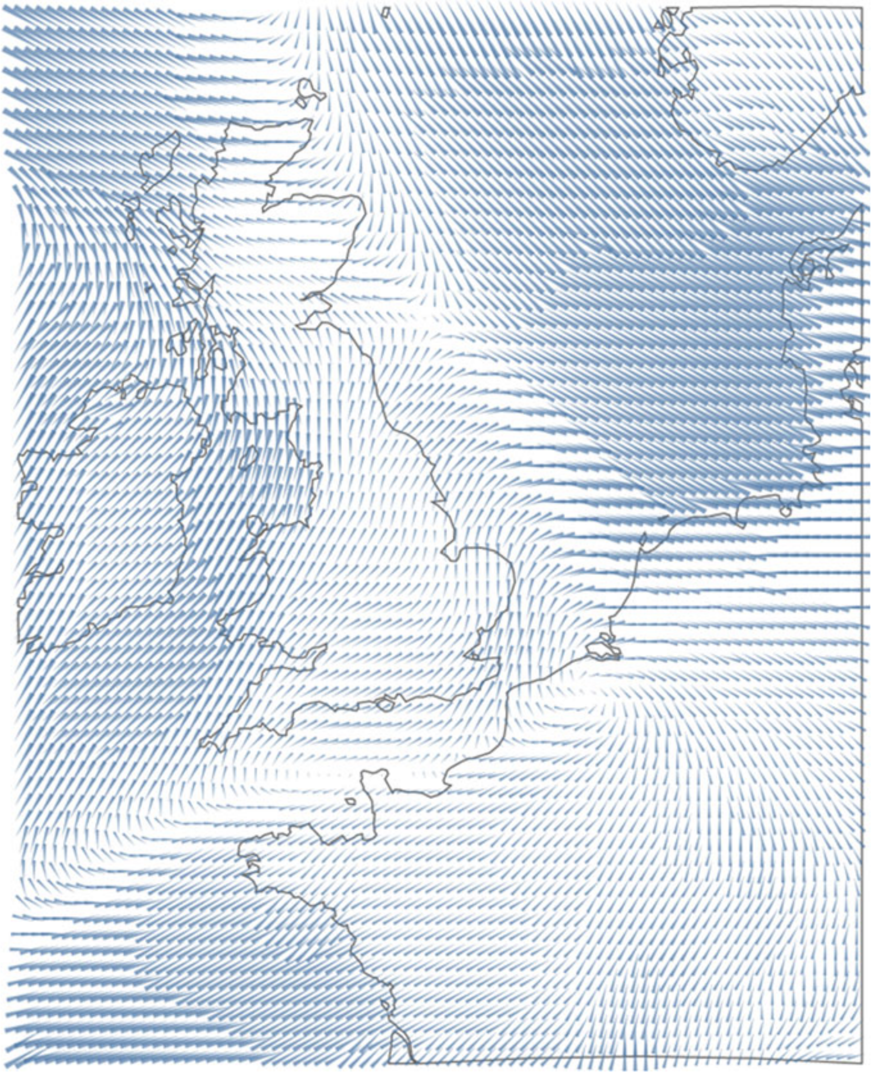

Fig. 7.13 A wind field map, in which arrows indicate wind direction (arrow orientation towards the thin end) and strength (arrow length) for grid squares. It indicates aggregated movement per grid cell. Based on https://github.com/gicentre/litvis/blob/master/examples/windVectors.md with the original author's permission and data from http://www.remss.com/measurements/ccmp/

7.6 Immersive Technologies—From Augmented to Virtual Reality

In the virtual and augmented reality (VR and AR) domains, there is almost "visible" excitement, both in academia (off and on for over 30 years) and in the private sector (more recently). A 2016 Goldman Sachs analysis predicted that VR and AR would be an 80 billion dollar industry by 2025 (reported on CNBC: https://www.cnbc.com/2016/01/14/virtual-reality-could-become-an-80b-industry-goldman.html). Arguably, geospatial sciences will not be the same once immersive technologies such as **augmented (AR)**, **mixed (MR)**, and **virtual reality (VR)** have been incorporated into all areas of everyday life. In this chapter, we use the shorthand **xR** to refer to all immersive technologies and use the individual acronyms (AR/MR/VR) to refer to specific technologies. A closely related term that has recently been gaining momentum is **immersive analytics**, described as a blend of visual analytics, augmented reality, and human-computer interaction (Marriott et al. 2018), which draws on knowledge and experience from several fields described in this chapter to develop visualizations of geospatial information that support thinking. We do not elaborate on immersive analytics; see, e.g., Billinghurst et al. (2018) and Yang et al. (2019). Current technologies for xR hold promise for the future, despite being strongly "gadget"-dependent and somewhat cumbersome and 'involved' to set up (i.e., they require *some* technical skill and dedication). Thus, it remains to be seen whether these immersive experiences will become commonplace. We describe and elaborate on these display technologies below. We begin by outlining several concepts that are important for xR technology use.

7.6.1 Essential Concepts for Immersive Technologies

Concepts characterizing immersive technologies and their definitions are sometimes subject to debate. This is mainly because their development involves multiple disciplines. Because there have been parallel developments in different communities, similar concepts might be named using different terms. The related technology also evolves quickly, and a newer/improved version of a concept/approach/method/tool typically gets a new name to distinguish it from the older versions or because technology actors want to "brand" their innovative approach, or there is a scientific paradigm shift and a new name is needed even though it was based on an older concept. As in many other interdisciplinary and fast-evolving scientific disciplines, there is considerable discussion and occasional confusion about terminology. This process of "maturing" terminology is not unique to immersive technologies. One of the first taxonomies that provided an overview of all xR technologies, and perhaps the most influential one, was proposed by Milgram and Kishino (1994), who used the concept of a continuum from reality to virtuality (see Fig. 7.14).

Fig. 7.14 Shown are examples from projects in ChoroPhronesis that demonstrate the reality-virtuality continuum proposed by Milgram and Kishino (1994). Figure designed by Mark Simpson

Their original definitions are more nuanced than this continuum and are challenging to apply in a fast-developing technology field. Nonetheless, it is useful to revisit some of their main distinctions for a conceptual organization of the terms in xR.

A confusing, yet central, term is **immersion** (see the "Virtual Reality" subsection below). Currently, the commonsense understanding of immersion is different than its rather narrow focus in the technical VR literature. For example, Slater (2009) distinguishes immersion from **presence**, with the former indicating a physical characteristic of the medium itself for the different senses involved. Presence is reserved for the psychological state produced in response to an immersive experience. To illustrate a simple example, Fig. 7.15 shows three experimental setups that were used in a recent study on how different levels of immersion influence the feeling of being present in a remote meeting (Oprean et al. 2018).

In this study, Oprean et al. (2018) compared a standard desktop setting (the lowest level of immersion) with a three-monitor setup (medium level of immersion) and an immersive headset (the Oculus Rift, DK2). One can "order" these technologies along a spectrum of immersiveness (as in Fig. 7.16), which helps in designing experiments to test whether or not feeling physically immersed affects aspects of thinking or collaboration (e.g., on the subjective feeling of team membership). Another key concept for immersive technologies, and a research topic in itself, is **interaction** (also discussed in the "Visualizing Geospatial Information" section). Interaction is important for any form of immersive technology because the classical "keyboard and mouse" approach does not work well (or at all) when the user is standing and/or moving. Interaction, along with immersion, is one of the four "I" terms proposed as the defining elements of VR; the other two are information intensity and intelligence of objects, as proposed by MacEachren et al. (1999a) in the 1990s. We elaborate on the four "I"s and other relevant considerations in the Virtual Reality section because they are discussed most often in the context of VR, and are relevant for other forms

Fig. 7.15 Different levels of immersion, with immersiveness increasing from top to bottom. Increased immersion is supported by a combination of an increased field of view and the use of an egocentrically fixed rather than an allocentrically fixed reference frame. Based on Oprean et al. (2017) with the original author's permission

of xR. In addition to Milgram and Kishino's (1994) continuum, there are many other ways to organize and compare immersive technologies. For example, a recent take on levels of realism and immersion is shown Fig. 7.16. This example extends the immersiveness spectrum by considering where visualization designs are located on an additional continuum: abstraction-realism.

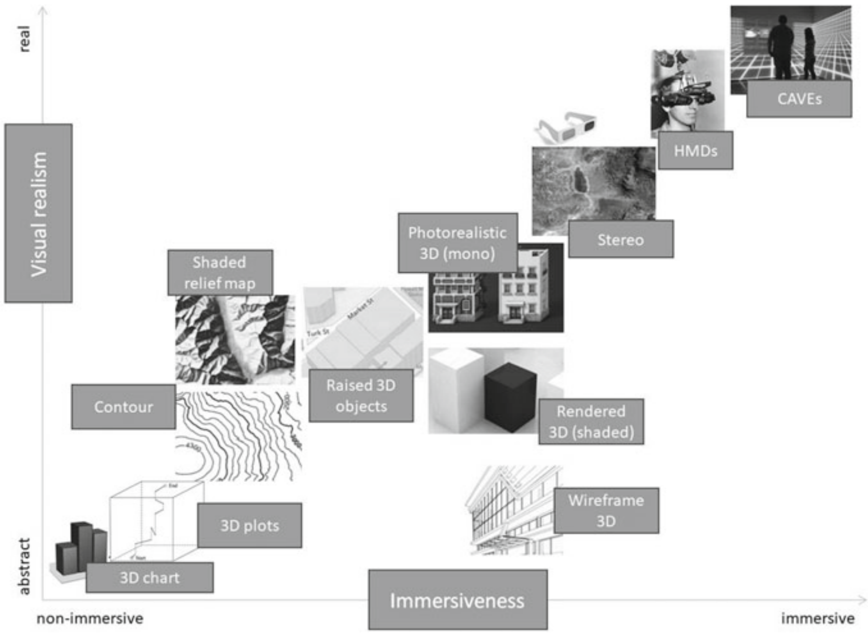

Fig. 7.16 Extending the immersiveness spectrum by also considering where specific visualization designs are located on an additional continuum: abstraction-realism. Figure by Çöltekin et al. (2016a, b), CC-BY-3.0

7.6.2 Augmented Reality

In Milgram and Kishino's (1994) model, the first step from reality toward *virtuality* is **augmented reality (AR)**. Augmented reality allows for the user to view virtual objects superimposed onto a real-world view (Azuma 1997). Technological advancements have allowed for augmented reality to evolve from bulky head-mounted displays (HMDs) in the 1960s to smartphone applications today (some examples are featured below), and through specialized (though still experimental) glasses such as Google Glass or Epson Moverio (Arth and Schmalstieg 2011). Although technology has truly advanced since the early—bulky and rather impractical—HMDs, there are still challenges in the adoption of augmented reality for dedicated geospatial applications in everyday life. These challenges are often technical, such as latency and the inaccuracy of sensors when using smartphones, and result in inaccuracies in registration of features and depth ambiguity (Arth and Schmalstieg 2011; Chi et al. 2013; Gotow et al. 2010). There are also design issues that should be considered and, ideally, user-evaluated when developing and designing a "geospatial" AR application (Arth and Schmalstieg 2011; Cooper 2011; Kounavis et al. 2012; Kourouthanassis et al. 2015; Kurkovsky et al. 2012; Olsson 2012; Tsai et al. 2016; Vert et al. 2014).

Akçayır and Akçayır (2017) and Wu et al. (2013) reviewed the current state of AR in education. They concluded that AR provides a unique learning environment because it combines digital and physical objects, an insight relevant to students and scientists who are learning about geographical systems. An example of AR in education and research is the "augmented reality sandbox" (https://arsandbox.ucdavis.edu) that has been widely used, for example, in an urban/landscape design experiment (Afrooz et al. 2018). A similar application is the "tangible landscape" (https://tangible-landscape.github.io) (Petrasova et al. 2015). Both of these applications superimpose an elevation color map, topographic contour lines, and simulated water on a physical sand model that can be physically (re)shaped by the user. A tourism-related science and education example is the "SwissARena", which superimposes a 3D model on top of topographic maps of Switzerland (Wüest and Nebiker 2018), enabling smartphone and tablet users to visit museums and other public spaces through an augmented experience. Motivated by a fundamental (rather than an applied) question, Carrera and Bermejo Asensio (2017) tested whether the use of AR improves participants' (spatial) orientation skills when interpreting landscapes. They found a significant improvement in participants' orientation skills when using a 3D AR application. However, some pedagogical questions (e.g., how should AR be used to complement the learning objectives; what is the gap between teaching and learning?) and other usability gaps (e.g., it was difficult to use at first, unsuitable for large classes, cognitive overload, expensive technology, and inadequate teacher ability to use the technology) identified by Akçayır and Akçayır (2017) and Wu et al. (2013) regarding the use of AR in teaching need to be addressed. Given that early research suggests that AR might aid in developing spatial skills, its potential in education (especially in science education) appears to be reasonably high. Furthermore, there appear to be several benefits of using AR in research. For example, it has been suggested that AR is an excellent tool for collaborative work among researchers (Jacquinod et al. 2016). At the time of this writing, there are no *common* examples of these types of applications in use, but there have been various experimental implementations of AR in research and scientific visualization (e.g., Devaux et al. 2018). Thus, most of the present excitement about AR seems to be based on belief and intuition, which can be correct but may also mislead.

7.6.3 Mixed Reality

As conceptualized in the Milgram and Kishino (1994) model (Fig. 7.15), the term Mixed Reality (MR)—sometimes referred to as Hybrid Reality—applies to everything in between the real world and a virtual world. Therefore, the term *includes* AR, and the issues described above about AR also apply to MR. MR also includes **augmented virtuality** (AV). AV refers to virtual environments that are designed so that physical objects still play a role. Of the two subcategories of MR (AR and AV), AR is more developed at this point in time. Nonetheless, AV is relevant in a number of VR scenarios. For example, when we want haptic feedback, we give users suits or gloves. It is also relevant when we want to interact with the virtual world using any kind of hardware. Using hardware to drive interaction is the current state of the art; that is, although there are an increasing number of gesture tracking methods that map functions onto the body's natural movements, several of the controls are physical objects, such as remote controls, often referred to as "wands", or small trackable objects attached to the viewers called "lights". Any combination (hybrid) environments of physical and virtual objects can be considered a form of MR. We do not expound on MR in this chapter, and any information presented in the AR section above and most of the information in the VR section below is relevant to MR.

7.7 Virtual Reality

How should we define virtual reality? There is no consensus on the "minimum requirements" of VR, though it is understood that an ideal VR system provides humans experiences that are indistinguishable from an experience that could be real. Ideally, a VR should stimulate *all* senses. That is, a virtual apple you eat should look, smell, and taste real, and when you bite, the touch and sounds should be just right. Current VR technologies are not there yet. The sense of vision (and the associated visualizations) has been investigated a great deal and audio research has made convincing progress, but we have a long way to go in terms of simulating smells, tastes, and touch. There are no hard and fast rules for "minimum requirements" for a display to qualify as VR, but there have been various attempts to systematically characterize and distinguish VR from other types of displays (see Fig. 7.16). Among these, Sherman and Craig (2003) list four criteria: *a virtual world* (graphics), *immersion*, *interactivity*, and *sensory feedback*. They distinguish interaction and sensory feedback in the sense that interaction occurs when there is an *intentional* user request whereas sensory feedback is embedded at the system level and is fed to the user based on tracking the user's body. In the cartographic literature, a similar categorization was proposed even earlier by MacEachren et al. (1999b) in which they describe the *Four 'I's*, adding *intelligence of objects* to Heim's (1998) original three 'I's: *immersion, interactivity, information intensity.* The *Four 'I's* and Sherman and Craig's criteria have clear overlaps in immersion and interactivity, and links between a "virtual world" and "information intensity" and between "sensory feedback" and "intelligence of objects" can be drawn. Notably, some authors make a distinction between *virtual reality* and *virtual environments*: the term virtual reality does not exactly refer to mimicking reality (but an experience that feels real to the user). Nonetheless, because the word *reality* can invoke such an impression, the term **virtual environment** emerged. The term originated because one can also show fictional (or planned) environments using a visualization environment, and thus, the term "environment" more effectively encapsulates the range of things one can do in such a visualization environment. Below, we give a brief history of VR in domains that are directly related to Digital Earth and elaborate on what was once described as a "virtual geographic environment" (VGE).

7.7.1 Virtual Geographic Environments

An extension of earlier conceptualizations of 'virtual geography' (e.g., Batty 1997; MacEachren et al. 1999a), the term VGE was formally proposed at the beginning of the 21st century (attributed to Lin and Gong 2001) around the same time as the seminal book by Fisher and Unwin (2001). Since its beginnings, the VGE concept and accompanying tools have significantly evolved. A modern description of a VGE is a digital geographic environment "generated by computers and related technologies that users can use to experience and recognize complex geographic systems and further conduct comprehensive geographic analyses, through equipped functions, including multichannel human-computer interactions (HCIs), distributed geographic modeling and simulations, and network geo-collaborations" (Chen and Lin 2018, p. 329). Since their conception, VGEs have attracted considerable attention in the geographic information science research community over the last few decades (e.g., Goodchild 2009; Huang et al. 2018; Jia et al. 2015; Konecny 2011; Liang et al. 2015; Mekni 2010; Priestnall et al. 2012; Rink et al. 2018; Shen et al. 2018; Torrens 2015; Zhang et al. 2018; Zheng et al. 2017). Much like the "digital twin" idea, and well-aligned with the Digital Earth concept, VGEs often aim to mirror real-world geographic environments in virtual ones. Such a mirrored virtual geographic environment also goes *beyond* reality, as it ideally enables its user to visually perceive invisible or difficult-to-see phenomena in the real world, and explore them inside the virtual world (e.g., looking at forests at different scales, examining historical time periods, seeing under the ocean's surface). As it can incorporate advanced analytic capabilities, a VGE can be superior to the real world for analysts. In an ideal VGE, one can view, explore, experience and analyze complex geographic phenomena. VGEs are not 'just' 3D GIS environments, but there are strong similarities between VGEs and *immersive analytics* approaches. A VGE can embed all the tools of a GIS, but a key point of a VGE is that they are meant to provide realistic experiences, as well as simulated ones that are difficult to distinguish from real-world experiences. A VGE would not be ideal if *only* analytics are needed, as 2D plans combined with plots may better facilitate the analyst's goals. The combination of a traditional GIS and the power of immersive visualization environments offers novel ways to combine human cognitive abilities with what machines have to offer (Chen and Lin 2018; Lin et al. 2013a).

7.7.2 Foundational Structures of VGEs

Lin et al. (2013b) designed a conceptual framework that includes four VGE subenvironments: *data*, *modeling and simulation*, *interaction*, and *collaborative* spaces. They posit that a geographic *database* and a geographic *model* are core necessities for VGEs to support visualization, simulation, and collaboration. Below, we briefly elaborate on the four VGE subenvironments (Lin et al. 2013b).

7.7.2.1 Data Space

The “data space” is conceptualized as the first step in the pipeline of creating a VGE. This is where data are organized, manipulated, and visualized to prepare the digital infrastructure necessary for a VGE. One can also design this environment so that users can “walk” in their data and examine it for patterns and anomalies (as in immersive analytics). The data is ideally comprehensive (i.e., “information intensity” is desirable), such that semantic information, location information, geometric information, attribute information, feature spatiotemporal/qualitative relationships and their evolution processes are considered and organized to form virtual geographic scenarios with a range of visualization possibilities (e.g., standard VR displays, holograms, or other xR modes) and thus support the construction of VGEs (Lü et al. 2019).

7.7.2.2 Modeling and Simulation Space

Models and simulations, as the abstraction and expression of geographical phenomena and processes, are important means for modern geographic research (Lin et al. 2015). With the rapid development of networks, cloud/edge computing, and other modern technologies, modeling and simulation capabilities allow for a large range of exploration and experimentation types (e.g., Wen et al. 2013, 2017; Yue et al. 2016). VGEs can also integrate such technologies. Chen et al. (2015) and Chen and Lin (2018) propose that doing so would provide new modes for geographic problem solving and exploration, and potentially help users understand the Digital Earth.

7.7.2.3 Interaction Space

In general, interaction is what shifts a user from being a passive ‘consumer’ of information and makes them active producers of new information (see the “Geovisualization” section earlier in this chapter). In VGEs, interaction requires a different way of thinking than for desktop setups because the aspiration is to create experiences that are comparable to those in the real world (i.e., mouse-and-keyboard type interactions do not work well in VGEs). Thus, there have been considerable efforts to track a user’s hands, head, limbs, and eyes to model natural interaction. Interaction tools play an important role in information transmission between the VGE and its users (Batty et al. 2017; Voinov et al. 2018).

7.7.2.4 Collaboration Space

In addition to the interaction between a human and a machine, it is important to consider the interactions between humans, ideally, as it occurs in the real world (or improving upon real-world collaboration). At present, there is an increasing demand for collaborative work, especially when solving complex problems. Complex geographic problem solving may require participants from different domains, and collaboration-support tools such as VGEs might help them communicate with each other. There are many examples of collaborative research based on VGEs (e.g., Chen et al. 2012; Li et al. 2015; Xu et al. 2011; Zhu et al. 2015). If the four subenvironments are well-designed, VGEs could become effective scientific tools and advance geography research: simulations in a VGE could be systematically and comprehensively explored to deepen scientists' understanding of complex systems such as human-environment interactions. Virtual scenarios corresponding to real-world scenarios with unified spatiotemporal frameworks can be employed to support integration of human and environmental resources. With Digital Earth infrastructure and modern technological developments, geographical problems at multiple scales can be solved and related virtual scenarios can be developed for deep mining and visual analysis (e.g., Lin et al. 2013b; Fig. 7.17). Importantly, VGEs can support collaborative exploration beyond reality. Working with virtual scenarios, users can communicate and conduct collaborative research free from the constraints of physical space (and in some cases, time).

This chapter so far has focused on theoretical constructs and examples of geographical visualization that can be used to represent and provide insights into our Earth system. However, it is also important to consider how such visualizations can

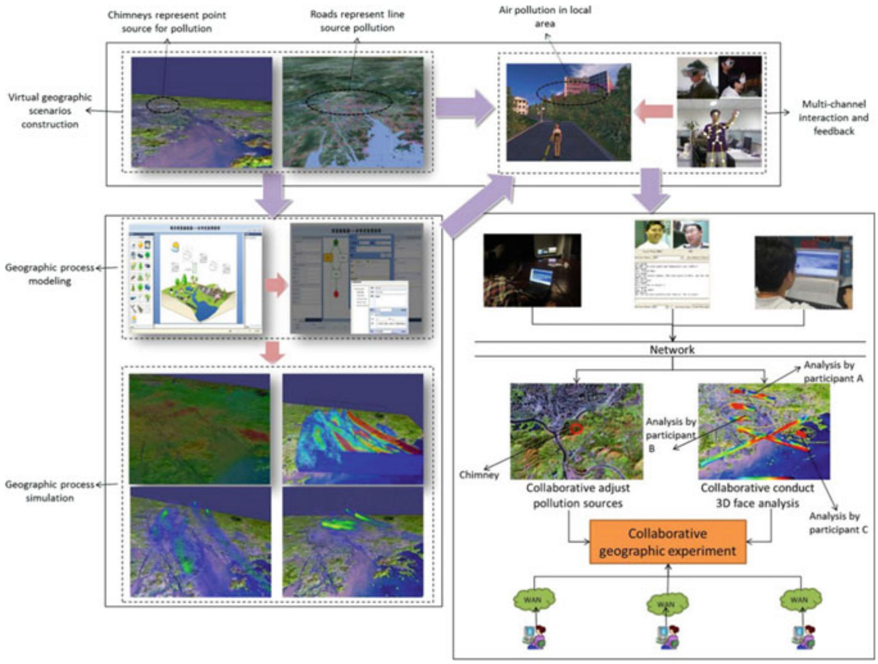

Fig. 7.17 A VGE example built for air pollution analysis (Lin et al. 2013a). Figure by Lin et al. (2013a). CC BY-NC-SA 3.0

be presented to policy and decision-makers to plan for a more sustainable future. The next section outlines a number of platforms for engaging such end users with packaged geographical information, known as *dashboards*.

7.8 Dashboards

A true Digital Earth describes Earth and all its systems, including ecosystems, climate/atmospheric systems, water systems, and social systems. Our planet faces a number of great challenges including climate change, food security, an aging population, and rapid urbanization. As policy-makers, planners, and communities grapple with how to address these critical problems, they benefit from digital tools to monitor the performance of our management of these systems using specific indicators. With the rise of big data and **open data**, a number of **dashboards** are being developed to support these challenges, enabled by geographical visualization technologies and solutions (Geertman et al. 2017). Dashboards can be defined as "graphic user interfaces which comprise a combination of information and geographical visualization methods for creating metrics, benchmarks, and indicators to assist in monitoring and decision-making" (Pettit and Leao 2017).

One can think of dashboards as installations that can provide key indicators of the performance of a particular Earth system, powered through the construct of Digital Earth. In 2016, the United Nations launched 17 Sustainable Development Goals to guide policy and funding priorities until 2030. Each of these goals include a number of indicators that can be quantified and reported within a Digital Earth dashboard, as illustrated, for example, such as in SDG Index and Dashboards (https://dashboards.sdgindex.org/#/) (Sachs et al. 2018).

For illustrative purposes, we focus on one SDG 11—Sustainable Cities and Communities, as there are a number of city dashboard initiatives that aim to provide citizens and visitors access to a rich tapestry of open data feeds. Data in these feeds are typically aggregated and presented to the user online and can include, for example, data on traffic congestion, public transport performance, air quality, weather data, social media streams, and news feeds. Users can interact with the data and perform visual analyses via different/multiple views, which might include graphs, charts, and maps. Examples include the London Dashboard (Gray et al. 2016) and the Sydney Dashboard (Pettit et al. 2017a), illustrated in Fig. 7.18.

There are also advanced dashboard platforms that support data-driven policy and decisions through analytics. For cities, there has been an increase in the number of city analytics dashboard platforms such as the Australian Urban Research Infrastructure Network (AURIN) workbench (Pettit et al. 2017b). The AURIN workbench provides users with access to over 3,500 datasets through an online portal. This portal provides data and includes more than 100 spatial-statistical tools (Sinnott et al. 2015). The AURIN workbench (Fig. 7.19) enables users to visualize census data and a number of other spatial datasets, including the results of statistical analyses through multiple coordinated (i.e., linked) views. Thus, it enables geovisual analytics as the user

Fig. 7.18 City of Sydney Dashboard. Figure provided by Chris Pettit

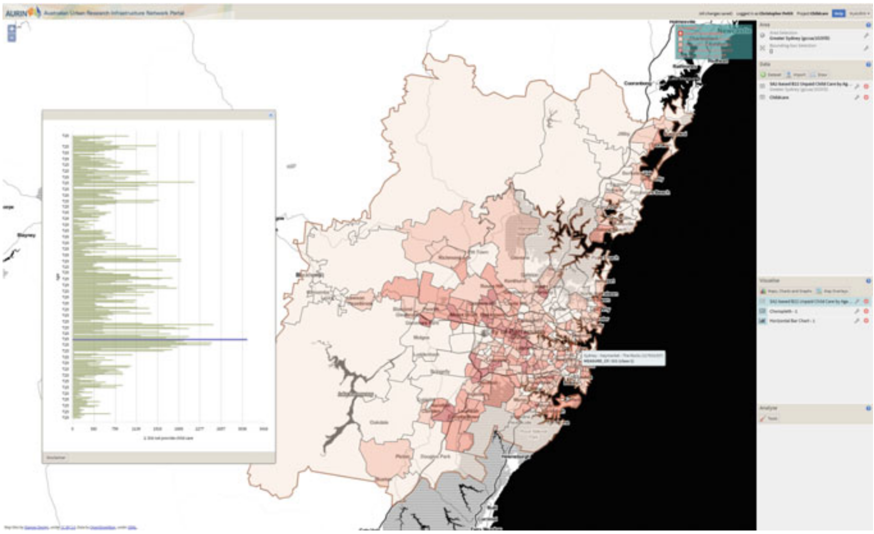

Fig. 7.19 The AURIN Workbench provides a rich geovisual analytics experience. Figure provided by Chris Pettit

can *brush* between maps, graphs, charts, and scatterplots to explore the various dimensions of a city (Widjaja et al. 2014). In an era of smart cities, big data, and city analytics, an increasing number of geographical visualization platforms include both data and simulations to benchmark the performance of urban systems.

Dashboard views of the performance of Earth systems such as urban systems have a number of pros and cons. Dashboards can potentially provide the best available data on the performance of an urban system or natural asset so that decisions can account for multiple dimensions, including sustainability, resilience, productivity, and liv-ability. Dashboards are also a window into the democratization of data and provide greater transparency and accountability in policy- and decision-making. However, there are a number of challenges in developing and applying dashboards; without good quality indicators and benchmarks, the utility of such digital presentations of performance can be questionable. Traditionally, dashboards have provided a unidirectional flow of information to their users. However, with the emergence of digital twins, there may be an opportunity for a true bidirectional flow of data between dashboards, their users and Earth systems.

7.9 Conclusions

Our understanding of the vision of Digital Earth is that it is a fully functional virtual reality system. To achieve such a system, we need to master every aspect of relevant technology and design and keep the users in mind. Visualization is an interdisciplinary topic with relevance in many areas of life in the digital era, especially given that there is much more data to analyze and understand than ever before. Because the Earth is being observed, measured, probed, listened to, and recorded using dozens of different sensors, including people (Goodchild 2007), the data we need to build a Digital Earth is now available (at least for parts of the Earth). Now, the challenge is to organize these data at a global scale following cartographic principles so that we can make sense of it. Herein lies the strength of visualization. By visualizing the data in multiple ways, we can create, recreate, and predict experiences, observe patterns, and detect anomalies. Recreating a chat with an old neighbor in our childhood living room 30 years later (e.g., instead of looking at a photo album) is no longer a crazy thought; we might be recording enough data to be able to do such things soon. The possibilities are endless. However, as inspiring as this may be, one must understand how to "do it right"; that is, we have much to learn before we will know what exactly we should show, when and to whom. In this chapter, we provided an overview of the current state of the art of topics related to visualization in the context of Digital Earth. We hope this chapter provided some insights into our current broad understanding of this challenge.

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Arzu Çöltekin is an Associate Professor at the Institute of Interactive Technologies of University of Applied Sciences and Arts Northwestern Switzerland. Her background is in geographic information science and engineering; and her research interests are at the intersection of visuospatial cognition, human-computer interaction, mixed reality and GIScience. She is a council member with the ISDE, chairs ISPRS Working Group on Geovisualization, Augmented and Virtual Reality; and is a co-chair of ICA Commission on Visual Analytics.

Amy L. Griffin is a Senior Lecturer in the School of Science at RMIT University in Melbourne, Australia. Her research is focused on understanding how perceptual, cognitive and emotional processes shape how people read maps and think with spatial information. She is currently a co-chair of the ICA Commission on Cognitive Issues in Geographic Information Visualization.

Aidan Slingsby is a Senior Lecturer at giCentre, Department of Computer Science, City, University of London. He has a background in GIS, but now works more generally in information visualisation and visual analytics. He is interested in the role of data visualization in the analysis of data, particularly those that are spatial and temporal.

Anthony C. Robinson is an Associate Professor of Geography at Penn State University. His science focuses on improving the utility of geospatial information through cartographic design and user evaluation. Dr. Robinson is Assistant Director of the GeoVISTA Center and Director of Online Geospatial Education at Penn State, and co-chairs the Commission on Visual Analytics for the International Cartographic Association.

Sidonie Christophe is a Senior Researcher in Geographic Information Sciences at the Paris-Est University, at the research Laboratory in Sciences and Technologies in Geographic Information. She focuses on the design, the perception and the uses of graphic representations for geovisualization, augmented and mixed reality and visual spatio-temporal analysis of urban and environmental dynamics. She is the co-chair of the ISPRS working group on "Geovisualization, VR & AR", and the co-chair of the ICA Commission on "Cognitive Issues in Geovisualization".

Victoria Rautenbach is a Senior Lecturer in the Department of Geography, Geoinformatics and Meteorology at the University of Pretoria, South Africa. Victoria is the scientific research secretary of the ISPRS WG IV/9 Geovisualization, Augmented and Virtual Reality. She is passionate about open source, open education and open data. Victoria currently serves on the OSGeo Board of Directors and the co-chair of GeoForAll.

Min Chen is a Professor and the Vice Director of Key Lab of Virtual Geographic Environment (Ministry of Education of PRC), Nanjing Normal University, China. His research interests are geographic modeling and simulation, virtual geographic environment. He is the executive editor of Annals of GIS and an editor of Environmental Modelling & Software.

Christopher Pettit is a Professor and the Director of City Analytics, UNSW Sydney. His expertise is in the convergence of the fields of city planning and digital technologies including Geographical Information Sciences (GIS). He is currently the Chair of the Board for CUPUM (Computer in Urban Planning and Urban Management).

Alexander Klippel is a Professor in Geography and Information Sciences at Penn State and the inaugural director of the Center of Immersive Experiences. This research interests lie at the interface of technology and cognition and address questions such as immersive learning, immersive decision-making, and the centrality of space for cognitive processes.

Chapter 8
Transformation in Scale for Continuous Zooming

Zhilin Li and Haowen Yan

Abstract This chapter summarizes the theories and methods in continuous zooming for Digital Earth. It introduces the basic concepts of and issues in continuous zooming and transformation in scale (or multiscale transformation). It presents the theories of transformation in scale, including the concepts of multiscale versus variable scale, transformation in the Euclidean space versus the geographical space, and the theoretical foundation for transformation in scale, the Natural Principle. It addresses models for transformations in scale, including space-primary hierarchical models, feature-primary hierarchical models, models of transformation in scale for irregular triangulation networks, and the models for geometric transformation of map data. It also discusses the mathematical solutions to transformations in scale (including upscaling and downscaling) for both raster (numerical and categorical data) and vector (point set data, line data set and area data) data. In addition, some concluding remarks are provided.

Keywords Continuous zooming · Transformation in scale · Natural principle · Multiscale · Variable scale

Z. Li (✉)
Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Hong Kong, China
e-mail: zl.li@polyu.edu.hk

H. Yan
Department of Geographic Information Science, Lanzhou Jiaotong University, Lanzhou, China

Z. Li
State-Province Joint Engineering Laboratory of Spatial Information Technology for High-Speed Railway Safety, Southwest Jiaotong University, Chengdu, China

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8.1 Continuous Zooming and Transformation in Scale: An Introduction

8.1.1 Continuous Zooming: Foundation of the Digital Earth

Continuous zooming is a fundamental function of a Digital Earth, as the demand for such a function has been vividly portrayed by then-US Vice President Al Gore in his famous speech "The Digital Earth: Understanding Our Planet in the twenty-first Century" (Gore 1998):

> Imagine, for example, a young child going to a Digital Earth exhibit at a local museum. After donning a head-mounted display, she sees Earth as it appears from space. Using a data glove, she zooms in, using higher and higher levels of resolution, to see continents, then regions, countries, cities, and finally individual houses, trees, and other natural and man-made objects.

The cascade scene seen by the young child is a result of continuous zooming. Such zooming can be realized by continuously displaying a series of Earth images taken at a given position and changing the focal length of the camera lens continuously or displaying images taken at different heights continuously but with at a fixed camera focal length.

In theory, to make the display visually smooth, the differences between two images should be sufficiently small, thus the number of images in such a series is very large, which demands huge data storage. Thus, it is a very difficult, if not impossible, problem.

8.1.2 Transformation in Scale: Foundation of Continuous Zooming

In practice, Earth images are acquired and stored at discrete scales (e.g., 1:500,000, 1:100,000, 1:10,000) or different resolutions (e.g., 100, 10, 1, 0.5 m), leading to the term *multiscale representation*. Figure 8.1 shows a series of satellite images covering Hong Kong Polytechnic University at six different scales, extracted from Google Maps. If such images at discrete scales are displayed in sequence, there will be a visual jump between two images. The obviousness of the visual jump is dependent on the magnitude of the scale difference. The smaller the difference between the two scales is, the less apparent the visual jump will be.

To minimize the effect of such visual jumps, some techniques are required to smooth the transformations from one scale to another scale to make the display appear like continuous zooming. This transformation in scale is the foundation of continuous zooming. Thus, transformation in scale, also called multiscale transformation, is the topic of this chapter.

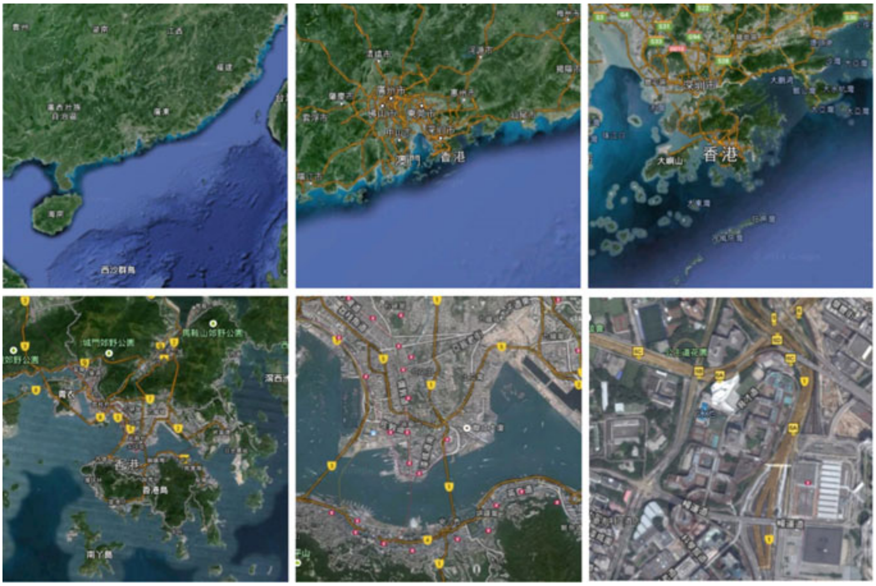


Fig. 8.1 A series of images covering HK Polytechnic University at different scales (from Google Maps)

8.1.3 Transformation in Scale: A Fundamental Issue in Disciplines Related to Digital Earth

Transformation in scale is one of the most important but unsolved issues in various disciplines related to Digital Earth, such as mapping, geography, geomorphology, oceanography, soil science, social sciences, hydrology, environmental sciences and urban studies. Typical examples are map generalization and the modifiable areal unit problem (MAUP). Although transformation in scale is a traditional topic, it has been a critical issue in this digital era.

Transformation in scale has attracted attention from disciplines related to Digital Earth since the 1980s because a few important publications on the scale issue in that period awakened researchers in relevant areas. Openshaw (1984) revisited the *MAUP*. Abler (1987) reported that multiscale representation was identified as one of the initiatives of the National Center for Geographic Information and Analysis (NCGIA), and noted that zooming and overlay are the two most exciting functions in a geographical information system. Since then, the scale issue has been included in many research agendas (e.g., Rhind 1988; UCGIS 2006) and has become popular in the geo-information community.

The first paper on the scale issue in remote sensing was also published in 1987 (Woodcock and Strahler 1987). Later, in 1993, the issue of scaling from point to regional- or global-scale estimates of the surface energy fluxes attracted great attention at the Workshop on Thermal Remote Sensing held at La Londe les Maures, France from September 20–24. Scale became a hot topic in remote sensing as well.

As a result, many papers on the scale issue have been published in academic journals and at conferences related to Digital Earth. Other papers have been p in the form of edited books, such as *Scaling Up in Hydrology Using Remote Sensing* edited by Stewart et al. (1996), *Scale in Remote Sensing and GIS* edited by Quattrochi and Goodchild (1997), *Scale Dependence and Scale Invariance in Hydrology* edited by Sposito (1998), *Modelling Scale in Geographical Information Science* edited by Tate and Atkinson (2001), *Scale and Geographic Inquiry: Nature, Society and Method* edited by Sheppard and McMaster (2004), *Generalisation of Geographic Information: Cartographic Modelling and Applications* edited by Mackaness et al. (2007), and *Scale Issues in Remote sensing* edited by Weng (2014). Authored research monographs have also been published by researchers, e.g., *Algorithmic Foundation of Multi-Scale Spatial Representation* by Li (2007) and *Integrating Scale in Remote Sensing and GIS* by Zhang et al. (2017).

8.2 Theories of Transformation in Scale

Transformation in scale is the modeling of spatial data or spatial representations from one scale to another by employing mathematical models and/or algorithms developed based on certain scaling theories and/or principles. This section describes such scaling theories and/or principles.

8.2.1 Transformation in Scale: Multiscale Versus Variable Scale

To facilitate zooming, not necessarily continuous, a common practice of service providers such as Google Maps, Virtual Earth and Tianditu is to organize maps and images into nearly 20 levels (scales or resolutions), from global level to street level. Figure 8.2 shows a series of maps covering Hong Kong Polytechnic University at six different scales (extracted from Google Maps). This follows the tradition of organizing maps by national map agencies. For example, the United States Geological Survey (USGS) produces topographic maps at scales of 1:500,000, 1:250,000, 1:100,000, 1:50,000 and 1:24,000; the Chinese State Bureau of Surveying and Mapping produces maps at scales of 1:4,000,000, 1:1,000,000, 1:250,000, 1:50,000 and 1:10,000; the Ordnance Survey of the UK produces maps at scales of 1:50,000, 1:25,000 and 1:10,000; and the German federal states produces maps at 1:1,000,000, 1:250,000, 1:100,000, 1:50,000, 1:25,000 and 1:10,000 scales. These maps at different scales contain information at different levels of detail, and thus are suitable for different

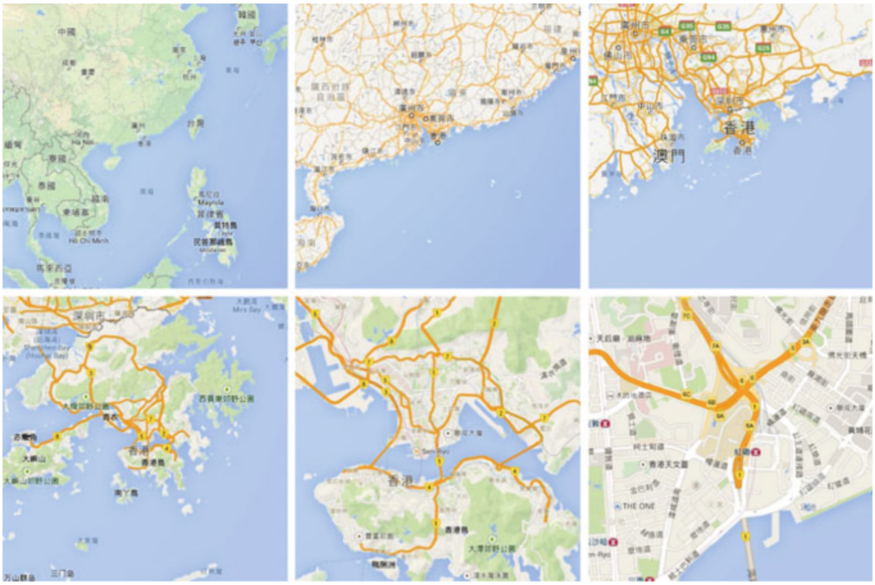


Fig. 8.2 A series of maps covering Hong Kong Polytechnic University at different scales (extracted from Google Maps)

applications. Such a scale is also called the *cartographic ratio*. Similarly, image data and digital elevation models (DEMs) are also produced and stored at discrete scales. In these two cases, the scale is normally indicated by *resolution*.

This kind of representation is called multiscale representation. In such cases, the cartographic ratio is uniform across a map and/or an image. Thus, such representations have multiple cartographic ratios. The cartographic ratio may vary across a representation (e.g., oblique view), leading to the term variable scale representation; the resolution may also vary across a representation, leading to the term variable resolution representation. As a result, the term multiscale might mean different things to different people, i.e., multi cartographic ratio, variable cartographic ratio, multi resolution and variable resolution. This leads to nine different kinds of transformations in scale, as shown in Fig. 8.3.

8.2.2 Transformations in Scale: Euclidean Versus Geographical Space

In *Euclidean space*, an increase in scale will commonly cause an increase in length, area and volume; and a decrease in scale will cause a decrease in length, area and volume, accordingly. Figure 8.4 shows an example of scale reduction and increase in

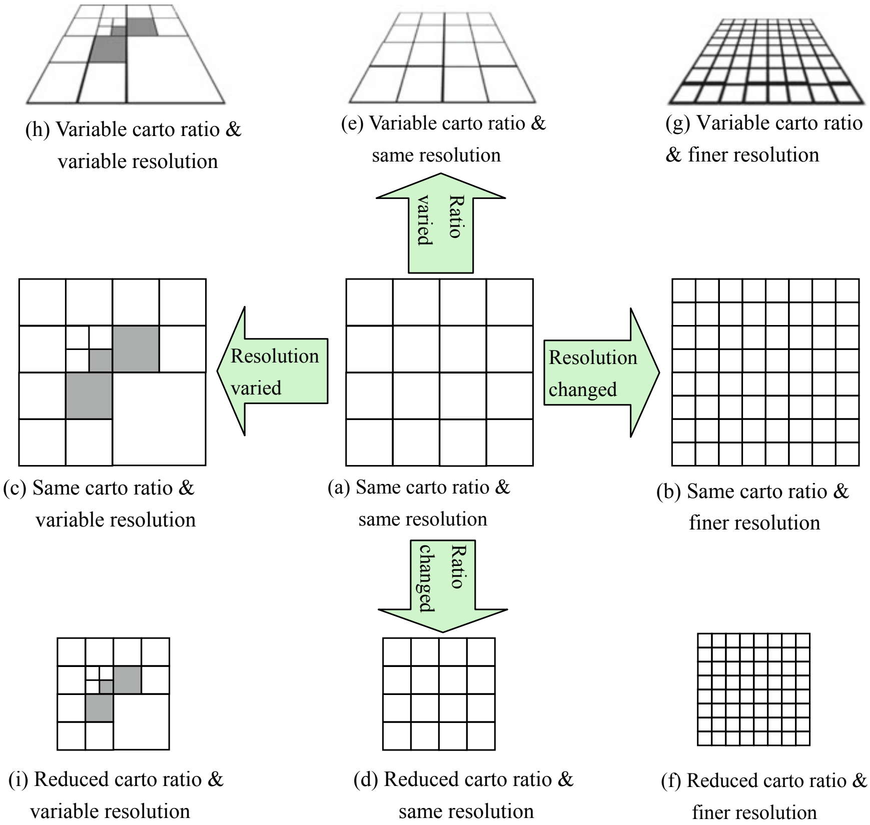


Fig. 8.3 Nine types of transformations in scale (Li 2008)

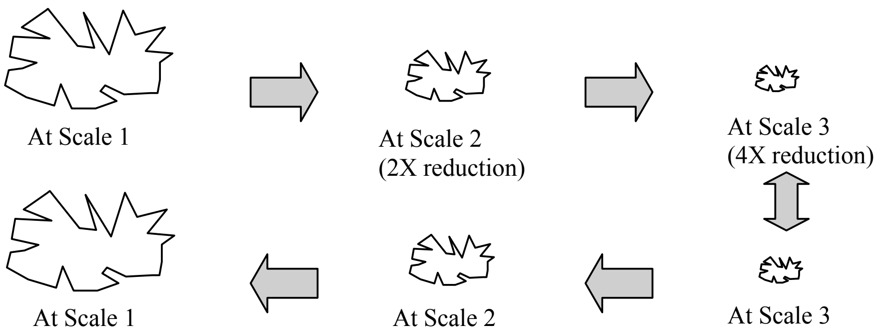


Fig. 8.4 Scale change in Euclidean space: a reversible process (Li 2007)

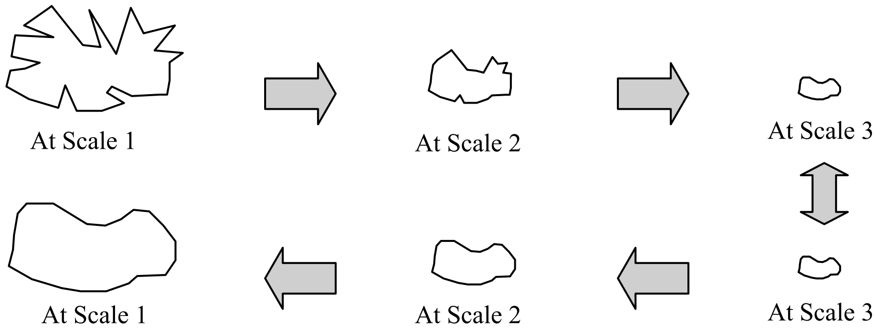


Fig. 8.5 Scale change in 2D geographical space: lost complexity is not recoverable (Li 2007)

a 2D Euclidean space. In such a transformation in scale, the absolute complexity of a feature or features remains unchanged. That is, the transformations are reversible.

However, the geographical space *is fractal*. If one measures a coastal line using different measurement units, then different lengths will be obtained. The smaller the measurement unit is, the longer the length obtained. Similarly, different length values will be obtained when measuring a coastal line represented on maps at different scales using identical measurement units at map scale. That is, the transformation in scale in fractal geographical space is quite different from that in Euclidean space.

For a given area on a terrain surface, the size of the graphic representation (or map space) on a smaller scale map is reduced compared with that on larger scale maps. The complexity of the graphics on a smaller scale map remain compatible with larger scale maps. However, the absolute complexity is reduced. As a result, if the graphics on a smaller map are enlarged back to the size on the larger scale map, the level of complexity of the enlarged representation will appear to be reduced. Figure 8.5 illustrates such a case. In a fractal geographical space, the level of complexity cannot be recovered by an increase in scale. In other words, the transformations in scale in such a geographical space are not reversible.

The transformation in scale is also termed *scaling*. The process of making the resolution coarser (or making the map scale smaller) is called *upscaling*. In contrast, the transformation process to make the resolution finer (or map scale larger) is called *downscaling*.

8.2.3 Theoretical Foundation for Transformation in Scale: The Natural Principle

One question that arises is "does such a transformation follow any principle or law?" The answer is "yes". Li and Openshaw (1993) formulated the *Natural Principle* for such a transformation in scale in fractal geographical space.

Li and Openshaw (1993) made use of the terrain surface viewed from different height levels as an example to illustrate the *Natural Principle*, as follows:

- When one views the terrain surface from the Moon, all terrain variations disappear, and one can only see a blue ball;
- When one views the terrain surface from a satellite, then the terrain surface becomes visible, but the terrain surface looks very smooth;
- When one views the terrain surface from an airplane, the main characteristics of the terrain variations become very clear, but small details do not appear; and
- When one views the terrain surface from a position on ground, the main characteristics of the terrain variations become lost, and one sees small details.

When the viewpoint is higher, the ground area corresponding to the human eyes' resolution becomes larger, but all detailed variations within this ground area can no longer be seen, and thus the terrain surface appears more abstract. These examples underline a universal principle, the *Natural Principle* as termed by Li and Openshaw (1993). It can be stated as follows:

> For a given scale of interest, all details about the spatial variations of geographical objects (features) beyond a certain limitation cannot be presented and can thus be neglected.

It follows that a simple corollary to this process can be used as a basis for transformations in scale. The corollary can be stated as follows (Li and Openshaw 1993):

> By using a criterion similar to the limitation of human eyes' resolution, and, neglecting all the information about the spatial variation of spatial objects (features) beyond this limitation, zooming (or generalization) effects can be achieved.

Li and Openshaw (1992) also term such a limitation as the smallest visible object (SVO) or smallest visible size (SVS) in other literature (Li 2007). Figure 8.6 illustrates

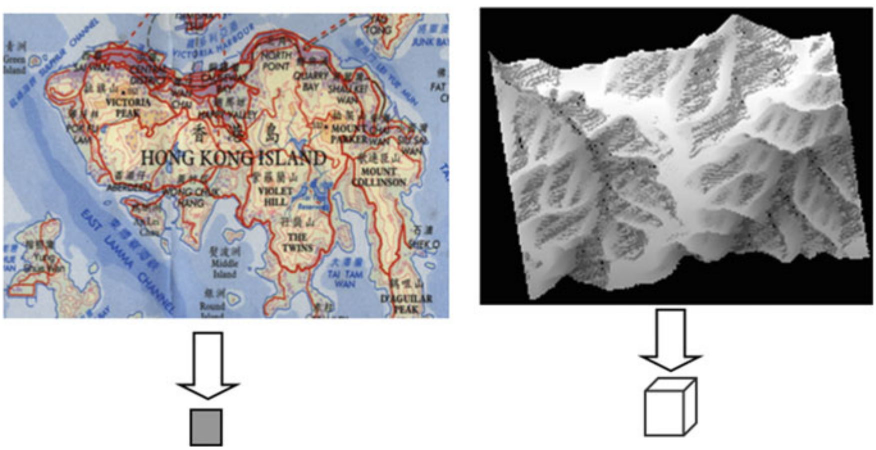


Fig. 8.6 The natural principle: spatial variations within a smallest visible size (SVS) to be neglected (Li 2007)

the idea of this corollary, that is, that all spatial variations within the SVS can be neglected, no matter how big they are on the ground.

Figure 8.7 illustrates the working example of applying the Natural Principle to a terrain surface. Figure 8.7a shows the views of a terrain surface at two different heights based on the Natural Principle, resulting in two quite different representations in terms of complexity. Figure 8.7b, c show the results viewed at levels L_A and L_B, respectively. In these two Figures, the zooming (or generalization) effects are very clear.

To apply the Natural Principle, the critical element to be considered is the value of this "certain limitation" or SVS, beyond which all spatial variations (no matter how complicated) can be neglected. Li and Openshaw (1992, 1993) suggested the following formula:

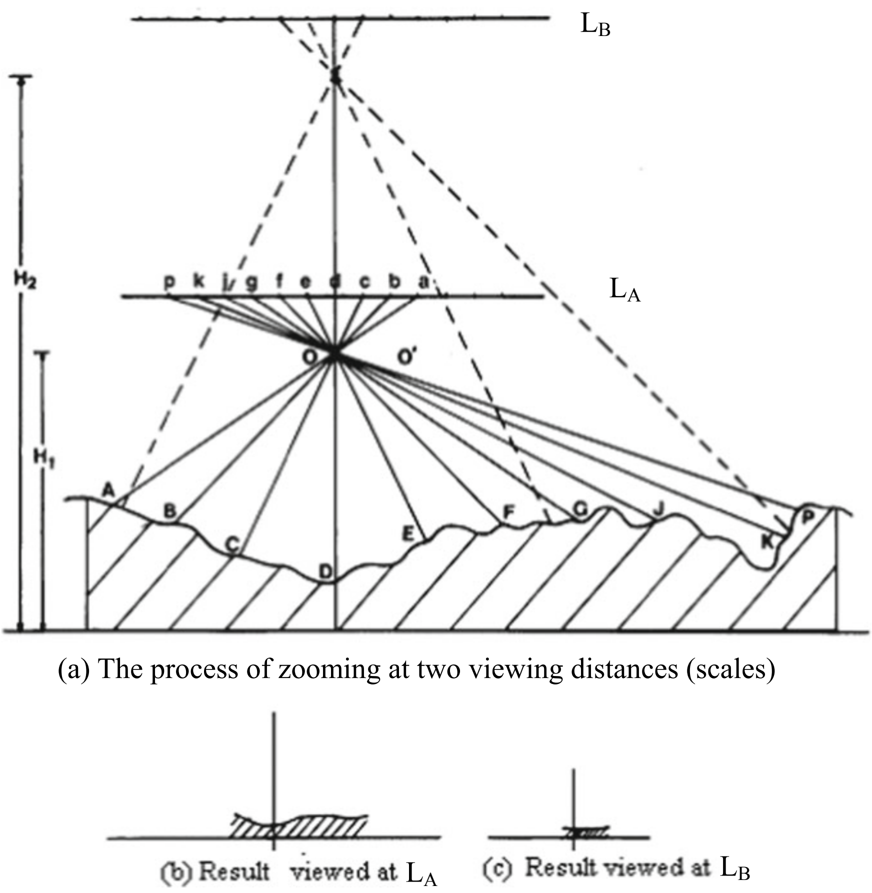


Fig. 8.7 Zooming effect of a terrain surface generated by the Natural Principle (Li and Openshaw 1993)

$$K = k \times S_T \times \left(1 - \frac{S_S}{S_T}\right) \quad (8.1)$$

where S_T and S_S are the scale factors of the target and source data, respectively; k is the SVS value in terms of map distance at the target scale and K is the SVS value in terms of ground distance at the target scale. Through intensive experimental testing, Li and Openshaw (1992) recommend a k value between 0.5 and 0.7 mm, i.e.,

$$k = \{0.5\ \text{mm},\ 0.7\ \text{mm}\} \quad (8.2)$$

8.3 Models for Transformations in Scale

To realize a transformation in scale, some transformation models must be adopted and algorithms and/or mathematical functions for these models are applied. The former is the topic of this section and the latter are described in Sect. 8.4.

8.3.1 Data Models for Feature Representation: Space-Primary Versus Feature-Primary

To record features in geographical space, two different viewpoints can be taken: feature-primary and space-primary (Lee et al. 2000).

In a feature-primary view, the geographical space is considered as being tessellated by features and the locations of these features are then determined. This kind of model is also called feature-based. In such a model, features are represented by vectors, leading to the popular term *vector data model*. Figure 8.8a–c show the representation of points, a line and an area using a vector model.

In a space-primary view, the geographical space is considered as being tessellated by space cells. In such a tessellation (partitioning), square raster cells are popularly employed, leading to the popular term *raster data model*. In each raster cell, there could be a feature or there might be no features. A point is represented by a pixel (picture element); a line is represented by a string of connected pixels and an area is formed by a set of connected pixels, as shown in Fig. 8.8d–f. The cells can be in any form, regular or irregular. Irregular triangular networks are another popular tessellation.

On a spherical surface, longitude/latitude is the coordinate system for feature-primary representation. The cells with an equal interval in latitude/longitude (e.g., $6' \times 6'$) are the raster equivalent of spherical tessellation (Fig. 8.9a). However, the actual area size of such a cell varies with the latitude. To overcome this problem, the quaternary triangular mesh (QTM) (Fig. 8.9b) has been used (e.g., Dutton 1984, 1996). The cells can be any shape (e.g., triangle, hexagon), regular or irregular.

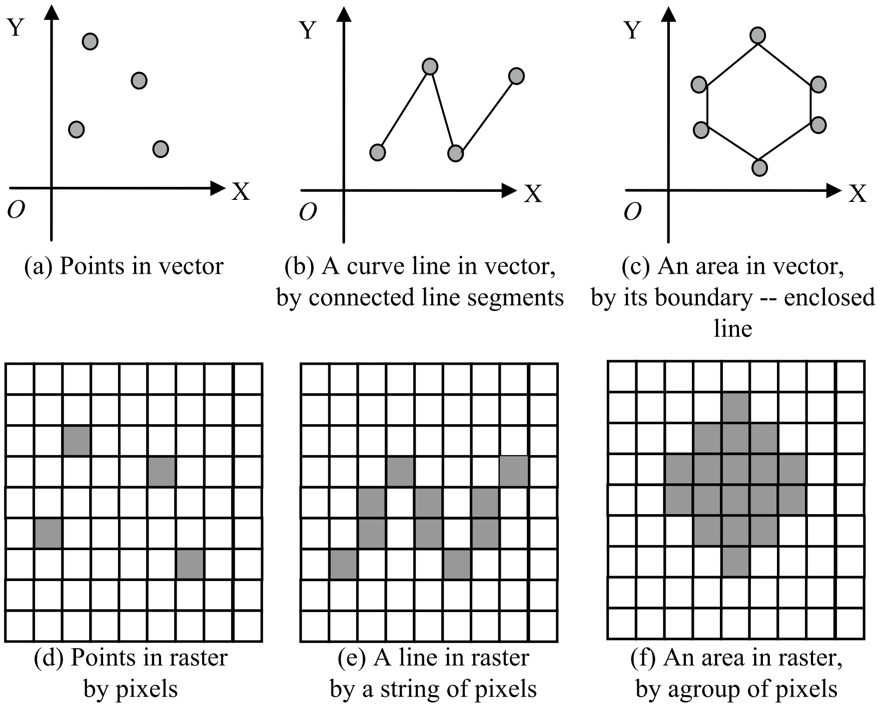


Fig. 8.8 Feature-primary and space-primary representations of spatial features: vector and raster models

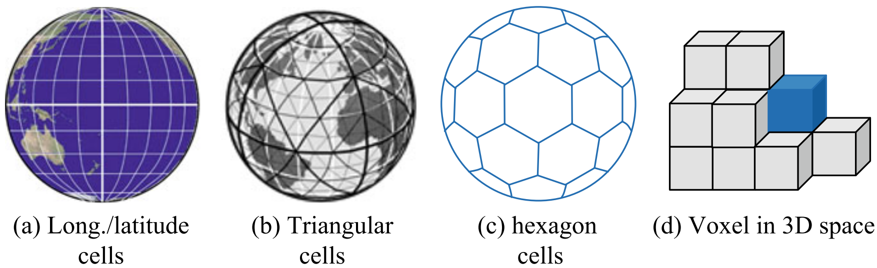


Fig. 8.9 Spatial tessellation of a spherical surface and a 3D space

Figure 8.9c shows the use of a regular hexagon diagram for such a tessellation. For 3D space, the voxel (volume element) is the raster equivalent for space tessellation (Fig. 8.9d).

As the natures of the raster and vector data models are quite different, the model for transformation in scale in these two data models might also differ. Thus, separate subsections are devoted to these topics.

8.3.2 *Space-Primary Hierarchical Models for Transformation in Scale*

Hierarchical models are popular for the multiscale representation of spatial data at discrete scales. For example, Google Maps, Virtual Earth and Tianditu have all adopted hierarchical models for the representation of images and maps. Figure 8.10 shows the first three zoom levels of the hierarchical model used by Google Maps (Stefanakis 2017). This model has a special name, the pyramid model, which is a result of aggregating a 2 × 2 pixel into one pixel. The number of pixels (squares) at the nth level is 4^{n-1}. A more general form of aggregation is to transform any N × N pixels into one pixel.

A more general form of transformation to create a hierarchical representation is to transform N × N pixels into M × M pixels, e.g., a 5 × 5 into a 2 × 2 or a 3 × 3 into a 2 × 2. In such cases, a resampling process (instead of simple aggregation) is required.

With a hierarchical model, the resolution and cartographic ratio at each level are not necessarily uniform. Typical examples of hierarchical models with variable resolutions are shown in Fig. 8.11, i.e., the quadtree and binary tree models.

With the pyramid and quadtree models, the hierarchical levels are fixed and the transformation in scale jumps from one level to another like stairs. To make the transformation absolutely smooth, we need to make the difference between two steps of the stairs infinitely small, to make the stairs become a continuous linear slope (see Fig. 8.12).

For hierarchical representation on a spherical surface, the Open Geospatial Consortium (OGC) approved a new standard called the Discrete Global Grid System (DGGS) (OGC 2019) The hierarchical representation of QTM as shown in Fig. 8.9b is an example of such a DGGS.

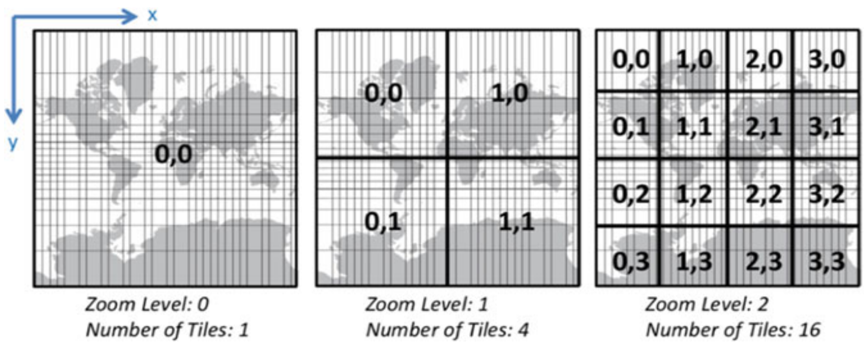


Fig. 8.10 Pyramid model used in Google Maps: the first three zoom levels (Stefanakis 2017)

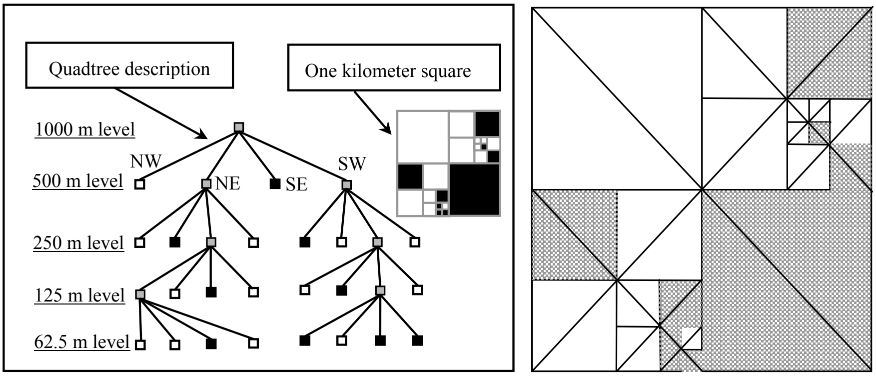


Fig. 8.11 Hierarchical representations of area features with quadtree and binary tree models

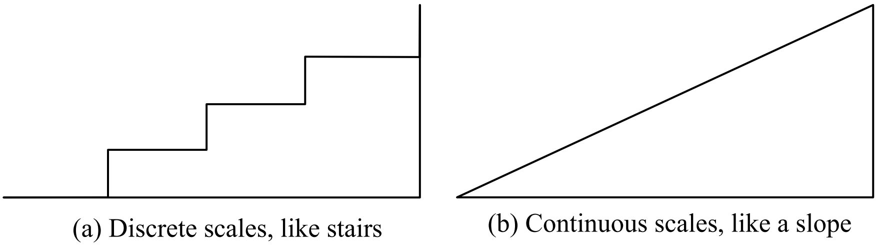


Fig. 8.12 Discrete and continuous transformations in scale: steps and a linear slope

8.3.3 Feature-Primary Hierarchical Models for Transformation in Scale

Hierarchical models have also been used to represent point, line and area features in feature-primary models. Figure 8.13 shows such a representation for the points on a line. At level 1, only two points, i.e., points (1, 1) and (1, 2), will be used to represent the line; at level 2, in addition to the two points at level 1, point 2 will also be used; and at level 3, points (3, 1) and (3, 2) will also be used. This kind of model has been employed for progressive transmission of vector data.

Figure 8.14 shows the hierarchical representation of a river network by the Horton and Shreve models. Figure 8.14a is a hierarchical representation based on river segments. The formation of such a representation starts from the level 1 branches. A segment of level 2 is formed by two or more segments of level 1. Similarly, a segment of level 3 is formed by two or more segments of level 2. All higher level segments are formed by following this principle. Figure 8.14b is a hierarchical representation formed by the Horton model based on a river stroke, which is a concatenated segment. Figure 8.14c is a hierarchical representation formed by the Shreve model. The numbering in this hierarchy is formed by adding the numbers of upstream branches.

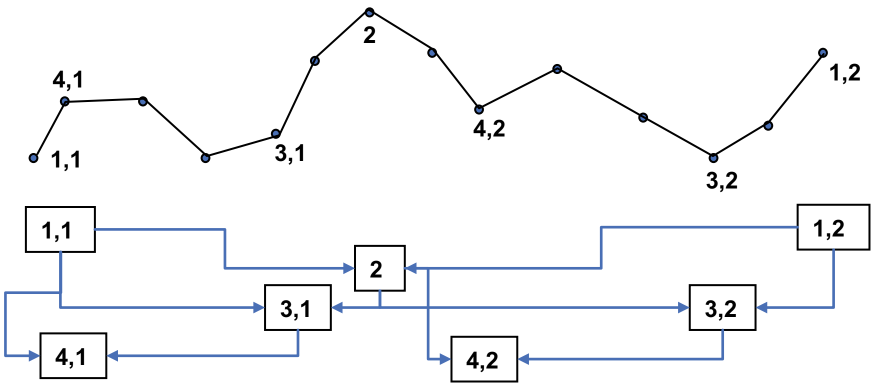


Fig. 8.13 Hierarchical representations of points on a line

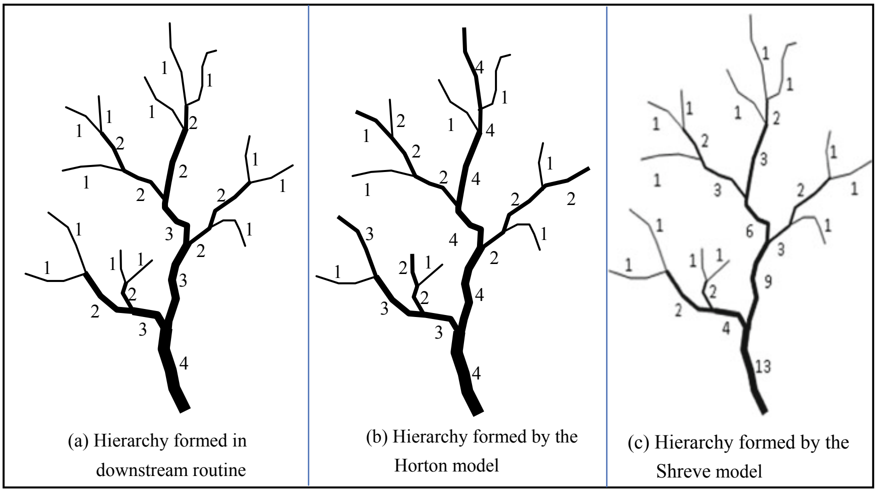


Fig. 8.14 Hierarchical representation of a river network using the Horton and Shreve models (Li 2007)

For example, the ranking value for the segment with the highest ranking is 13, which is a result of adding 9 and 4. Such a numbering of ranking is not continuous.

Figure 8.15 shows the hierarchical representation of two transportation networks. In this case, the importance of each road is evaluated based on geometric information and/or thematic information. A ranking value is assigned to each road.

Figure 8.16 shows a hierarchical representation of area features. The area features in the whole area are first connected by a minimum spanning tress (MST) as a whole group, i.e., Group A. Group A is then subdivided into subgroups B and C by breaking the tree at the connection with the largest span. Similarly, Group B is broken into D and E, and Group C is broken into F and G. The subdivision goes on

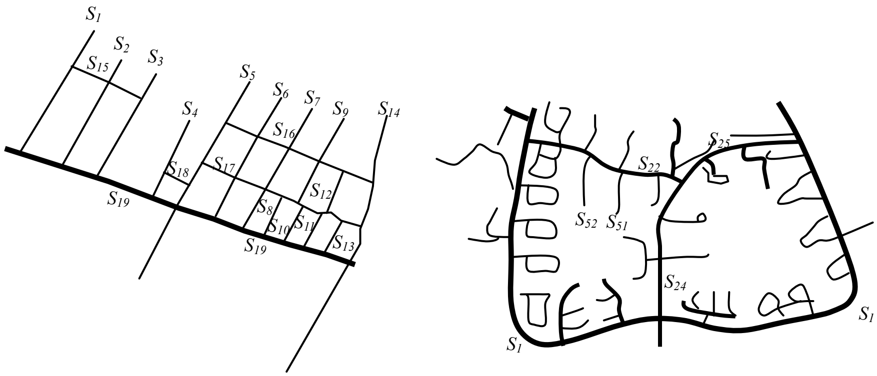


Fig. 8.15 Hierarchical representations of transformation networks (Zhang and Li 2009)

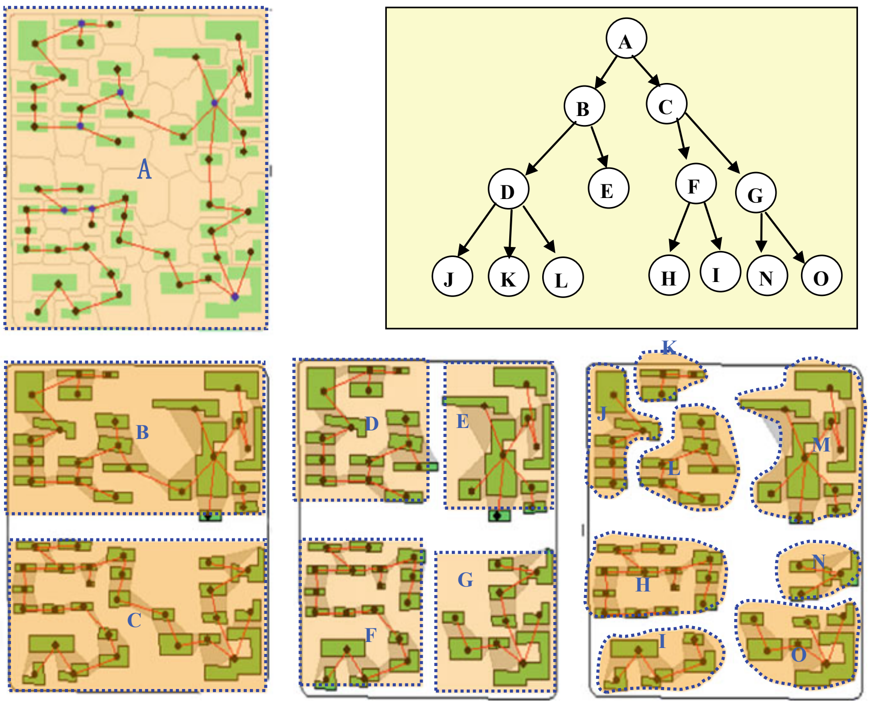


Fig. 8.16 Hierarchical representations of area features (Ai and Guo 2007)

until a criterion is met or until the complete hierarchy is constructed. In the end, a hierarchical representation is formed.

8.3.4 Models of Transformation in Scale for Irregular Triangulation Networks

An irregular triangulation network is an irregular space tessellation that has been widely used for digital terrain models (DTMs). In such a representation, the resolution is variable across the space. Therefore, special models should be used to make the resolution transformable from one to another. Four basic transformation models have been developed for such a purpose (Li 2005):

- *Vertex removal*: A vertex in the triangular network is removed and new triangles are formed.
- *Triangle removal*: A complete triangle with three vertices is removed and new triangles are formed.
- *Edge collapse*: An edge with two vertices is collapsed to a point and new triangles are formed.
- *Triangle collapse*: A complete triangle with three vertices is collapsed to a point and new triangles are formed.

Figure 8.17 illustrates these four transformation models.

8.3.5 Models for Geometric Transformation of Map Data in Scale

The hierarchical model described in Sect. 8.3.2 is suitable to represent raster image data because images are numerical data that naturally record the earth and such a recording follows the Natural Principle described in Sect. 8.2.3. Figure 8.18 shows four images with different resolutions, the result of a “2×2 into “1×1” aggregation. These images appear to be very natural. However, for the categorical data of topographic maps, such a simple transformation does not work well, and there is a need for other transformation models.

Topographic maps are produced via a complicated intellectual process that consists of abstraction, symbolization, generalization, selective omission and simplification. During this process, small details are ignored (or grouped together). All features are represented by symbols (geometric or pictorial). The colors of the symbols are not necessarily the natural colors of features. The graphic symbols are annotated with text (e.g., name of a street/town/city). There are requirements for minimum size, minimum separation and minimum differentiation for graphic elements. Thus, when a map at a larger scale (Fig. 8.19c) is simply reduced by 4 times (equivalent to

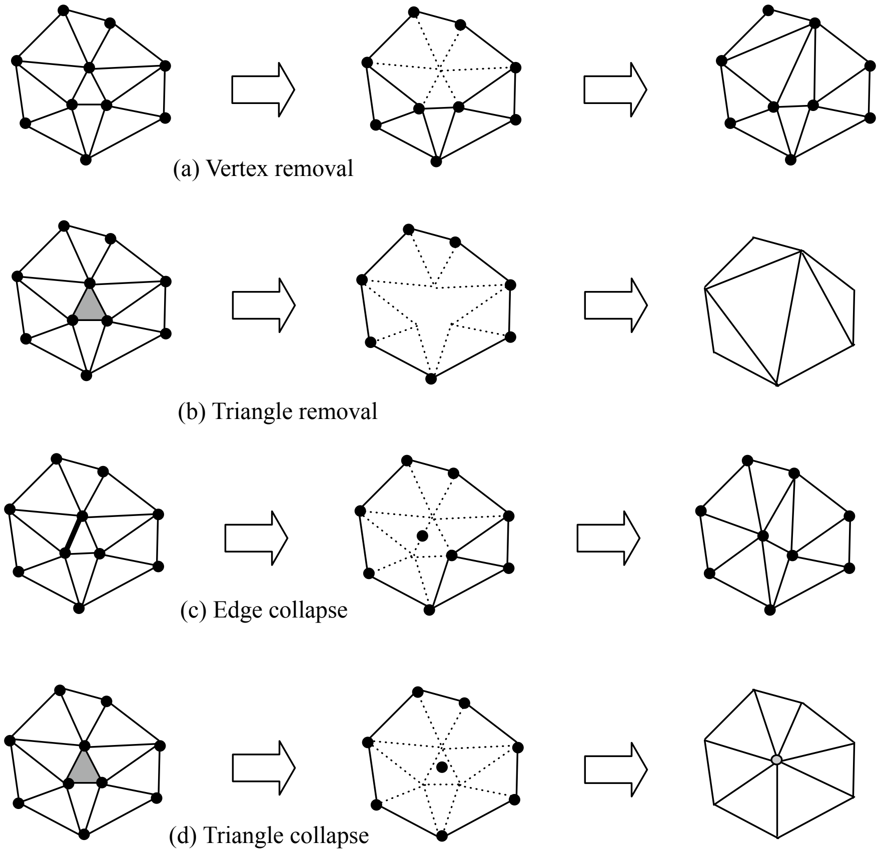


Fig. 8.17 Basic models for geometric transformation in scale for a triangular network (Li 2005)

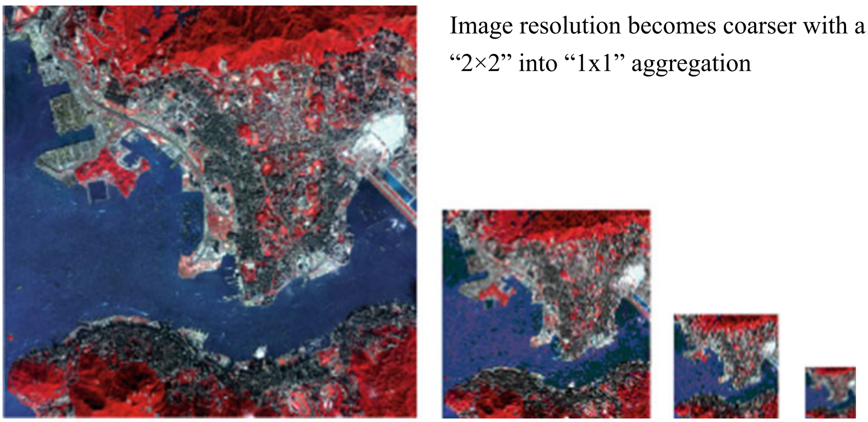
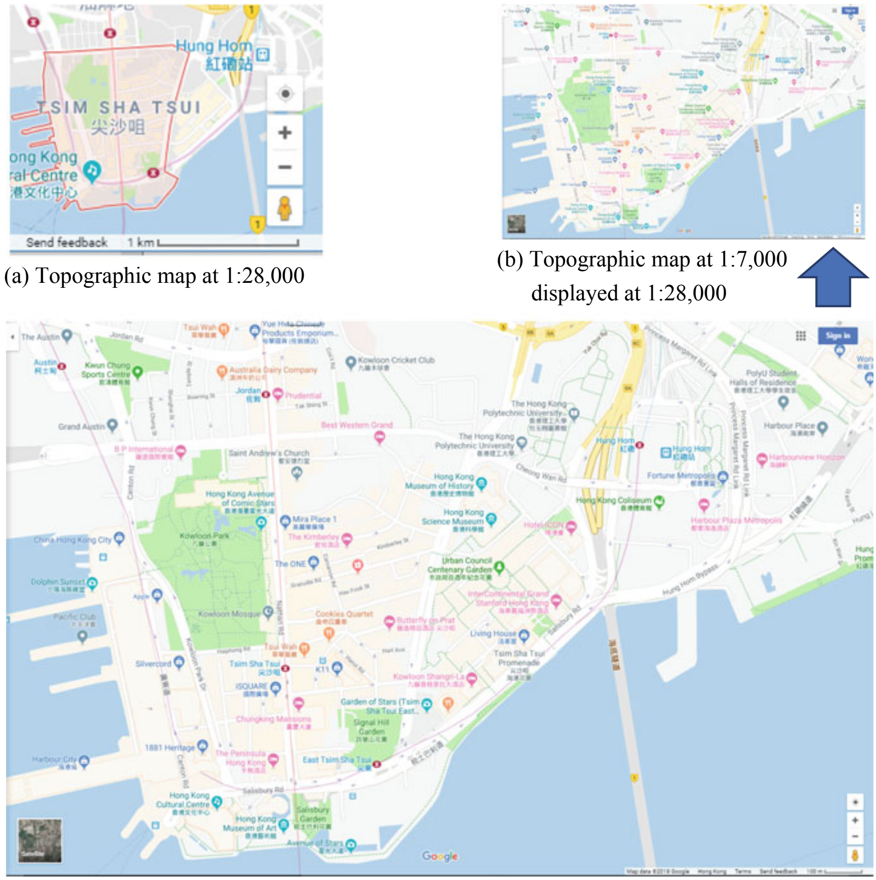


Fig. 8.18 Four images with the same cartographic ratio but different resolutions



(a) Topographic map at 1:28,000

(b) Topographic map at 1:7,000 displayed at 1:28,000

(c) Topographic map at 1:7,000

Fig. 8.19 Kowloon Peninsula represented on maps at two different scales, via generalization and simple scale reduction (extracted from Google Maps)

a “2 × 2 into 1” aggregation), the graphics (Fig. 8.19b) become unclear because the minimum requirements can no longer be met. Figure 8.20 illustrates such a situation with the aggregation of buildings as an example. A set of special models is needed for the transformation of map data from one scale to another to make the graphics at the smaller scale clear (Fig. 8.19a).

The transformation of maps from a larger scale to a smaller scale is called map generalization and has long been studied in the cartographic community. Some transformation models have been identified by researchers. In the traditional textbook by Robinson et al. (1984), only four models are listed, i.e., classification, induction, simplification and symbolization. In the 1980s, more models were identified, and a list of 12 models was produced by McMaster and Shea (1992). Many of these models were still too general to be precisely implemented in a computer system.

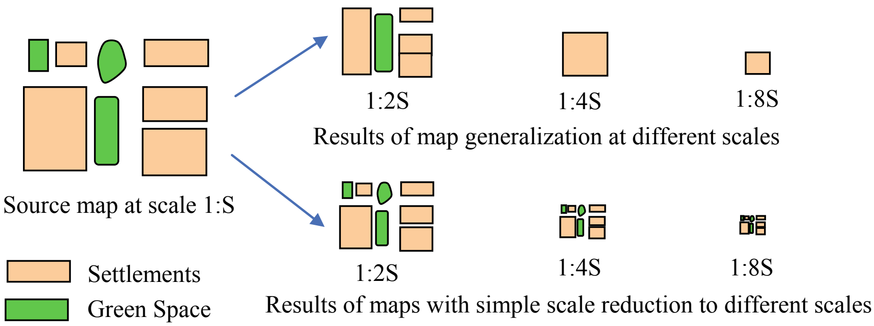


Fig. 8.20 Comparison of map generalization and simple scale reduction

More recently, Li (2007) produced 40 detailed models for implementation. These models are divided into six sets: three sets for individual points, individual lines and individual areas and the other three sets for a class of points, a class of lines and a class of areas. Tables 8.1, 8.2, 8.3, 8.4, 8.5 and 8.6 list the six sets of models.

Table 8.1 Models for geometric transformations in scale of individual point features (Li 2007)

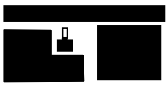
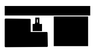
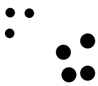
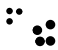
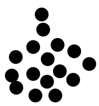
Transformation model	Large-scale	Photo-reduced	Small-scale
Displacement (move because it is too close to another feature)			
Elimination (too small to represent, thus removed)			
Magnification (enlarged due to importance)			

Table 8.2 Models for geometric transformations in scale of a set of point features (Li 2007)

Transformation model	Large-scale	Photo-reduced	Small-scale
Aggregation (group points and make a new one)			
Regionalization (delineate a boundary outlined by points and make a new area feature)			

(continued)

Table 8.2 (continued)

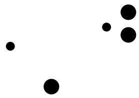
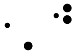
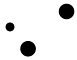
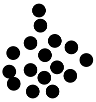
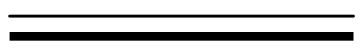
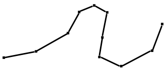
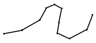
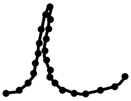
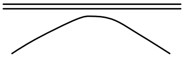
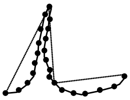
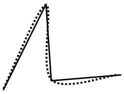
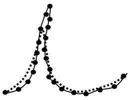
Transformation model	Large-scale	Photo-reduced	Small-scale
Selective Omission (retain more important points and omit less important ones)			
(Structural) Simplification (cluster complexity; the main structure is retained)			
Typification (typical pattern kept while points removed for clarity)			

Table 8.3 Models for geometric transformations in scale of individual line features (Li 2007)

Transformation model		Large-scale	Photo-reduced	Small-scale
Displacement (to move a line away from the position because it is too close to another feature)				
Elimination (to remove the line because it is too minor to be included)				
(Scale-driven) generalization (main structure suitable at target scale retained but small details removed)				
Partial modification (to modify the shape of a segment within a line)				
Point reduction (to reduce the number of points by removing less important points)				
Smoothing (to make the data appear smoother)	*Curve-fitting* (to fit a curve through a set of points)			
	Filtering (to filter out the high-frequency components or small details of a line)			

(continued)

Table 8.3 (continued)

Transformation model	Large-scale	Photo-reduced	Small-scale
Typification (typical patterns of the line bends retained while removing some of them)			

Table 8.4 Models for geometric transformations in scale of a set of line features (Li 2007)

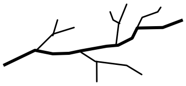
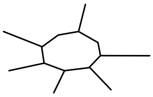
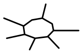
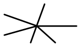
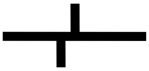
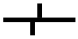
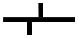
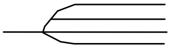
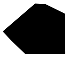
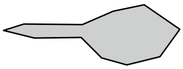
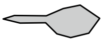
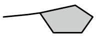
Transformation model		Large-scale	Photo-reduced	Small-scale
Selective omission (to select more important points and remove less important points)				
Collapse (to reduce the dimension)	Ring-to-point			
	Double-to-single			
Enhancement (to keep the characteristics clear)				
Merging (to combine to two or more close lines together)				
Displacement (to move one away from others or both away from each other)				

Table 8.5 Models for geometric transformations in scale of individual area features (Li 2007)

Transformation model		Large-scale	Photo-reduced	Small-scale
Collapse (to reduce the dimension of features)	Area-to-point			
	Area-to-line			
	Partial			
Displacement (to move the area to a slightly different position to solve the conflict problem)				

(continued)

Table 8.5 (continued)

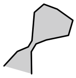
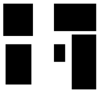
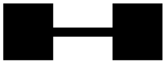
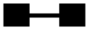
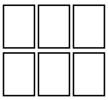
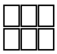
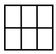
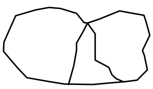
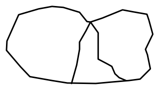
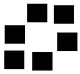
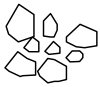
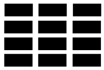
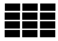
Transformation model		Large-scale	Photo-reduced	Small-scale
Exaggeration (to enlarge one or two dimensions of a small area)	*Directional thickening* (to enlarge an area feature in a direction)			
	Enlargement (to uniformly magnify in all directions)			
	Widening (to widen the bottleneck of an area feature)			
Elimination (to eliminate data that is too small to represent				
(Shape) Simplification (to reduce the complexity of a boundary)				
Split (to split an area into two because the connection between them is too narrow)				

Table 8.6 Models for geometric transformations in scale of a set of area features (Li 2007)

Transformation model	Large-scale	Photo-reduced	Small-scale
Aggregation (to combine area features, e.g., buildings separated by open space)			
Agglomeration (to make area features bounded by thin area features into adjacent area features)			
Amalgamation (to combine area features, e.g., buildings separated by another feature such as roads)			
Dissolving (to split a small area into pieces and merge these pieces into adjacent areas)			

(continued)

Table 8.6 (continued)

Transformation model	Large-scale	Photo-reduced	Small-scale
Merging (to combine two adjacent areas into one)			
Relocation (to move more than one feature around to solve the crowding problem)			
(Structural) Simplification (to retain the structure of area patches by selecting important ones)			
Typification (to retain the typical pattern, e.g., a group of areas aligned in rows and columns)			

8.3.6 Models for Transformation in Scale of 3D City Representations

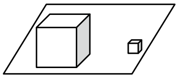
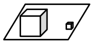
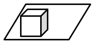
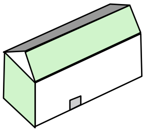
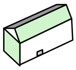
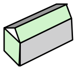
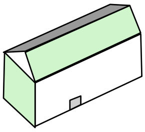
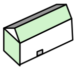
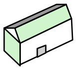
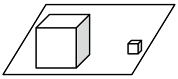
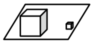
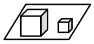
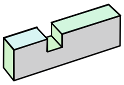
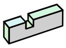
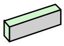
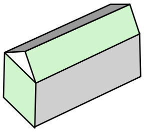
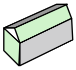
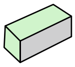
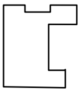
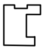
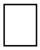
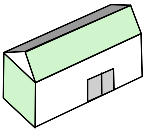
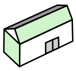
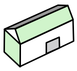
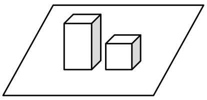
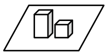
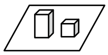
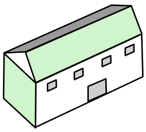
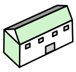
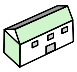
For 3D representation of digital cities, the CityGML, which was officially adopted by the OGC in 2008, specifies five well-defined consecutive levels of detail (LOD) as follows, an example of which is shown in Fig. 8.21 (Kolbe et al. 2008):

- LOD 0—regional, landscape
- LOD 1—city, region
- LOD 2—city districts, projects
- LOD 3—architectural models (outside), landmarks
- LOD 4—architectural models (interior)

For the transformation in scale of 3D features, a set of models is listed in Table 8.7, which is a summary of models proposed in the literature.

Fig. 8.21 The five levels of detail (LoD) defined by CityGML (Kolbe et al. 2008)

Table 8.7 Models for transformation in scale of 3D features

Transformation model		At large scale	Photo-reduced	At small scale
Elimination	Geometric elimination			
	Thematic elimination			
Exaggeration	Thematic exaggeration			
	Geometric exaggeration			
Simplification	Vertical simplification			
	Flattening			
	Squaring			
	Thematic simplification			
Displacement				
Typification				

8.4 Mathematical Solutions for Transformations in Scale

In the previous section, several sets of models for the transformation in scale were described. These models express what is achieved in such transformations, e.g., the shape is simplified, important points retained, and/or the main structure is preserved. To make these transformations work, mathematical solutions (e.g., algorithms and mathematical functions) must be developed for each of these transformations. A selection of these solutions is presented in this section.

8.4.1 Mathematical Solutions for Upscaling Raster Data: Numerical and Categorical

For **raster-based numerical data** such as images and digital terrain models (DTMs), aggregation is widely used to generate hierarchical models. In recent years, wavelet transform (e.g., Mallat 1989), Laplacian transform (Burt and Adelson 1983) and other more advanced mathematical solutions have also been employed. The commonly used aggregation methods are by mode, by median, by average, and by Nth cell (i.e., Nth cell in both the row and column). Figure 8.22 shows a "3 × 3 to 1 × 1" aggregation with these four methods. The 6 × 6 grid is then aggregated into a 2 × 2 grid.

If the new cell interval is not multiples of the original cells, then interpolation must be applied to resample the data. Bilinear and weighted averaging interpolations are widely used for resampling. Figure 8.23 shows the resampling of a 3 × 3 grid into a 2 × 2 grid using weighted averaging interpolation.

Bilinear interpolation can be performed for any four points (not along a line). The mathematical function is as follows:

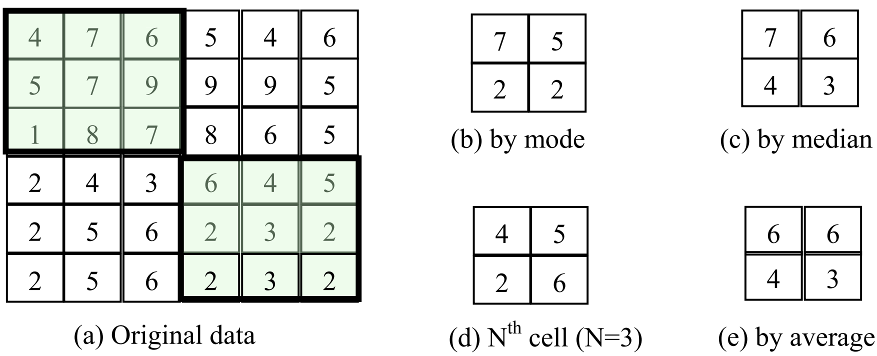
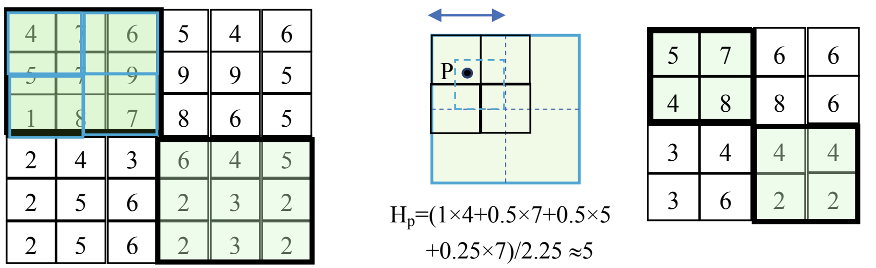


Fig. 8.22 "3 × 3 to 1 × 1" aggregation of numerical data



(a) Original data (6×6 grid) (b) Area-weighted interpolation (c) Result: 4×4 grid

Fig. 8.23 "3 × 3 to 2 × 2" resampling of numerical data

$$z = a_0 + a_1 x + a_2 y + a_3 xy \tag{8.3}$$

where a_0, a_1, a_2, a_3 is the set of four coefficients, which are to be determined by four equations that are formed by making use of the coordinates of four reference points, i.e., the centers of the four grid cells in Fig. 8.23b: $P_1(x_1, y_1, z_1)$, $P_2(x_2, y_2, z_2)$, $P_3(x_3, y_3, z_3)$ and $P_4(x_4, y_4, z_4)$. The mathematical formula is as follows:

$$\begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 & x_1 y_1 \\ 1 & x_2 & y_2 & x_2 y_2 \\ 1 & x_3 & y_3 & x_3 y_3 \\ 1 & x_4 & y_4 & x_4 y_4 \end{bmatrix}^{-1} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} \tag{8.4}$$

Once the coefficients a_0, a_1, a_2, a_3 are computed, the height Z_P of any point P with a given set of coordinates (x_P, y_P) can be obtained by substituting (x_P, y_P) into Eq. (8.1).

The mathematical expression of weighted averaging interpolation is as follows:

$$z = \frac{\sum_{i=1}^{n} w_i z_i}{\sum_{i=1}^{n} w_i} \tag{8.5}$$

where w_i is the weight of the ith reference point; z_i is the height of the ith reference point; and n is the total number of the reference points used. In the case of Fig. 8.23b, n = 4.

Weights may be determined by using different functions. The simplest weighting function assigns an equal weight to all reference points. However, it seems unfair to those reference points that are closer to the interpolation point, as such points should have a higher influence on the estimate. As a result, distance-based or area-based weighting are more commonly used. The inverse of distance is most popularly used:

$$w = \frac{1}{d} \ or \ w = \frac{1}{d^2} \tag{8.6}$$

where d is the distance from a reference point to the interpolation point. In the case of interpolating the height of P in Fig. 8.23b, the four distances from the four (old) cell centers to point P will be used. Figure 8.23b also shows that the distance of each cell center to the interpolation point P is directly related to the size of the area contributed by each (old) cell to the new cell. If the area size is denoted as A, the weighting function is

$$w_i = A_i \tag{8.7}$$

For example, if the area of the new cell is composed of 100% of the upper left cell, 50% of the upper right cell, 50% of the lower left cell and 25% of the lower right cell, the weights of these four cells are 1.0, 0.5, 0.5 and 0.25, and the result of the interpolation is:

$$z_p = 1 \times 4 + 0.5 \times 7 + 0.5 \times 5 + 0.25 \times 7)/2.25 \approx 5$$

For the **raster-based categorical data**, the averaging and median are no longer applicable. The mode (also called the majority in some literature) is still valid and widely used. Figure 8.24b shows such a result. However, the value for the upper right cell is difficult to determine as there is no mode (majority) in the 3 × 3 window at the upper right corner of the original data (Fig. 8.24a). Notably, some priority rules or orders are in practical use. For example, a river feature is usually given a priority because thin rivers are likely to be broken after aggregation. Figure 8.25 shows the improvement in the connectivity of river pixels with water as the priority. Figure 8.24c-e show the results with different options, e.g., random selection and central pixel. It is also possible to consider the statistical distribution of the original data (e.g., A = 8, T = 10, W = 6, S = 11) to try to maintain the distribution as much as possible.

In the aggregation/resampling process, as illustrated in Figs. 8.22, 8.23 and 8.24, a moving window is used but the question of the most appropriate window size has rarely been addressed. Li and Li (1999) suggested that the size of the moving window for aggregation/resampling should be computed based on the resolutions

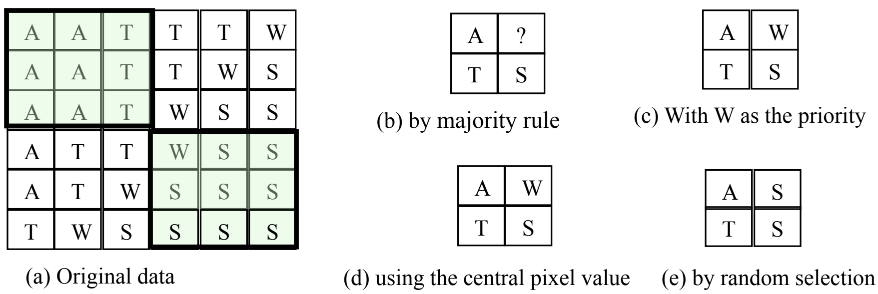
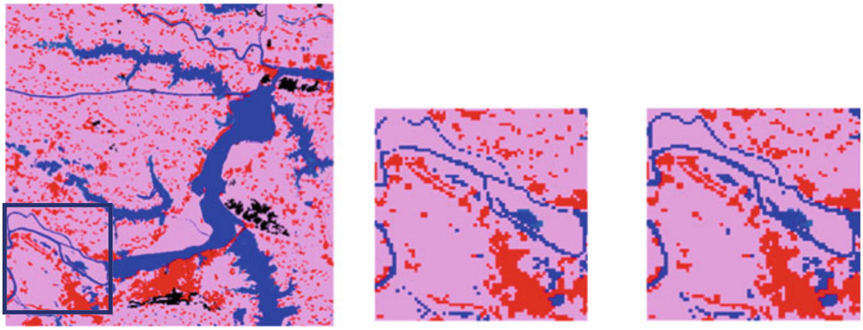


Fig. 8.24 Aggregation of raster-based categorical data



(a) Original data (b) "3×3 to 1" aggregation (c) "3×3 to 1" aggregation with water as the priority

Fig. 8.25 Aggregation of landcover data with priority (extracted from Tan 2018)

(scales) of the input and output, following the *Natural Principle* (Li and Openshaw 1993) described in Sect. 8.2.3. Mathematically,

$$W = \frac{K}{R_{in}} \tag{8.8}$$

where R_{in} is the resolution (scale) of the input data; K is the SVS value in terms of ground distance at the target scale computed by Eq. (8.1), and W is the size of the window's side in terms of pixel numbers (of input data).

8.4.2 Mathematical Solutions for Downscaling Raster Data

Downscaling produces a finer spatial resolution raster data than that of the input data through prediction. It is possible to use simple resampling (as described in Sect. 8.4.1) to achieve downscaling. However, methods based on spatial statistical analysis are more theoretically grounded and have become popular (Atkinson 2008, 2013), particularly area-to-point prediction (ATPP). Double dictionary learning has also been used (Xu and Huang 2014).

Area-to-point kriging (ATP Kriging or ATPK) (Kyriakidis 2004) is the typical method. ATP Kriging can ensure the coherence of predictions, such as by ensuring that the sum of the downscaled predictions within any given area are equal to the original aggregated count. Some variants of ATP Kriging have also been developed, e.g., ATP Poisson Kriging (Goovaerts 2008, 2009, 2010), indicator cokriging (Boucher and Kyriakidis 2006) and ATP regression Kriging (Wang et al. 2015). In this section, the base version of ATP Kriging is described.

The basic principle behind Kriging is weighted averaging. The weights are optimized by using the semivariogram computed from the original data.

$$Z_{e,p} = \sum w_i \times Z_i \tag{8.9}$$

where $Z_{e,p}$ is the estimated (interpolated) value; Z_i is the value of the ith reference point; w_i is the value of the ith reference point and $\sum w_i = 1$.

The interpolated value $Z_{e,p}$ is very likely to deviate from the actual value at point p, $Z_{a,p}$. The difference is called the estimation error. The variance of these deviations is expressed by Eq. (8.10).

$$\sigma_z^2 = \frac{\sum_{i=0}^{n} (Z_{e,p} - Z_{a,p})_i^2}{n} \tag{8.10}$$

The basic principle of Kriging is to produce the minimum estimation variance by choosing a set of optimal weights. Such weights are obtained by solving a set of simultaneous equations:

$$\begin{aligned} w_1 \times \gamma(d_{11}) + w_2 \times \gamma(d_{12}) + \cdots\cdots + w_m \times \gamma(d_{1m}) + \lambda &= \gamma(d_{1P}) \\ w_1 \times \gamma(d_{21}) + w_2 \times \gamma(d_{22}) + \cdots\cdots + w_m \times \gamma(d_{2m}) + \lambda &= \gamma\left(d_{2p}\right) \\ \cdots\cdots \\ w_{1m} \times \gamma(d_{m1}) + w_{12} \times \gamma(d_{m2}) + \cdots\cdots + w_{1m} \times \gamma(d_{mm}) + \lambda &= \gamma(d_{mP}) \\ w_1 + w_2 + \cdots\cdots + w_m &= 1 \end{aligned} \tag{8.11}$$

where w_i is the weight of the ith reference point; λ is the Lagrange multiplier; and $\gamma(d)$ is the semivariogram value of points with distance d apart, which can be expressed as follows:

$$\gamma(d) = \frac{\sum_{i=0}^{n_d} (Z_i - Z_{i+d})_i^2}{n_d} \tag{8.12}$$

In ATP Kriging, the interpolation finds an estimate for a point at higher resolution. In such a case, a cell point at coarser resolution corresponds to an area at higher resolution. Therefore, the set of simultaneous equations is as follows:

$$\begin{aligned} w_1 \times \gamma(d_{11}) + w_2 \times \gamma(d_{12}) + \cdots\cdots + w_m \times \gamma(d_{1m}) + \lambda &= \gamma(d_{1A}) \\ w_1 \times \gamma(d_{21}) + w_2 \times \gamma(d_{22}) + \cdots\cdots + w_m \times \gamma(d_{2m}) + \lambda &= \gamma(d_{2A}) \\ \cdots\cdots \\ w_{1m} \times \gamma(d_{m1}) + w_{12} \times \gamma(d_{m2}) + \cdots\cdots + w_{1m} \times \gamma(d_{mm}) + \lambda &= \gamma(d_{mA}) \\ w_1 + w_2 + \cdots\cdots + w_m &= 1 \end{aligned} \tag{8.13}$$

where $\gamma(d_{iA})$ is the point-to-block semivariogram value from the ith point to area A. It is the same as the average of the point-to-point semivariogram value between the ith point and the points within A.

8.4.3 *Mathematical Solutions for Transformation (in Scale) of Point Set Data*

As discussed in Sect. 8.3.5, a number of transformations are possible, such as regionalization, aggregation, selective omission, structural simplification, and typification. In both aggregation and regionalization, the clustering plays a central role. In aggregation, a cluster is represented by a point; in regionalization, a cluster is represented by an area. Thus, clustering is discussed here.

Clustering is one of the most primitive activities of human beings (Anderberg 1973; Xu and Wunsch 2005). Clustering of spatial points is one of the main tasks in digital earth such as in spatial data mining and exploratory spatial analysis (Estivill-Castro and Lee 2002; Miller and Han 2009; Openshaw et al. 1987). Numerous clustering methods are available. The classic algorithms are the K-means algorithms, and the ISODATA algorithm is an important extension of K-means (Ball and Hall 1967). Classification by K-means is achieved by minimizing the sum of the square error over all K clusters (i.e., the objective function) as follows:

$$E = \sum_{k=1}^{K} \sum_{x_i \in C_k} \left| x_i - \bar{C}_k \right|^2 \tag{8.14}$$

where $\bar{C}_k$ is the mean of the cluster C_k. The procedure of this algorithm is as follows:

(1) arbitrarily select K points from data set (X) as initial cluster centroids;
(2) assign each point in X to the cluster whose centroid is closest to the point;
(3) compute the new cluster centroid for each cluster; and
(4) repeat Steps (2) and (3) until no change can be made.

However, Li et al. (2017) noted that (a) all clustering algorithms discover clusters in a geographical dataset even if the dataset has no natural cluster structure and (b) quite different results will be obtained with different sets of parameters for the same algorithm. These two problems lead to the difficulty in understanding the implications of the clustering results. Consequently, Li et al. (2017) proposed a scale-driven clustering theory. In this theory, scale is modeled as a parameter of a clustering model; the scale dependency in the spatial clustering is handled by constructing a hypothesis testing; and multiscale significant clusters can be discovered by controlling the scale parameters in an objective manner. The basic model can be written as

$$\mathrm{C} = f(D, A) \tag{8.15}$$

where C is the clustering result; f is the clustering model; A is the analysis scale (the size of clusters or the degree of homogeneity within clusters); and D is the data scale (e.g., resolution and extent).

The clustering consists of two major tasks, i.e., estimation of the density for each point and detection of dense regions. The procedure is as follows:

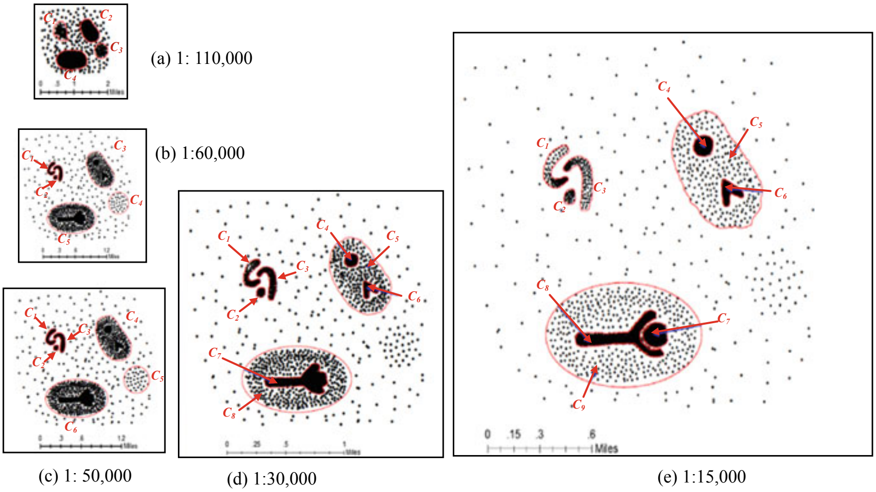


Fig. 8.26 Scale-driven clustering: five results produced at five different scales from the same simulated dataset (Li et al. 2017)

(1) Control the data scale: Determine the SVS (smallest visible size) based on input and output data scales and following the Natural Principle, and ignore all the points within an SVS in the calculation of point data density.
(2) Identify high-density points: The probability density function (PDF) of the dataset is estimated with adaptive analysis scales. The PDF are statistically tested against a null distribution. Points with a significantly higher density are then identified.
(3) Group the high-density points into clusters: Clusters with different densities are formed by adaptively breaking the long edges in the triangulation of high-density points. The significance of clusters obtained at multiscales can be statistically evaluated.

Figure 8.26 shows an example of transforming a set of point data into five different scales. When the output scale decreases (or the resolution becomes coarser), fewer classes can be identified by this clustering technique.

8.4.4 Mathematical Solution for Transformation (in Scale) of Individual Lines

As discussed in Sect. 8.3.5, there are eight different types of transformation for individual lines and the algorithms/mathematical solutions for the transformation models are discussed in detail by Li (2007). In this section, two classic algorithms are described in detail, i.e., the Douglas–Peucker algorithm (Douglas and Peucker 1973) and the Li–Openshaw algorithm (Li and Openshaw 1992).

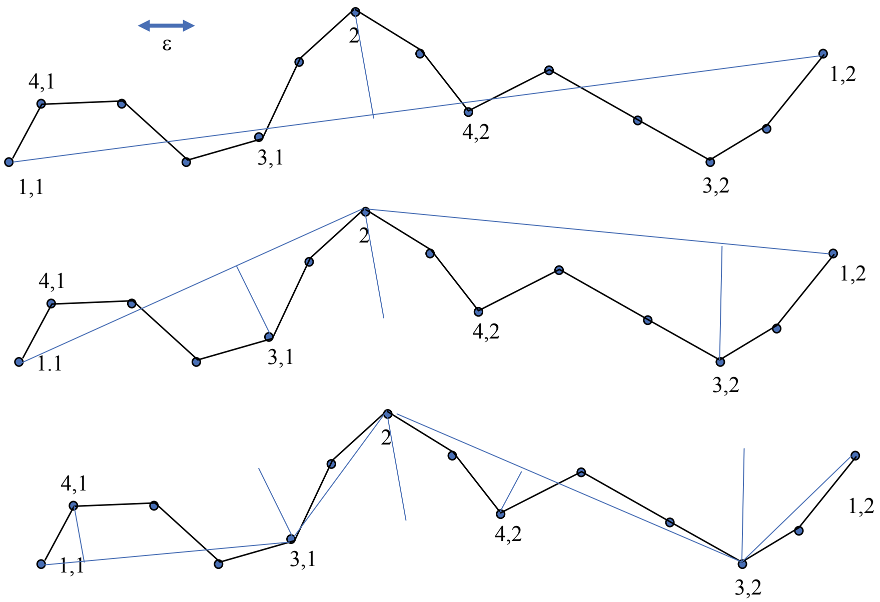


Fig. 8.27 Douglas–Peucker algorithm for generation of a point hierarchy

In Fig. 8.13, a hierarchical representation of the points on a line is presented. The order of these points is sorted by the Douglas–Peucker algorithm. The working principle of this algorithm is illustrated in Fig. 8.27. A curve line is given with an ordered set of points, and a distance tolerance ε (> 0) is set. The basic idea is to use a straight line connecting the first and last points to represent the curve line if the deviations from all line points to the straight line are smaller than ε. In this case, only the two end points are selected and all middle points are regarded as being insignificant and can be removed.

The algorithm first selects two end points (i.e., the first and last points). It then searches for the point that has the largest deviation from the straight-line segment connecting these two end points, i.e., at point 2 in Fig. 8.27. If the deviation is larger than ε, then this point is selected; otherwise, all other points can be ignored. In this example, point 2 is selected and it splits the line into two pieces. The search is then carried out for both pieces. Then, points (3, 1) and (3, 2) are selected. These two points split the whole line into four pieces, and the search will be carried out for these four pieces. The process continues until all the deviations are smaller than ε.

Visvalingham and Whyatt (1993) and Li (2007) noted that the Douglas–Peucker algorithm may cause huge shape distortion. To overcome this problem, Visvalingham and Whyatt (1993) believed that the size of an area "sets a perceptual limit on the significance" and is the most reliable metric for measuring the importance of points since it simultaneously considers the distance between points and angular measures. They used the *effective area* of a point as the threshold, as illustrated in Fig. 8.28. For example, the effective area of point 2 is the area covered by the triangle formed

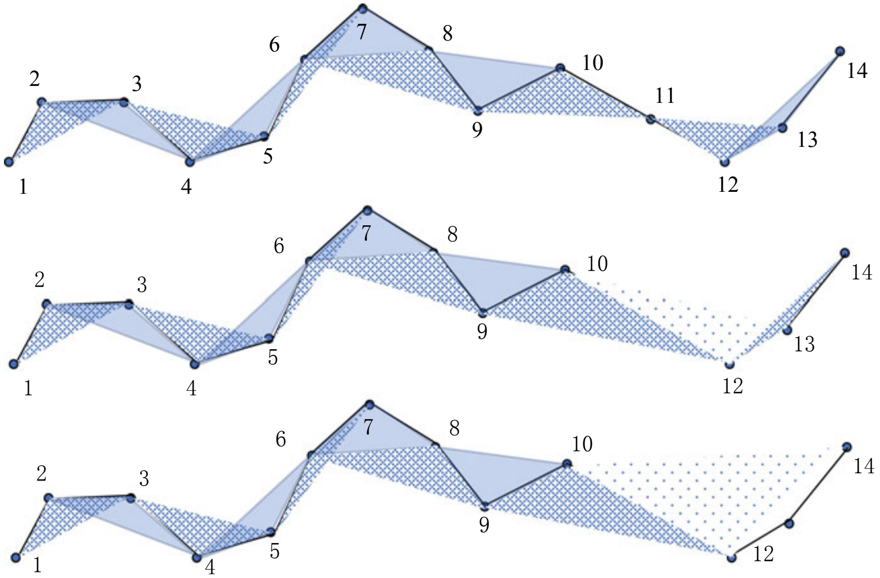


Fig. 8.28 Effective area as a metric in Visvalingham–Whyatt algorithm for generation of a point hierarchy

by points 1, 2 and 3. The basic idea of this algorithm is to progressively eliminate the point with smallest effective area from the list, and the effective areas of the two points adjoining the recently deleted point should be immediately updated. In this example, point 11 is first eliminated and point 13 is removed. The points are ranked from least to most important according to the sequence of elimination.

Many researchers (Li and Openshaw 1992; Visvalingham and Whyatt 1993; Weibel 1996) have noted that the Douglas–Peucker algorithm will create self-intersection (with the line itself) and cross-intersections (between neighboring lines). This problem is associated with all the algorithms with an objective of point reduction or curve approximation. Li and Openshaw (1992) argued that these algorithms are not suitable for generalization (i.e., transformation in scale) because they are normally evaluated with the original curve line (but do not correspond with the curve line at other scales) as the benchmark. To perform transformation in scale for line features, the Li–Openshaw algorithm should be employed as this algorithm, "by virtue of its raster structure, implicitly (but not explicitly) avoids self-overlaps" (Weibel 1996). Even for a very complex coastline, it can produce results that are extremely similar to those manually generalized to various scales, as illustrated by Fig. 8.29. Many recent evaluations also indicate that the Li–Openshaw algorithm produces reasonable and genuine results (e.g., Zhu et al. 2007).

The Li–Openshaw algorithm follows the *Natural Principle* (Li and Openshaw 1993) described in Sect. 8.2.3, i.e., to neglect all spatial variations within the SVS that is computed by using input and output scales. The SVS is mimicked by a cell or

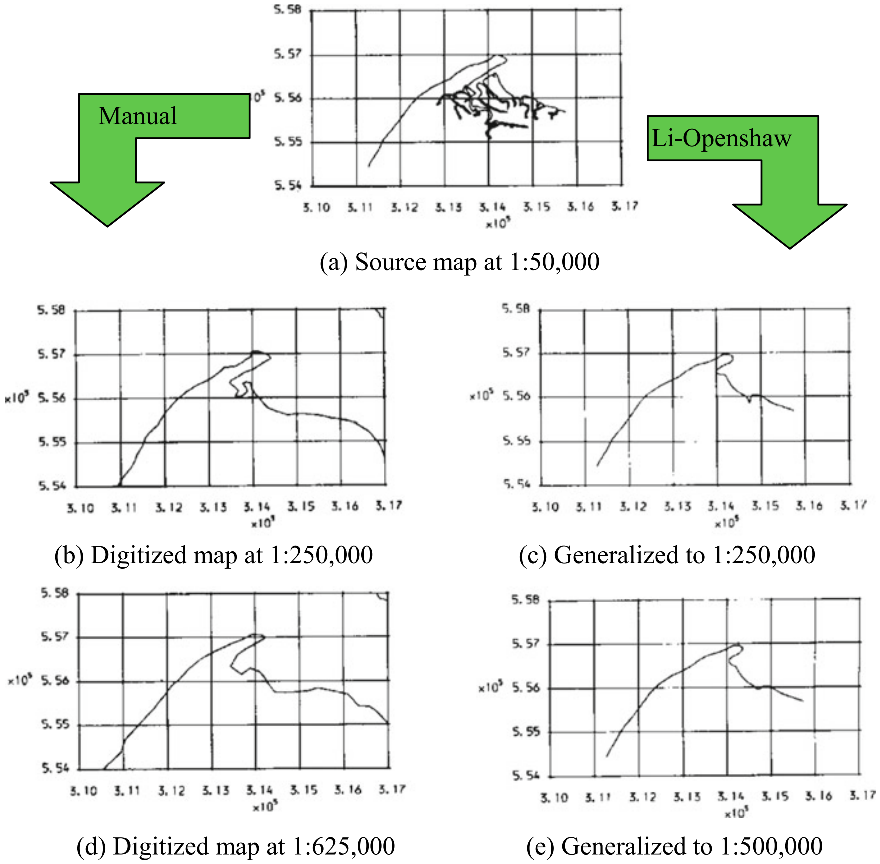


Fig. 8.29 A comparison of the results of manual generalization and the Li–Openshaw algorithm (Li 2007)

pixel although other geometric elements are also possible (e.g., hexagon by Raposo in 2013). The cells can be organized in the form of a none overlapped tessellation or with overlaps. If there is no overlap, it becomes a pure raster template. Figure 8.30 shows the generalization (transformation) process with a raster template. In this example, each SVS is represented by a raster pixel and the result is represented by pixels, as shown in Fig. 8.30b, or by its geometric center.

Three algorithms were developed by Li and Openshaw (1993) in different modes, raster node, vector mode and raster-vector mode. The algorithm in raster-vector mode was recommended. Figure 8.31 shows the generalization by the Li–Openshaw algorithm in raster-vector mode. The first point to be recorded is the starting point. The second point is somewhere within the second cell. In this implementation, the middle point between the two intersections between cell grids and the line (Fig. 8.31b) is used. If there is more than one intersection, the first (from the inlet direction) and

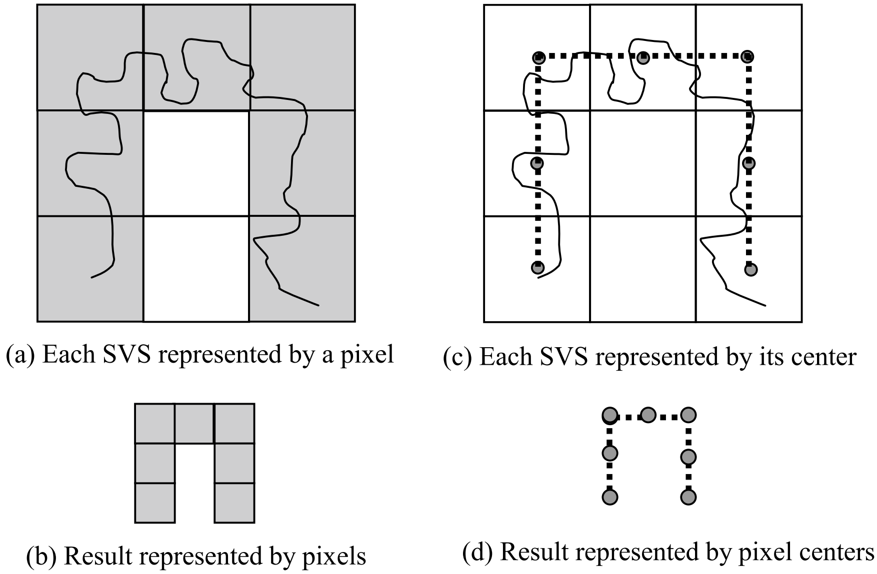


Fig. 8.30 Li–Openshaw algorithm in raster mode; each cell is an SVS (Li 2007)

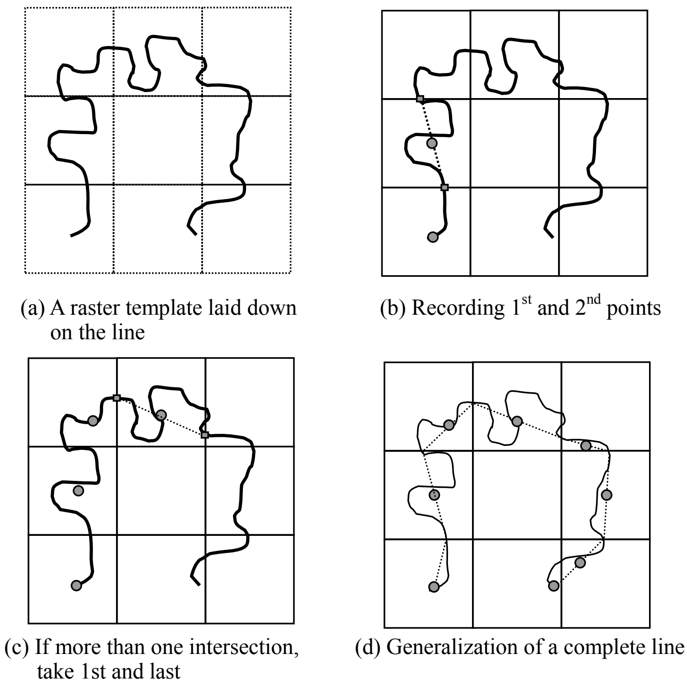


Fig. 8.31 Li–Openshaw algorithm in raster-vector mode (Li 2007)

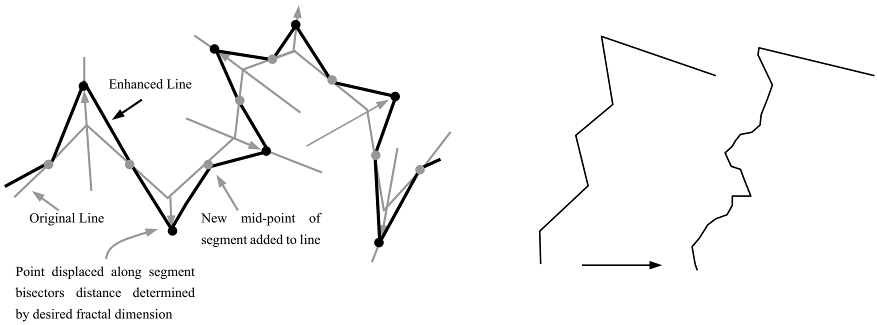


Fig. 8.32 Downscaling of a line by fractal enhancement (Clarke 1995)

the last (outlet direction) intersections are used to determine the position of the new point ((Fig. 8.31c). The final result of the generalization of a complete line is given in Fig. 8.31d.

Similar to the algorithm in raster mode, overlap between SVSs can also be adopted, although it is not too critical. Notably, it is not necessary to take the average to represent a cell. It does not matter what point within the cell is used, as the cell itself is an SVS. Thus, it is also possible to take an original point, which is considered a critical point to represent the cell.

Some work has also been carried out to downscale the lines, i.e., to add more details to the lines. A typical example of such work is that by Dutton (1981), which adds more details to the line by following the fractal characteristics of the line itself (see Fig. 8.32).

8.4.5 Mathematical Solutions for Transformation (in Scale) of Line Networks

In geographical space, three types of line networks are commonly used, contour line networks, hydrological networks and transportation networks. Some hierarchical models were presented in Sect. 8.3.3. The mathematical solutions for the transformation in scale of these networks are discussed in detail by Li (2007). Here, only the construction of a hierarchy for transportation networks is described.

The first approach is based on the *importance of roads*. As road networks are stored in segments and intersections in a database, two steps are required, to build strokes and to order strokes, as illustrated in Fig. 8.33. To build strokes means to concatenate continuous and smooth network segments (see Fig. 8.33a) into a whole (see Fig. 8.33b). To order strokes means to rank the strokes in a descending order based on their importance from high to low (see Fig. 8.33b). The importance of each stroke can be calculated according to various properties, i.e., geometric properties such as length (Chaudhry and Mackaness 2005), topological properties such

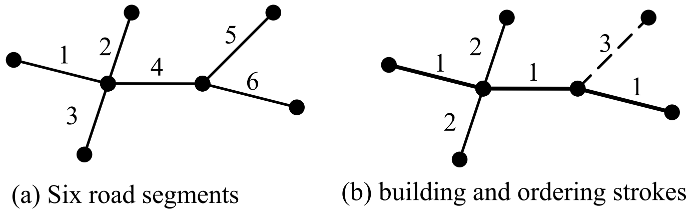


Fig. 8.33 Stroke formation and ordering

as degree, closeness and/or betweenness (Jiang and Claramunt 2004), and thematic properties such as road class. A comparative analysis of the methodology for building strokes was carried by Zhou and Li (2012). With each stroke, given an importance, a stroke-based hierarchy of a line network can be built.

The importance of strokes can be evaluated by the connectivity of strokes in the network. ego-network analysis and weighted ego-network analysis are possible methods (Zhang and Li 2011). Figure 8.34 shows the basic structure of three types of ego-networks and the weight of each link, also called the proportional link strength.

The proportional link strength of each link (p_{ij}) from node i to any of its immediate neighbor nodes can be defined as the reciprocal of the degree of connectivity (k) of node i. Mathematically,

$$p_{ij} = \frac{1}{k_i} \qquad (j \in i_{ne}) \tag{8.16}$$

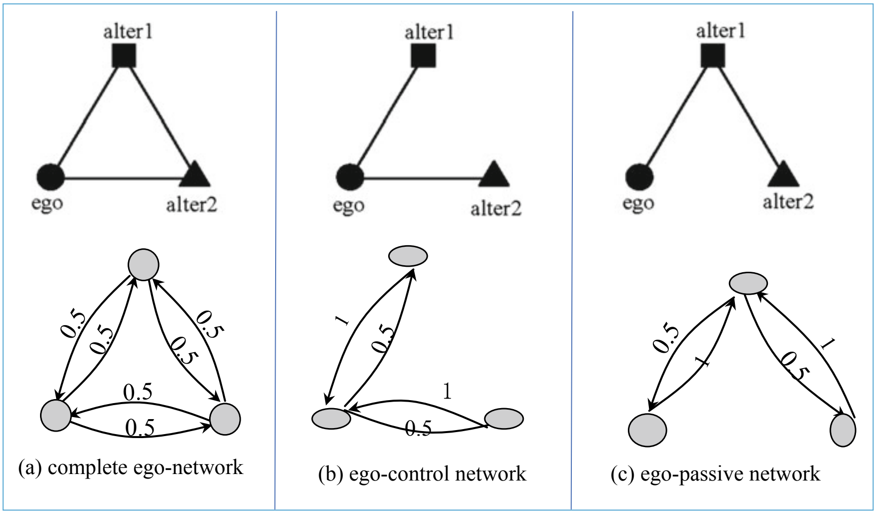


Fig. 8.34 Ego-networks and proportional link strength

For instance, in Fig. 8.34a, the ego is connected to both alter1 and alter2, so its degree of connectivity is 2; thus, the strengths of links from this ego to alter1 and to alter2 are both 1/2 = 0.5. The strengths of other links are also indicated in Fig. 8.34.

If node *i* and node *j* are not directly linked but are linked via another node *q* in the neighbor (*ne*), the strength of the link from node *i* to node *j (i.e., p_{ij})* is defined as:

$$p_{ij}^{'} = p_{iq}p_{qj} \tag{8.17}$$

The total link strength (C_{ij}) from node *i* to node *j* is defined as the square of the sum of the direct link strength and the indirect link strength from node *i* to node *j*. Mathematically,

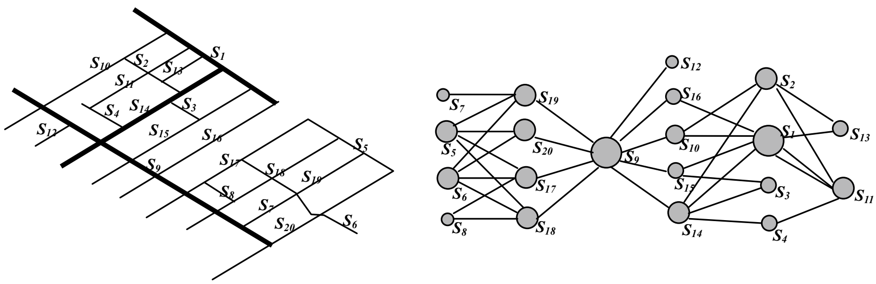
$$C_{ij} = \left(p_{ij} + \sum p_{ij}^{'}\right)^2 = \left(p_{ij} + \sum_{q=1}^{m} p_{iq}p_{qj}\right)^2 \tag{8.18}$$

The C_{ij} value reveals the constraint of *i* by j. The larger the C value is, the larger the constraint over *i*, and the smaller the opportunity for *i*.

To apply this concept to a transport network, the physical road network is first concerted into a connectivity graph, and the link strength values are computed for each node in the connectivity graph. Figure 8.35 shows an example. Roads can then be ranked by the link strength values.

The ego-network is a feasible and effective solution for the formation of hierarchies for road networks. However, Zhang and Li (2011) identified two significant limitations, the deviation of the link intensity definition from reality and the so-called 'degree 1 effect'. They subsequently developed a weighted ego-network analysis method.

Another important development is the *mesh density-based approach* proposed by Chen et al. (2009). The so-called mesh is a closed region surrounded by several road segments. In this approach, the density of each mesh in the road network is computed according to the following formula:



(a) A regular road network (b) The connectivity graph

Fig. 8.35 Formation of a network hierarchy by ego-network analysis (Zhang and Li 2009)

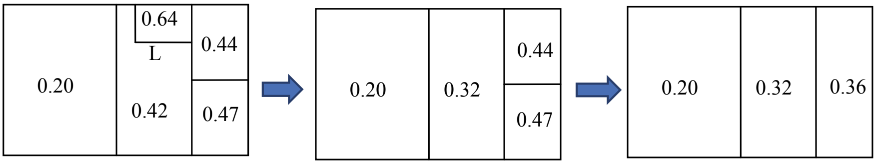


Fig. 8.36 Mesh density-based approach

$$D = \frac{P}{A} \tag{8.19}$$

where P is the perimeter of the mesh and A is the area of the mesh.

Then, the meshes with the highest density are merged progressively, as illustrated in Fig. 8.36. In this Figure, the mesh with density of 0.64 is first merged into the that with a density of 0.42 and segment L is eliminated. The density (0.32) of the new mesh is then updated. The process is iterated until only one mesh is left.

Generally, a road network is often a hybrid of linear and areal patterns, thus Li and Zhou (2012) proposed the construction of hybrid hierarchies, i.e., an integration of a line hierarchy and an area hierarchy.

8.4.6 Mathematical Solutions for Transformation of a Class of Area Features

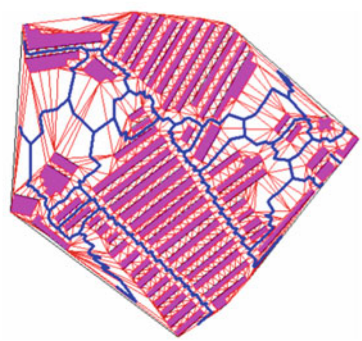
Section 8.3.5 described how a hierarchy of areas could be structured by a minimum spanning tree. In that example, the centroid of a polygon was used to represent the polygon. However, if the polygon is thin and/or irregular, then the edge length is not necessarily a good measure for closeness. Densification of points along the polygon edge will make the problem simpler. Figure 8.37 shows such an example. Figure 8.38 shows the transformation of buildings into suitable representations at different scales.

Li (1994) argued that the transformation in scale should be better performed in raster space (because a scale reduction causes a space reduction and the raster format takes care of space) and proposed the use of techniques in mathematical morphology for transformation in scale. Li et al. have developed a complete set of algorithms for such transformations based on mathematical morphology.

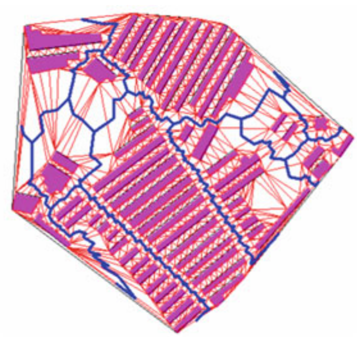
One such algorithm is the aggregation of areas into groups and transformation into representations at different scales (Su et al. 1997). The mathematical model for the aggregation is:

$$\mathrm{C} = (\mathrm{A} \oplus \mathrm{B}_1)\ \Theta\ \mathrm{B}_2 \tag{8.20}$$

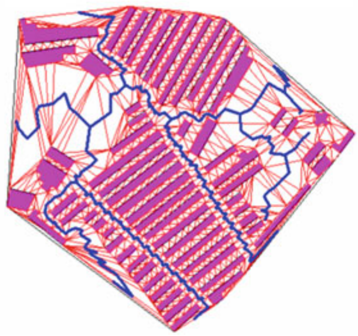
where A is the representation (image) showing the original area features and B_1 and B_2 are the two structuring elements.



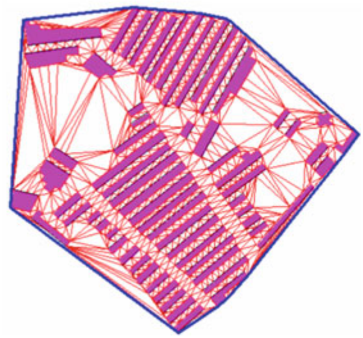
(a) Grouping for generalization to 1:25,000



(b) Grouping for generalization to 1:50,000



(c) Grouping for generalization to 1:100,000



(d) Grouping for generalization to 1:250,000

Fig. 8.37 Grouping of buildings at 1:10000 scale for generalization to various scales (Li et al. 2004)

(a) 1:25,000, by typification

(b) 1:50,000, by typification and aggregation

(c) 1:100,000, by aggregation

(d) 1:250,000, by aggregation

Fig. 8.38 Transformation of grouped buildings to various scales (Li et al. 2004)

The success of applying this model to area combination depends on the proper size and shape of the structuring elements B_1 and B_2. Su et al. (1997) suggest that the size of B_1 and B_2 should be determined by the input and output scales, following the Natural Principle described in Sect. 8.2.3. Figure 8.39 shows the combination of

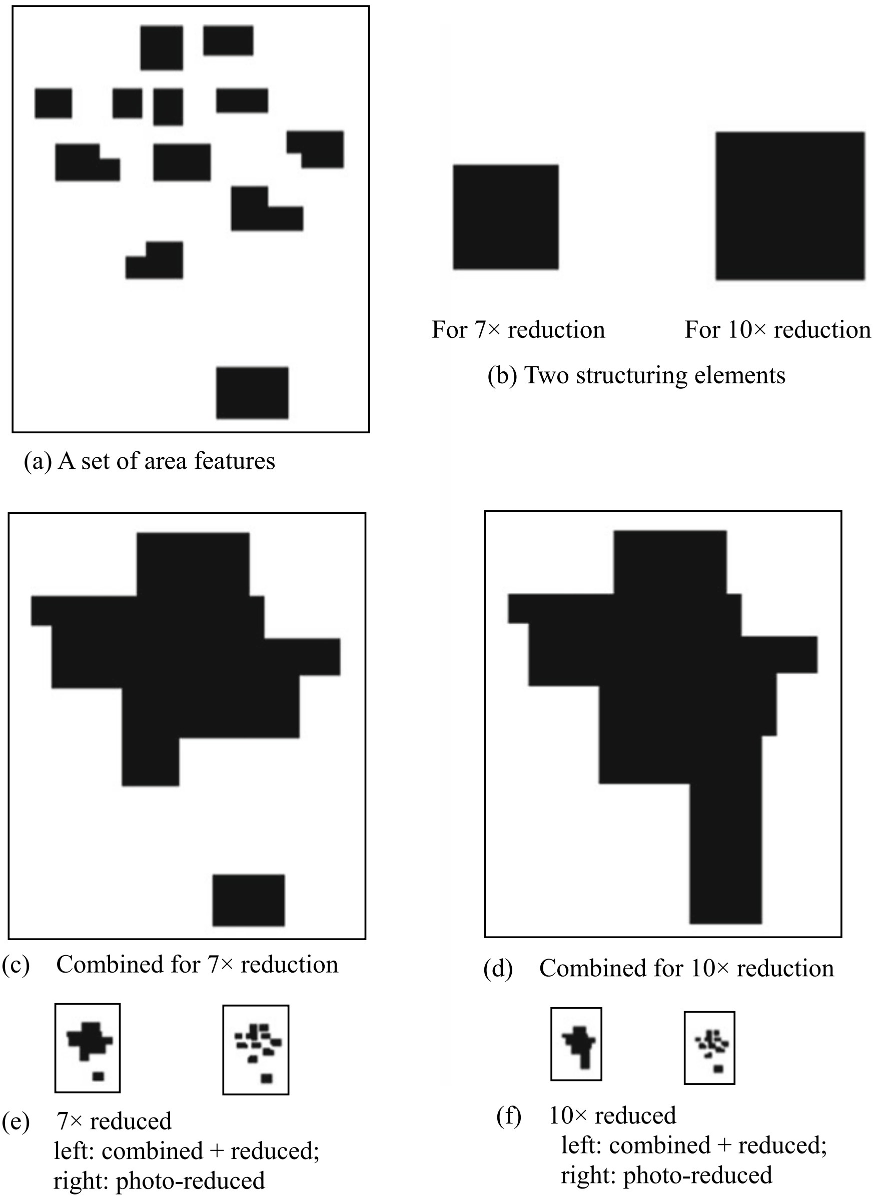


Fig. 8.39 Combination of area features at different scales (Extracted from Su et al. 1997)

Fig. 8.40 Shape refinement by the SLLM algorithm (Su et al. 1997)

(a) A settlement with an irregular shape (b) Simplified by the SLLM algorithm

buildings using this model for two different scales: one for a scale reduction by 7 times and the other by 10 times. The results are also compared with those using simple photoreduction. The combined results are very reasonable. However, the combined results are very irregular and the simplification of boundaries could be discussed. A detailed description of such a simplification is omitted here but can be found in the work of Su et al. (1997) and the book by Li (2007). The result is shown in Fig. 8.40.

8.4.7 Mathematical Solutions for Transformation (in Scale) of Spherical and 3D Features

In the previous sections, mathematical solutions for transformation of 2D features have been presented. Mathematical solutions for transformation of spherical (e.g., Dutton 1999) and 3D features (e.g., Anders 2005) have also been researched, although the body of literature is much smaller than that for map generalization. In recent years, there have been more papers on the generalization of buildings-based CityGML (e.g., Fan and Meng 2012, Uyar and Ulugtekin 2017); details on such methodologies are omitted here due to page limitations.

8.5 Transformation in Scale: Final Remarks

The beginning of this chapter emphasized that continuous zooming is at the core of Digital Earth as initiated by Al Gore. Continuous zooming is a kind of transformation of spatial representation in scale. In this chapter, the theoretical foundation for transformations in scale was presented in Sect. 8.2. Then, models for such transformations were described in Sect. 8.3 for raster and vector data, images, digital terrain models and map data. A selection of algorithms and/or mathematical functions for achieving these transformations was presented in Sect. 8.4.

Notably, the content of this chapter was concentrated on the theories and methodology to achieve continuous zooming and some important issues related to transformation in scale have been omitted, such as temporal scale, scale effect and optimum scale selection. For the content of the models for transformation in scale, emphasis was on the representations. Thus, other models such as geographical and environmental processes were excluded. However, these aspects are important but were omitted due to page limitations.

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Zhilin Li is the Chair Professor of Geo-informatics at the Hong Kong Polytechnic. His research interests include multi-scale modelling and representation, cartographic language and cartographic information theory and mapping from satellite images. He was a vice president of the International Cartographic Association.

Haowen Yan is a professor in geographic information science at Lanzhou Jiaotong University, China. His research interests are map generalization, spatial relations and spatial data security. He is now one of the three editors-in-chief of Journal of Geovisualization and Spatial Analysis published by Springer-Nature.

Chapter 9
Big Data and Cloud Computing

Yun Li, Manzhu Yu, Mengchao Xu, Jingchao Yang, Dexuan Sha, Qian Liu and Chaowei Yang

Abstract Big data emerged as a new paradigm to provide unprecedented content and value for Digital Earth. Big Earth data are increasing tremendously with growing heterogeneity, posing grand challenges for the data management lifecycle of storage, processing, analytics, visualization, sharing, and applications. During the same time frame, cloud computing emerged to provide crucial computing support to address these challenges. This chapter introduces Digital Earth data sources, analytical methods, and architecture for data analysis and describes how cloud computing supports big data processing in the context of Digital Earth.

Keywords Geoscience · Spatial data infrastructure · Digital transformation · Big data architecture

9.1 Introduction

Digital Earth refers to the virtual representation of the Earth we live in. It represents the Earth in the digital world from data to model. Data are collected and models are abstracted to build the digital reality. Massive amounts of data are generated from various sensors deployed to observe our home planet while building Digital Earth. The term "big data" was first presented by NASA researchers to describe the massive amount of information that exceeds the capacities of main memory, local disk, and even remote disk (Friedman 2012). According to the National Institute of Standards and Technology (NIST), "*Big Data is a term used to describe the large amount of data in the networked, digitized, sensor-laden, information-driven world*" (Chang and Grady 2015). This definition refers to the bounty of digital data from various data sources in the context of Digital Earth, which focus on big data's geographical aspects of social information, Earth observation (EO), sensor observation service (SOS), cyber infrastructure (CI), social media and business information (Guo 2017; Guo et al. 2017; Yang et al. 2017a, b). Digital Earth data are collected from satellites,

Y. Li · M. Yu · M. Xu · J. Yang · D. Sha · Q. Liu · C. Yang (✉)
Department of Geography and GeoInformation Science, NSF Spatiotemporal Innovation Center, George Mason University, Fairfax, VA, USA
e-mail: cyang3@gmu.edu

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Table 9.1 Definition of the "9Vs" of big data

"V"	Definition
Volume	The vast data size that traditional data storage and computing technologies cannot easily capture, store, manipulate, analyze, manage and present
Variety	The diversity of data formats and sources. The data formats include text, geometries, images, video, sounds or a combination
Velocity	The speed of data production, storage, analysis, and visualization based on advanced development of data collection methods, i.e., the massive number of sensors in the Interest of Things (IoT) and social media networks
Veracity	The varying reliability, accuracy, or quality of data sources
Validity	The accuracy and correctness of Earth data for the intended usage
Variability	The meaning of data continues to change, particularly for Earth data that relies on natural language processing
Vulnerability	Data security is an important part of typical and big Earth data because some geospatial data contain identification information related to people or governments
Volatility	The timeliness and freshness of Earth data
Visualization	Visualization of Earth data is challenging with limited memory, poor scalability and functionality, and various data increasing at a high velocity
Value	Value reflects the tremendous straightforward and potential scientific and social worth based on imaginative insight and analysis results

sensors, simulation models, mobile phones, utilities, vehicles, and social networks in different formats, e.g., imagery, text, video, sound, geometries and combinations of them (Yang et al. 2017a, b). Digital Earth data are naturally big data because of the variety of data sources and enormous data volume.

The increasing availability of big Earth data has provided unprecedented opportunities to understand the Earth in the Digital Earth context. In recent research, big data have been characterized by 5 Vs (volume, variety, velocity, veracity, and value) (Gantz and Reinsel 2011; Zikopoulos and Barbas 2012; Marr 2015). Firican (2017) extended the 5 Vs into big data characteristics including variability, validity, vulnerability, volatility and visualization (as defined in Table 9.1 and further elaborated below).

Volume

The volume of remote sensing imagery collected by satellites and drones easily reaches the TB and PB levels. For example, the Integrated Multi-satellite Retrievals for GPM (IMERG) data product records global precipitation information every half hour, producing up to 3.45 TB data yearly (Huffman et al. 2015). Other location-based data such as social media (e.g., Twitter) and VGI (e.g., OpenStreetMap) are constantly growing.

Variety
Data sources include sensors, digitizers, scanners, numerical models, mobile phones, the Internet, videos, emails, and social networks in the context of Digital Earth. All types of geospatial data require a more effective data structure, framework, index, model, management methodology, and tactics. In addition, these geospatial data are formatted in various data models, e.g., vector and raster, structured and unstructured.

Velocity
The speed of Earth data collection and generation has increased with the development of advanced techniques such as drone observation for disaster monitoring. For example, with the massive number of object-based sensors in the IoT, the data generation of IoT nodes is fast since most sensors continuously generate data in real time.

Veracity
The accuracy of geospatial data varies by data source (Li et al. 2016). Taking precipitation as an example, the quality of remote sensing images such as TRMM and IMERG depends on the sensor configuration, calibration methods, and retrieval algorithms. Precipitation information in MERRA (Modern Era Retrospective-analysis for Research and Applications) data relies on the sophistication of meteorological models. Stationary data collected by rain gauges are more accurate even though they are sparse.

Validity
Similar to veracity, validity concerns the accuracy and correctness of Earth data for the intended usage. In addition to data selection in which data are chosen with appropriate spatial and temporal resolutions and variables for a specific application, data preprocessing, e.g., data augmentation, interpolation, outlier detection, also play an important role in uncovering information from big Earth data. Consistent data quality, common definitions and metadata can benefit the community, resulting in Earth data of high validity.

Variability
Variability refers to the continuous change in the meaning of data in the context of big Earth data, particularly for data that relies on natural language processing. For example, Twitter data emerged as an additional source for natural disaster management (Yu et al. 2018), as tweets posted during disasters can be collected to aid situational awareness. The meaning of words constantly changes over time, for example, the word “Irma” may be a name but started to represent the strongest observed hurricane in the Atlantic in most tweets around October 2017.

Vulnerability
Security is a challenging aspect because some geospatial data contain identifiable information or are sensitive. For example, cellular data have been widely utilized to analyze human activities in smart city applications, however, showing phone numbers may divulge people’s private affairs.

Volatility
Volatility refers to the timeliness and freshness of Earth data, i.e., how long the Earth data stay useful and relevant to applications and how long the data should be kept. Due to the velocity and volume of big Earth data, it is impossible to store all the data in a live database without any performance issues. A series of rules should be established for data currency, availability and rapid retrieval (Firican 2017), e.g., historical and less frequently visited Earth data could be archived on a lower-cost tier of storage.

Visualization
Visualization of Earth data is a challenging task with limited memory due to poorly scalable, low-functionality, and high-velocity datasets. Traditional methods may fail to render billions of points, polylines and polygons when visualizing geospatial vector data, therefore graphical methods, e.g., data clustering, parallel coordinates, cone tree or circular network diagrams, should be used to represent Earth data (Firican 2017).

Value
Value presents a low-density pattern in the current big data ecosystem where only a small portion of data is utilized in practice. Earth data occupies 80%+ of our data assets (Dempsey 2012), but most datasets are not excavated and are under-utilized. With appropriate spatiotemporal resolution and analysis methods, the 9Vs have been addressed to obtain actionable knowledge to increase the value of big data.

Data collection strategies, data storage facilities, data analysis methods, and data access services facilitate the transformation from the other 9Vs to the 10th V of value. With the continuing increases in the volume and complexity of data, there are challenges in the life cycle of data management, including data storage, data query, data analysis, data sharing, and many other aspects. Managing big data requires an extensible, interoperable and scalable architecture that supports data storage and analysis. Fortunately, recent years have witnessed the evolution of cloud computing, which brings potential solutions to support the life cycle of big data management.

Cloud computing is a new computing paradigm for delivering computation as a fifth utility, which became popular earlier than big data (Yang et al. 2011a). It has the features of elasticity, pooled resources, on-demand access, self-service and pay-as-you-go characteristics (Mell and Grance 2011) and was termed spatial cloud computing in the context of Digital Earth (Yang et al. 2011a). Big data technologies, e.g., big data storage and big data analytics, evolve and benefit significantly from their integration with cloud computing.

To provide a comprehensive overview of how cloud computing supports big data in the context of Digital Earth, this chapter introduces Digital Earth data sources (Sect. 9.2), data analysis methods (Sect. 9.3), architecture for big data analysis (Sect. 9.4), and cloud computing and its support of big data management (Sect. 9.5). Two examples of EarthCube and Data Cube are introduced in Sect. 9.6 to exemplify cloud-based big data frameworks in the Digital Earth context.

9.2 Big Data Sources

With the advanced developments in Earth observation systems, various Earth data have been gathered at a high velocity from five major sources: (1) remote sensing, (2) in situ sensing, (3) simulation, (4) social media, and (5) infrastructure management (Fig. 9.1). Each covers more than one characteristic of big data. This section discusses the five data sources.

Remote sensing data
Referring to the USGS's definition, remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring the reflected and

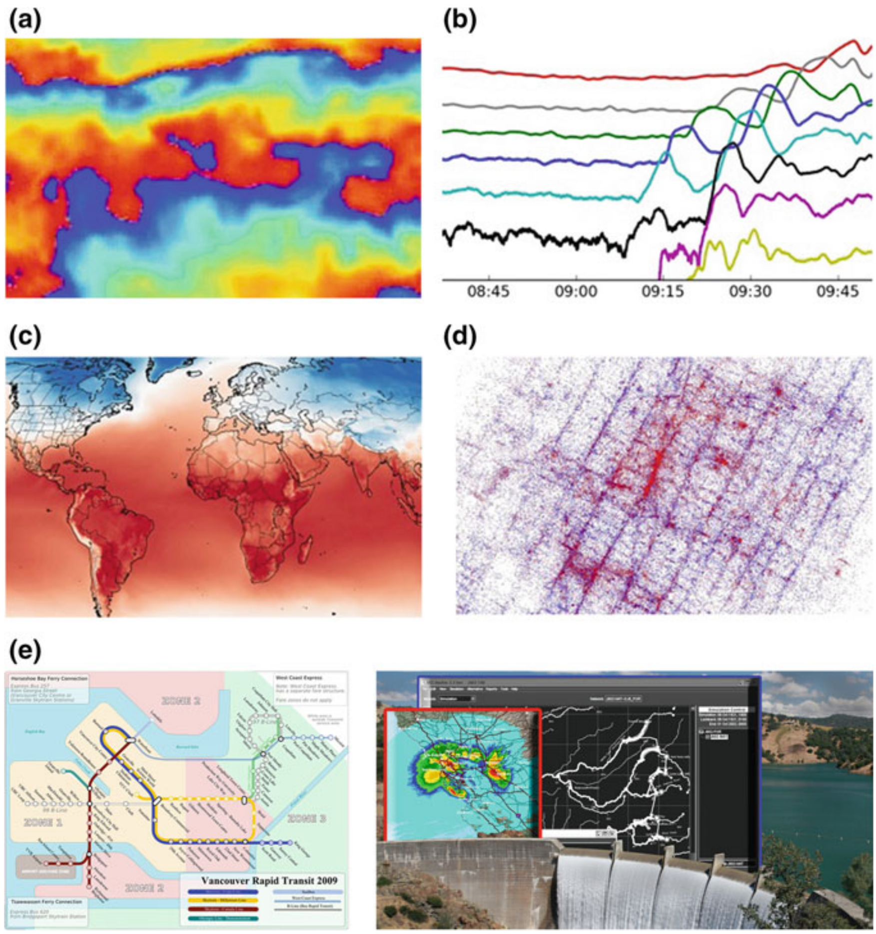

Fig. 9.1 Big Earth data sources: **a** remote sensing data (JPL 2001); **b** in situ data (NOAA 2017); **c** simulation data (Lipponen 2017); **d** social media data (Gundersen 2013); and **e** infrastructure data (Canada Line Vancouver Transit Map 2019; Robert 2000)

emitted radiation at a distance from the targeted area (USGS 2019). Such remotely observed data serve as a vital source for tracking natural phenomena, the growth of a city, changes in farmland or forest, and discovery of the rugged topography of the ocean floor. According to the Earth Observing System Data and Information System (EOSDIS) 2014 statistics, EOSDIS manages over 9 PB of data and adds 6.4 TB of data to its archives every day (NASA 2016). As data precision and density increase over time, data volume increases exponentially. In addition, ongoing international initiatives monitor the Earth in near-real time using satellites to support rapid data collection for quick and effective emergency response (Zhang and Kerle 2008). Remote sensing data are big data due to the big volume, variety, veracity and volatility.

In situ data
According to NOAA (National Oceanic and Atmospheric Administration), in situ data are measurements made at the actual location of the object. In contrast to remote sensing, in situ sensing harvests data directly at the observation location, and often provides continuous data streams to reflect the actual situation with very low latency. Examples of such measurements are (1) tall tower networks (NOAA ESRL/GMD) that provide regionally representative measurements of carbon dioxide (CO_2) and related gases and (2) moored and drifting buoys for marine/ocean data collection. In situ data are big data considering the volume, velocity, and veracity.

Simulation data
Simulation datasets or reanalysis datasets refer to the outputs of Earth models (e.g., climate) based on geophysical principles. By assimilating observations with models, better initial conditions can be leveraged and simulation results can be significantly improved, especially for short-term predictions. Simulation datasets can be used in various applications. For example, the precipitation, evaporation, and runoff from MERRA datasets can drive river flow models and enhance the study of sensitive ecosystems such as estuaries (Rienecker et al. 2011). In addition, the reanalysis winds used in transport models support the evaluation of aerosols. Simulation data are big data due to its volume, variety and validity.

Social media data
In recent years, social media has become one of the most popular sources of big data and provides valuable insights on event trends and people's references. Social networks such as Twitter and Facebook generate a vast amount of geo-tagged data every second and are transforming social sciences (Yang et al. 2017a). Scientists from economics, political science, social science, and geoscience domains utilize big data mining methods to detect social interactions and analyze health records, phone logs, and government records (Balakrishna 2012). For example, in Digital Earth, social media and crowdsourcing data can provide trends of the urban flooding events or wildfire spread, as well as support near-real time situational awareness when other types of data are limited or hard to obtain. However, social media data have high uncertainty and vary in format and quality. Tweet content analysis highly relies on natural language processing, but word meaning constantly changes. Social media

data are big data due to its volume, velocity, variety, veracity, validity, variability and volatility.

Infrastructure data
Infrastructure data serve as a vital data source of Digital Earth information, especially for developing smart cities. For example, basic infrastructure data (e.g., utility, transportation, and energy), healthcare data and governance data (e.g., environmental and construction management) should be proposed, planned and provided by local official departments and business agencies for a smart city (Hashem et al. 2016). Some infrastructure data may contain sensitive information. Taking water distribution management systems as an example, a synthetic data methodology was proposed to reproduce water consumption data according to privacy constraints (Kofinas et al. 2018). With the upgrades in infrastructure, Internet of Things (IoT) data, geo-tagged or geo-referenced data are continuously produced by various devices, sensors, systems and services (Boulos and Al-Shorbaji 2014). In the near future, various applications based on IoT data will benefit individuals and society. For example, near-real time data including temperature and wind information gathered by IoT sensors could support real-time urban microclimate analysis (Rathore et al. 2017). Infrastructure data are big data due to its volume, velocity, variety, veracity, vulnerability, validity and volatility.

Earth data are continuing to grow in volume and complexity. Big data analytical methods are utilized to mine actionable knowledge from big Earth data to convert the 9Vs of Earth data to the 10th V, which is discussed in the next section.

9.3 Big Data Analysis Methods

The advancements in remote sensing, social networking, high-performance simulation modeling and in situ monitoring provide unprecedented big data about our planet. The large volume and variety of data offer an opportunity to better understand the Earth by extracting pieces of knowledge from these data. This section discusses data analysis methods from the three aspects of data preprocessing, statistical analysis and nonstatistical analysis. The characteristics, applications, and challenges of these methods are introduced below.

9.3.1 Data Preprocessing

Real-world data are usually incomplete, noisy and inconsistent due to data collection limitations and sensor issues. Raw data may contain errors or outliers, lack specific attributes or have discrepancies in the descriptions. Therefore, data preprocessing (e.g., data cleaning, fusion, transformation, and reduction) are required to remove noise, correct data, or reduce data size.

Low-quality values (missing values, outliers, noises, inconsistent values) in raw data are often removed or replaced with user-generated values, e.g., interpolation values. The missing value is usually represented with a symbol (e.g., N/A) in raw data and easily recognize. Outliers and inconsistent values are hidden in the raw data and can be detected through statistical analysis. Taking water usage behavior analysis as an example, data preprocessing is necessary to turn smart water meter data into useful water consumption patterns because IoT sensors may fail to record data (Söderberg and Dahlström 2017).

Data transformation also plays an essential role in data preprocessing. Multiple Digital Earth data, e.g., climate data, soil moisture data, crop data, are converted to monthly z-score data before analysis to eliminate the seasonal trends that usually make the patterns of interest undiscoverable. Aggregation, another important data transformation method, groups data based on numerical attributes (Heuvelink and Pebesma 1999). In the Earth science domain, aggregating raw data to the county or state levels could uncover essential patterns for decision making, urban planning, and regional development.

Another trend in Digital Earth data analysis is multisource data fusion, which provides comprehensive data retrieved from several data sources. Generally, vector and raster data store Earth information with different spatial-temporal resolutions; thus, data must be converted to the same resolution by interpolating the lower resolution data or aggregating the higher resolution data for intelligent analysis to investigate scientific questions at a specific scale. Sharifzadeh and Shahabi (2004) introduced a spatial aggregation method that takes the sensor data distribution into account. Spatial interpolation is interpolation of point and areal data. Point interpolation is applied to contour mapping and areal interpolation is used in isopleth mapping (Lam 1983). In addition to spatial interpolation, temporal interpolation predicts values between timestamps (Lepot et al. 2017).

9.3.2 Statistical Analysis

In the era of big data, statistical analysis is a common mathematical method of information extraction and discovery. Statistical methods are mathematical formulas, models, and techniques used to find patterns and rules from raw data (Schabenberger and Gotway 2017). Data mining is the process of discovering patterns from large datasets involving statistical analysis. Through data mining, historical data can be transformed into knowledge to predict relevant phenomena. Both traditional statistics and data mining methods are discussed in this section. These methods include but are not limited to regression analysis, spatiotemporal analysis, association rules, classification, clustering, and deep learning.

Regression analysis
Regression models the relationships between a dependent variable and one or more explanatory variables (Yoo et al. 2014; Anderson 2015) by estimating the values of

a dependent variable when the values of the independent variables are known and the relationships exist. Regression models describe the strength or weakness of the relationship between several variables. For example, Blachowski (2016) proposed a weighted spatial regression method that identified four significant factors inducing land subsidence: thickness, inclination, the depth of coal panels, and the slope of the surface. There are challenges in spatial data analysis using regression methods, especially for situations that are complicated enough to result in serious residuals in the regression models.

Spatiotemporal analysis
Spatiotemporal data analysis investigates the trajectories and trends of spatiotemporal data. Li et al. (2016) investigated the spatiotemporal trends in the fluctuations of housing price data. Spatial data analytics and modeling techniques were used to identify the spatial distribution of housing prices at the micro level and explore the space-time dynamics of residential properties in the market, as well as the detected geographic disparity in terms of housing prices. Rahman and Lateh (2017) analyzed the temperature and rainfall time series data from 34 meteorological stations distributed throughout Bangladesh over 40 years (1971–2010) to statistically evaluate the magnitude of temperature and rainfall changes across space and time. Spatiotemporal analysis is still in its initial stage of development. Challenging questions remain, such as what kinds of patterns can be extracted from time series data and which methods and algorithms should be applied.

Association rule
Association rule learning is the process of discovering strong relationships between variables, i.e., rules, in a large database using measurements of support and confidence (Agrawal et al. 1993). In Digital Earth, Yang (2011b, 2016) applied association rules to mine the variables of Atlantic hurricanes from 1980 to 2003 and discovered a combination of factors related to rapid intensification probability, the low vertical shear of the horizontal wind (SHRD = L), high humidity in the 850–700 hPa range (RHLO = H), and tropical cyclones in an intensification phase (PD12 = H). Compared with traditional statistical methods, the rule-based mining method can find combinations of factors instead of a single factor related to an event.

Classification
Classification learning is the task of mapping input variables to discrete output variables called labels or categories, for example, ‘building’ or ‘road.’ It is the process of recognizing, differentiating and understanding objects. Support Vector Machine (SVM) is a classical classification algorithm in which a kernel-based metric is used to differentiate objects. Jiang et al. (2018b) integrated the ranking support vector machine (RankSVM) model from the computer science community with ocean data attributes to support data ranking in ocean portals. An SVM model is also used to predict geological lithofacies from wireline logs.

Clustering
Clustering is the process of splitting a set of objects into closely related groups, and each group is regarded as a cluster. Objects falling in the same cluster are more

similar to each other than those in other clusters. In Digital Earth, clustering plays an important role in pattern analysis. Hong and O'Sullivan (2012) clustered empirical datasets in Auckland, New Zealand for ethnic residential cluster detection, which is useful to understand contemporary immigrants and ethnic minorities in urban areas. Zhao et al. (2017) proposed a method to generate urban road intersection models from low-frequency GPS trajectory data. These patterns identified from empirical data are crucial for urban transportation planning and management.

Deep learning
As a new paradigm of machine learning, deep learning has achieved remarkable success in discovery of implicit knowledge (LeCun et al. 2015). In Digital Earth, deep learning algorithms have been adopted to solve domain problems. For example, Guo and Feng (2018) used multiscale and hierarchical deep convolutional features to assign meaningful semantic labels to the points in a three-dimensional (3D) point cloud, which is essential for generating 3D models. Li and Hsu (2018) proposed a deep learning approach to automatically identify terrain features (i.e., sand dunes, craters) from remote sensing imagery. Compared with traditional induction-based approaches, the deep learning approach could detect diverse and complex terrain features more accurately and process massive available geospatial data more efficiently.

9.3.3 Nonstatistical Analysis

In addition to statistical analysis, nonstatistical analysis methods also play an essential role in helping us descriptively understand Earth phenomena. This section introduces two representative models in Digital Earth, linked data and 3D city modeling.

Linked data
Linked data are structured data in which datasets are interlinked in the collection, which is useful for semantic queries and reasoning (Bizer et al. 2011). With linked data, data are sharable, and the relationships among the data are recorded. Standard web technologies such as RDF (Resource Description Framework) provide a way to build shareable linked data. In Digital Earth, heterogeneous Earth data (multidisciplinary, multitemporal, multiresolution, and multilingual) can be integrated based on linked data principles for decision making and knowledge discovery (Vilches-Blázquez et al. 2014). For example, Mc Cutchan (2017) proposed a structure of embedding geographic data into linked data and forecasted spatial phenomena with associated rules extracted from the linked data.

3D city modeling
A trend in Digital Earth analysis is to build a real 3D model with the aid of a computer, especially for cities where most human activities occur. 3D models provide real three-dimensional information for analysis, going beyond simple visualization of 3D objects. 3D informatics has become a cornerstone for a series of city-related

applications such as urban planning, skyline analysis, crisis and disaster management, route selection and navigation (El-Mekawy 2010). For example, Amirebrahimi et al. (2016) assessed and visualized flood damage using 3D urban modeling and a building information model (BIM), improving the resilience of the community to floods using detailed 3D information.

Knowledge distillation from Earth data has demonstrated excellent improvements in our understanding of the planet we live. As Earth data increase faster than ever, state-of-the-art analysis methods should be developed to handle the increasingly complicated spatiotemporal data. In addition, an extensible, interoperable and scalable architecture is a prerequisite for massive geographic data analysis, and we present a big data analysis architecture in the next section.

9.4 Architecture for Big Data Analysis

To support Earth data access/query/analysis in a reasonable response time, it is crucial to build a sophisticated analytical platform with robust architecture to reveal insights from the data (Yang et al. 2017a, b). Generally, the architecture of analytical platforms consists of a data storage layer, a data query layer, a data processing layer, and a visualization layer (Fig. 9.2).

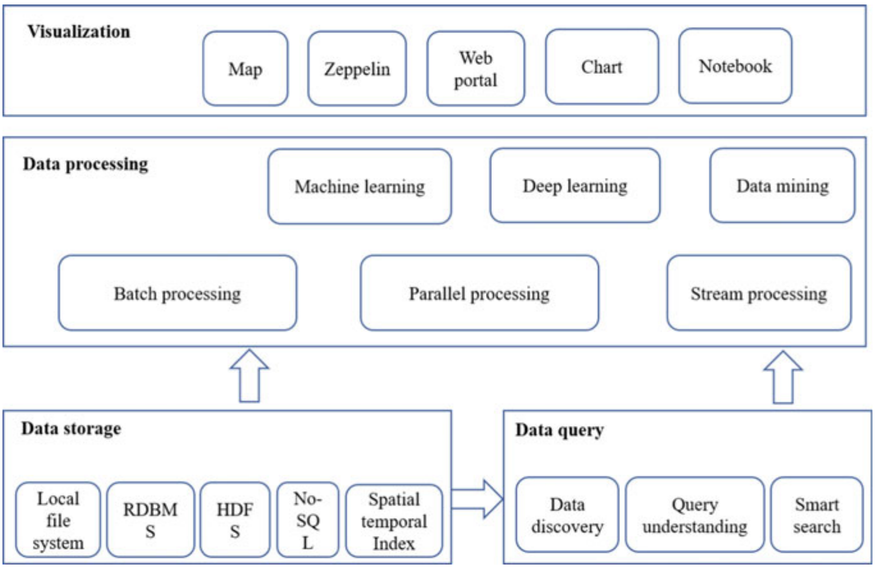

Fig. 9.2 Architecture for big data analyses

9.4.1 Data Storage Layer

Digital Earth is heavily involved in processing big data from Earth observations and model simulations, and these vast amounts of high-dimensional array-based spatiotemporal data pose challenges for data storage (Li et al. 2017b). Customizations are indispensable in integrating advanced data storage technologies with big Earth data storage, as general distributed file systems such as Hadoop are not designed to store spatiotemporal data.

A robust and stable data storage framework is the foundation of the data analysis architecture. A series of research efforts focused on optimizing spatiotemporal data storage in distributed file systems or databases. For example, Hu et al. (2018a) reorganized NetCDF (Rew and Davis 1990), a standard data format for array-based raster data, into CSV files and deployed them within SciDB (Cudre-Mauroux et al. 2009), a scalable multidimensional array clustering database. Zhao et al. (2010) converted NetCDF data into CDL (network Common data form Description Language) files and distributed them on HDFS (Hadoop Distributed File System). MERRA data, which store reanalysis Earth climatic variables in NetCDF format, were transformed into Hadoop Sequence Files to be processed by standard MapReduce functions (Duffy et al. 2012). Li et al. (2015) decomposed array-based raster data and stored them with HBase, a NoSQL database built upon HDFS in a cloud computing environment for efficient data access and query.

To enable efficient big data query, logical query capabilities have been proposed to support spatiotemporal query of array-based models such as SciHadoop (Buck et al. 2011). A spatiotemporal index was designed to efficiently retrieve and process big array-based raster data using MapReduce and a grid partition algorithm atop the index to optimize the MapReduce performance (Li et al. 2017a). SciHive was developed as an extension of Hadoop Hive, mapping arrays in NetCDF files to a table and calculating the value range for each HDFS to build a distributed adaptive index (Geng et al. 2013, 2014). Malik (2014) introduced a Z-region index into GeoBase to facilitate array-based data storage.

9.4.2 Data Query Layer

To help data consumers efficiently discover data from the massive available Earth data, the Digital Earth communities have built various data portals to improve the discovery, access, and usability of Earth data. The portals are normally supported by text search and spatiotemporal search and include the GeoPortal,[1] GeoNetwork[2] Spatial Web Portal (Xu et al. 2011), Global Earth Observation System of Systems GEOSS Clearinghouse (Liu et al. 2011; Nativi et al. 2015; Giuliani et al. 2017),

[1]https://www.geoportal.gov.pl/.

[2]https://geonetwork-opensource.org/.

GeoSearch (Lui et al. 2013) and many others. For example, GEOSS is a cloud-based framework for global and multidisciplinary Earth observation data sharing, discovery, and access (Nativi et al. 2015). In the framework, datasets or workflows are registered into shared collections or global catalogs, allowing for end users to search for workflows and datasets across multiple granularity levels and disciplines.

In addition, open-source information retrieval frameworks, e.g., Apache Lucene or its variants such as Solr and Elasticsearch (McCandless et al. 2010), were adopted to establish an Earth data portal instead of implementing a search engine for Earth data from scratch. Lucene uses the Boolean model and the practical scoring function to match documents to a query. Solr and Elasticsearch improve the Lucene index to enable big data search capabilities. The Physical Oceanography Distributed Active Archive Center (PO. DAAC) serves the oceanographic community with 514 collection level datasets and massive granule level data atop Solr (Jiang et al. 2018a). Elasticsearch is the fundamental component of NOAA's OneStop portal in which data providers manage data and metadata with increased discoverability and accessibility.

However, solely relying on open source solutions is insufficient for Earth data discovery because these solutions only rely on a keyword-based relevance score for ranking and ignore other user preferences, e.g., data processing level, sensor type. A few related research efforts have been conducted in the Earth science domain to make data search engines smarter and more intelligent. For example, an algorithm combing Latent Semantic Analysis (LSA) and a two-tier ranking was reported to build a semantic-enabled data search engine (Li et al. 2014a, b). Jiang et al. (2018a) developed a smart web-based data discovery engine that mines and utilizes data relevancy from metadata and user behavior data. The engine enables machine-learned ranking based on several features that can reflect users' search preferences.

9.4.3 Data Processing Layer

Data processing layer is a core component of the data analytics architecture. To analyze terabyte and petabyte datasets with low time latency, even in a real-time manner, sophisticated parallel computing algorithms and scalable computing resources are required in the big data processing framework (Yang et al. 2015a). Advanced open-source parallel computing solutions, e.g., Hadoop MapReduce, Spark, and their variants in the Earth data domain have been leveraged to support data analysis and mining tasks with better performance.

Hadoop MapReduce is a high-performance batch processing parallel framework that solves large computational problems on distributed storage systems (White 2012). It transfers the algorithm code to data nodes rather than moving data blocks to a compute node to avoid I/O bottlenecks. Spark enables high-performance data analysis with in-memory computing. An in-memory data structure called the Resilient Distributed Dataset (RDD) manages datasets distributed in a Spark cluster (Zaharia et al. 2012). However, the original distributed frameworks have limitations on big spatiotemporal data processing. Yu et al. (2015) noted that the system scalability for spatiotemporal data and interactive performance are the two main challenges for big Earth data processing. To solve these problems, scientists and engineers have customized open-source solutions for spatiotemporal data analysis.

SpatialHadoop is a MapReduce-based framework with native support for spatial data including a simple spatial high-level language, a two-level spatial index structure, a fundamental spatial component built on the MapReduce layer and three basic spatial operations (range query, k-NN query, and spatial link) (Eldawy and Mokbel 2015). GeoSpark provides operational tools for spatial big data processing based on Spark (Yu et al. 2015). The Spatial Resilient Distributed Datasets (SRDDs) structure represents spatial data blocks in memory and index objects using quad-tree and r-tree in each RDD partition (Lenka et al. 2016). ClimateSpark integrates Spark SQL and Apache Zeppelin to develop a web portal that facilitates interaction among climatologists, climate data, analytical operations and computing resources (Hu et al. 2018b). As an extension of Scala, GeoTrellis supports high-performance raster data analysis. GeoMesa provides spatiotemporal data persistence on Hadoop and column-family databases (e.g., Accumulo, HBase), as well as a suite of geospatial analytical tools for massive vector and raster data (Hughes et al. 2015).

As described in this section, a service-oriented, scalable architecture usually contains three major layers to provide desirable functionalities and capabilities: (1) the bottom data storage layer provides physical data storage, (2) the data query layer enables data discovery capabilities with proper functionality and interoperability, and (3) the data processing layer supports extensible, interoperable and scalable analytical functionalities based on open source solutions and their variants from the geoscience communities. With the architecture, big Earth data could be accessed and analyzed with low time latency or even in real time. However, it is challenging to set up such architecture and share data stored inside them due to the requirements of storage resources, computing resources, complicated configurations, and domain knowledge. Fortunately, the paradigm of cloud computing, discussed in the next section, brings potential solutions to ease the process of analytical framework setup and data sharing.

9.5 Cloud Computing for Big Data

9.5.1 Cloud Computing and Other Related Computing Paradigms

Grid computing and High Performance Computing (HPC) have been utilized for big data analytics. Grid computing, a distributed system of computer resources, performs large tasks using loosely coupled computers in a distributed system (Hamscher et al. 2000). The European Data Grid project utilizes grid computing to support exploration of multi-petabyte datasets (Segal et al. 2000) and the TeraGrid GIScience gateway utilized grid computing to perform computationally intensive geographical analytics

(Wang and Liu 2009). HPC uses supercomputers to run applications in parallel, efficiently and quickly, and is used in the PRACE project to serve European scientists with high-performance computing capabilities to conduct research (Hacker et al. 2010).

Cloud computing virtualizes computer resources as a resource pool to provide computing resources over the network by optimizing resource usage in terms of the CPU, RAM, network, and storage. Cloud computing has intrinsic connection to the Grid Computing paradigm (Foster et al. 2008) in that both are distributed computing systems. Cloud computing relies on remote servers whereas grid computing connects servers or personal computers over a common network using a Wide Area Network (WAN) to perform parallel tasks (Foster et al. 2008). Compared with HPC, cloud computing is cost effective and easy to use. Although cloud computing can provide high performance computing capability, HPC is irreplaceable for some applications since supercomputers are required to process very complicated processes such as climate simulations. In addition, resources in cloud computing are controlled by the service providers and users have limited controls.

In addition to cloud computing, other new computing paradigms have emerged to build a comprehensive and economic computing framework. For example, edge computing can process data at the edge of network due to the advancement of the IoTs. IoT applications usually produce a massive amount of streaming data and require near-real time response; thus, cloud computing alone is not an optimal solution for data collection and analysis for such real-time applications. In edge computing, edge nodes serve as data providers and consumers to protect data privacy and make full use of the computing capacity of edge nodes. Less data is transferred to the cloud computing platform after data preprocessing in edge nodes, reducing the response time and bandwidth cost (Shi et al. 2016).

Mobile computing with portable computing nodes has become an important computing paradigm with the improvements in the computing and storage capacity of smart devices such as smartphones and tablets (Qi and Gani 2012). Although services provided by mobile computing are not as reliable as edge computing and cloud computing due to the restrictions in battery volume and network connection, mobile computing can collect data and reach end users where cloud computing and edge computing are inaccessible.

These computing paradigms have advantages and disadvantages, and can be integrated to complement each other and provide reliable and effective data storage and processing frameworks according to the data characteristics and computing requirements. Cloud computing and big data are the two most important technologies in Digital Earth. The following section discusses the utilization of cloud computing to support big data management in Digital Earth.

9.5.2 *Introduction to Cloud Computing*

As a new computing paradigm, cloud computing delivers scalable, on-demand, pay-as-you-go access to a pool of computing resources (Mell and Grance 2011; Yang et al. 2011a). Practically, cloud computing aims to maximize the utilization rate of physical resources and provide virtual resources to aid applications and services. Cloud computing relies on several technologies including virtualization, network security, and high availability to provide services over the network. These technologies make it easier, more efficient, and more economical to set up architecture for big data analysis.

Virtualization is the fundamental technology for cloud computing, which abstracts an application, operating system, or data store from the underlying hardware or software. Virtualization creates a "layer of abstraction" between the physical systems and a virtual environment in the virtualization process (Big Data Virtualization). Server virtualization optimizes the use of redundant computing and storage resources by virtualizing distributed computer resources (e.g., CPU, RAM, Network, and Disk) and managing them in the same resource pool. With virtualization, cloud computing can provide on-demand big data services and support big data technologies including big data storage, process, analysis, visualization, and remote collaboration (Fig. 9.3). Virtualizing big data resources as a pool serves as a user-friendly interface and makes big data analytics accessible to end users.

As one of the cloud solutions, public clouds are the most accessible cloud computing services offered by third-party providers (e.g., Amazon Web Services (AWS), Microsoft Azure, Alibaba Cloud) over the Internet. Public clouds are available to the public and may be offered on a pay-per-usage model (Li et al. 2010). In contrast to public clouds, private clouds are dedicated for use inside an organization. Private cloud resources can be managed by an organization or by a third-party vendor,

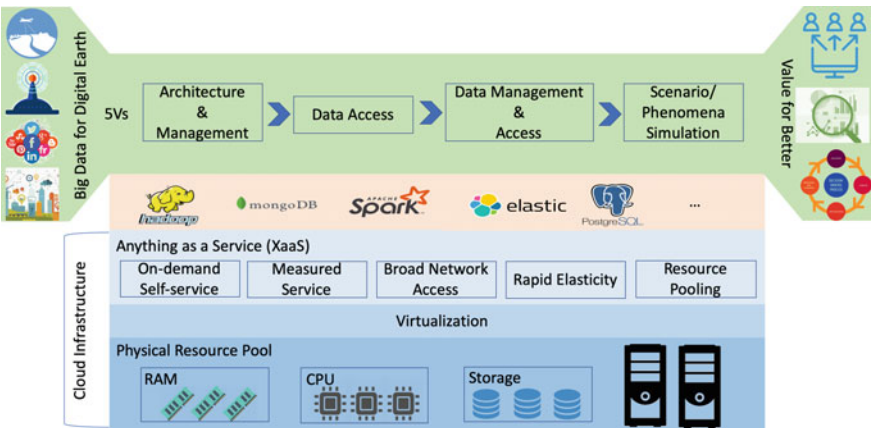

Fig. 9.3 Cloud computing for big data analysis

regardless of the physical location of the resources (Dillon et al. 2010). The computing resources in a private cloud are isolated and delivered via a secure private network.

The advanced features of auto scaling and load balancing through resource monitoring further maximize the capability of cloud computing resources. Based on the individual performance of a machine, autoscaling can be applied to allow for some servers to rest during times of low load to save electricity costs and automatically add more instances during times of high demand. In addition, load balancing improves the distribution of workloads across multiple instances to optimize resource use, minimize response time, and avoid overloading any single instance.

9.5.3 Cloud Computing to Support Big Data

Cloud computing combines distributed computing resources into one virtual environment, providing big data analytics and solutions during the life cycles of big data. Three main categories of cloud computing services are (1) Infrastructure as a Service (IaaS), (2) Software as a Service (SaaS), and (3) Platform as a Service (PaaS). Together with Data as a Service (DaaS), Model as a Service (MaaS; Li et al. 2014a, b) and workflow as a service (WaaS; Krämer and Senner 2015), cloud computing offers big data researchers the opportunity of anything as a service (XaaS; Yang et al. 2017b).

Cloud Storage for Big Data Storage

The characteristics of big data in high volume lead to challenges for data storage. Cloud computing's potential for unlimited storage support helps solve the volume challenge of big data, as the cloud provides virtually customizable storage with elastically expandable and reducible size. An alternative solution is Data Storage as a Service (DSaaS) enabled by block storage, which is the capability of adding external storages as "blocks". With block storage, it is possible to enlarge the storage size without physically loading hard drives. Virtually unlimited scalable storage offered by cloud computing grants users the capability of dynamic adjustment to satisfy the storage requirements of data with high volume and velocity. The modularized virtual resource offers effortless data sharing within production environments by allowing for an external data block to be detached and remounted from one machine to another. External data storage can be automatically backed up to prevent users from losing data, and backups that are securely saved at the back-end server can be easily transferred and restored. In addition, information security is guaranteed because the physical location cannot be obtained from the disk drive (Mayama et al. 2011).

Cloud Computing for Big Data Processing

Processing large volumes of data requires dedicated computing resources, e.g., faster CPUs and networks and larger disks and RAMs (Yang et al. 2017b). Cloud computing provides on-demand resources and delivers configurable resources including mountable external storage spaces, computing resources (CPU, RAM), and network services. Traditionally, a computer uses approximately two-thirds of the power of a busy computer (JoSEP et al. 2010), and cloud computing has the potential to provide on-demand computing resources. Isolated virtual structures have been created for big data systems to enhance system stabilities, which can be easily managed in different file systems and replicated through backup images to provide fast configuration recovery. The ability to replicate environments automates the expansion of compute nodes in virtual machine clusters, thereby efficiently utilizing resource pools to support big data analytics. With the foundational support of storage for big data, data processing inherits the advantages of fast data acquisition and relocation.

Although cloud computing could serve as an excellent infrastructure option for big data processing, several aspects should be considered to minimize the bottleneck effect for the general processing speed, such as the choice of cloud volume type according to I/O demand and cloud bandwidth selection according to application requirements.

Cloud Computing for Big Data Analytics

Popular big data analytical platforms such as Apache Hadoop are traditionally installed on physical machine clusters, resulting in a waste of computing resources due to hardware redundancy (CPU and RAM). With the virtual clusters provided by cloud computing through virtualization technology, distributed analytical platforms can be migrated to the virtual clusters from physical machine clusters, optimizing the usage of computing resources in an efficient manner.

With the aid of autoscaling and load balancing, deploying on-demand and scalable big data analytical platforms could easily provide resilient analytical frameworks and minimize waste of computing resources. Autoscaling supports parallel algorithms on distributed systems and architectures for scalability. It allows for the expanded resources to function when the algorithms or programs are enabled with parallel computing capability. Without it, public cloud providers such as AWS could not offer automatic scalability (JoSEP et al. 2010). The load balancer distributes workloads among virtual clusters and triggers autoscaling functions when analytics require higher computing configurations. The virtual system as a whole could dynamically fit higher computing requirements by launching more virtual duplications as needed. The load balancer acts as a virtual network traffic distributor and can be optimized to better allocate overall resources.

Cloud Computing for Big Data Sharing and Remote Collaboration

Traditional deployment of big data systems requires complicated settings and efforts to share data assets. It lacks access control and often leads to data security and data privacy issues. Cloud computing enhances the sharing of information by applying modern analytical tools and managing controlled access and security (Radke and Tseng 2015). Virtualization enables different parties to share data assets to achieve various goals and objectives under a centralized management system. With the support of cloud computing, it is possible to flexibly share data and remotely collaborate, which involve interdisciplinary collaborations and advanced workflows. Though data sharing, computational resource sharing, and production environment sharing, cloud computing can potentially be used to build a perceptual environment to support various businesses and applications (Li et al. 2015). Unfortunately, workflow sharing remains challenging due to domain boundaries (Yang et al. 2017b).

9.6 Case Study: EarthCube/DataCube

Big data and cloud computing enable Earth scientists and application developers to create web-accessible frameworks and platforms to efficiently store, retrieve and analyze big Earth data. In the Earth science domain, scientists have proposed a series of data models, frameworks, and initiatives to ensure the success of heterogeneous data sharing and analysis. For example, a 10-year framework initiative on sustainable consumption and production from 2013 to 2023 was launched by the United Nations Environmental Program (UNEP). The Future Earth framework, an international research program in the environmental science community, serves as an evolving platform to support transitions toward sustainability (Lahsen 2016). Microsoft's Eye-On-Earth platform aids climate change research in several European countries by collecting and sharing water and air quality data (Microsoft 2011). As part of the European program to monitor the Earth, the Copernicus Data and Information Access Service (DIAS) platform collects and processes data from remote and in situ sensors and provides reliable information covering six thematic areas including land, ocean, atmosphere, climate, emergency, and security (Bereta et al. 2019). Through its Exploitation Platforms (EP) initiative, the European Space Agency (ESA) built several cloud-based Thematic Exploitation Platforms (TEPs) in a preoperational phase for geo-hazard monitoring and prevention (Esch et al. 2017). The CASEarth Poles comprise a comprehensive big data platform of the three poles including the Arctic, Antarctic and the Tibetan plateau within the framework of the "Big Earth Data Science and Engineering" program of the Chinese Academy of Science (Guo et al. 2017). One of the current initiatives is the NSF EarthCube originated from the NSF GEO Vision report (NSF Advisory Committee for Geosciences 2009). In this section, we introduce the EarthCube project and a big data infrastructure, Data Cube, as two cases of big data and cloud computing in the context of Digital Earth.

9.6.1 EarthCube

NSF EarthCube involves (1) Building Blocks (BBs), to develop novel infrastructure capabilities and demonstrate their value in a science context; (2) Research Coordination Networks (RCNs), to engage the science community around joint goals; (3) Conceptual Designs (CDs), to develop broad architecture design and explore integrative systems; (4) Integrative Activities (IAs), to explore concepts for the design of an enterprise architecture, and (5) Data Infrastructures (DIs) to lay the groundwork for shared data. The EarthCube concept originated from the NSF GEO Vision report (NSF Advisory Committee for Geosciences 2009), which was issued by the Advisory Committee for NSF's Geosciences Directorate (GEO) and identified the future focus of the Earth science community as '*fostering a sustainable future through a better understanding of our complex and changing planet*.' To achieve the GEO vision, the GEO and Office of Cyberinfrastructure (OCI) jointly launched the EarthCube (NSF 2011) initiative as a driving engine to build a geospatial cyberinfrastructure (similar to a Digital Earth infrastructure, Yang et al. 2010) to (1) understand and forecast the behavior of a complex and evolving Earth system; (2) reduce vulnerability and sustain life; and (3) train the workforce of the future.

EarthCube (2012) is targeted at (1) transforming the conduct of data-enabled geoscience-related research, (2) creating effective community-driven cyberinfrastructure, (3) allowing for interoperable resource discovery and knowledge management, and (4) achieving interoperability and data integration across disciplines (Fig. 9.4).

In addition, EarthCube is evolving within a rapidly growing, diverse, and wide-ranging global environment. In addition to the collaboration within EarthCube, there are other contributing entities ranging from individual data sets and software applications to national and international cyberinfrastructure systems. The NSF has funded the development of EarthCube through individual EarthCube awards since 2013. In 2016, the NSF awarded 11 new EarthCube activities, for a total of 51 awards. A sampling of efforts in EarthCube that benefit from big data and cloud computing are introduced below.

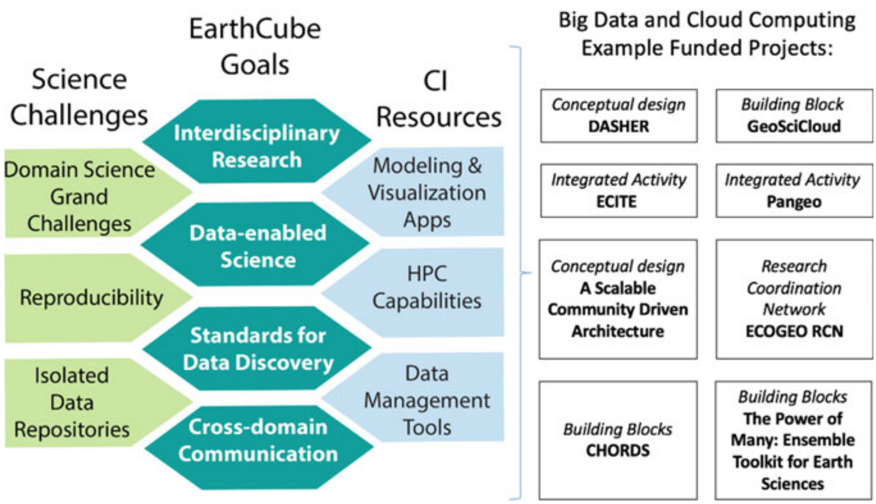

Fig. 9.4 Examples of related projects (derived from EarthCube goals, EarthCube Office 2016)

Conceptual design DASHER

Yang et al. (2015b) proposed a conceptual EarthCube Architecture, DASHER (Developing a Data-Oriented Human-Centric Enterprise Architecture for EarthCube), to support EarthCube and facilitate data communication and social collaboration in pursuit of collaborative Earth sciences research. The final product is a four-volume report containing different viewpoints that describe EarthCube architecture from different conceptual perspectives such as capabilities, operations, services, and projects. It provides a comprehensive conceptual reference for developing a detailed and practical architecture to address the requirements of the EarthCube community. DASHER was one of the first projects funded by EarthCube to design the conceptual framework integrating computational resources and big data sources.

Building Block GeoSciCloud

GeoSciCloud (Deploying Multi-Facility Cyberinfrastructure in Commercial and Private Cloud-based Systems) investigated two medium-size NSF funded data centers to deploy data collections with cloud-based services in different environments to assess feasibility and impact (EarthCube 2019). These environments include (1) commercial cloud environments offered by Amazon, Google, and Microsoft and (2) NSF-supported extensive computing facilities that are just beginning to offer services with characteristics of cloud computing.

GeoSciCloud helps EarthCube compare and contrast these three environments (the Extreme Science and Engineering Discovery Environment (XSEDE), commercial cloud, and current infrastructure) in the massive data ingestion to the cloud, data processing time, elasticity, the speed of data egress from multiple environments, overall costs of operation, interoperability, and reliability of real-time data streaming.

Integrated Activity ECITE

The EarthCube Integration and Test Environment (ECITE) is an outgrowth of activities of the EarthCube Testbed Working Group. The ECITE approach focuses on integrating existing effective technologies and resources as well as capabilities built by the EarthCube community using a cloud platform to provide a federated and interoperable test environment (EarthCube 2016). ECITE engages scientists and technologists from multiple disciplines and geographic regions across the Earth science community to develop requirements, prototype, design, build, and test an integration test-bed that will support cross-disciplinary research. The hybrid federated system will provide a robust set of distributed resources including both public and private cloud capabilities. This research addresses timely issues of integration, testing and evaluation methodologies and best practices with a strong interoperability theme to advance disciplinary research through the integration of diverse and heterogeneous data, algorithms, systems, and sciences.

Integrated Activity Pangeo
Pangeo[3] (an open-source big data climate science platform) integrates a suite of open-source software tools that can tackle petabyte-scale Atmosphere/Ocean/Land/Climate (AOC) datasets. Pangeo aims to cultivate an ecosystem in which the next generation of open-source analysis tools for ocean, atmosphere and climate science can be developed, distributed, and sustained. These tools must be scalable to meet the current and future challenges of big data, and the solutions should leverage the existing expertise outside of the AOC community. The resulting software improvements contribute to upstream open source projects, ensuring the long-term sustainability of the platform. The result is a robust new software toolkit for climate science and beyond. This toolkit will enhance the Data Science aspect of EarthCube. Implementation of these tools on the cloud was tested, taking advantage of an agreement between commercial cloud service providers and the NSF for big data solicitation.

9.6.2 Data Cube

The term 'data cube' was originally used in Online Analytical Processing (OLAP) of business and statistical data but has more recently been used in Earth domains as an approach to manage and analyze large and rapidly growing datasets. In Digital Earth, a data cube represents a multidimensional (n-D) array that stores gridded data or array-based data produced by remote sensing and simulation (Zhang et al. 2005). A data cube can be based on regular or irregular gridded, spatial and/or temporal data with multiple parameters. To support the management, sharing, and serving of Digital Earth data, tools and models, different cyberinfrastructures have been developed based on data cubes. Examples include the EarthServer that provides data cube services for Earth observations based on the RASDAMAN array database (Baumann et al. 2016). Another example is the Earth Observation Data and Processing Platform developed by the European Commission to integrate and analyze the combination of satellite and in situ Earth observations for sustainable development goals (Soille et al. 2016). The Committee on Earth Observation Satellites (CEOS) provides a data processing infrastructure based on data cubes to support Earth science objectives in developing countries, with a focus on remote sensing data (Nativi et al. 2017). The platform automatically ingests different remote sensing data into an N-dimensional data array.

Challenging issues in providing data services in data cube infrastructure include interoperability, rapid data access and transfer, and real-time processing and analysis (Strobl et al. 2017). Interoperability issues occur because datasets from various sources can have distinct parameterizations, spectral band definitions, projections, file formats, and database structures. One solution is to standardize the preprocessing procedure before storage and sharing with the community. The Open Geospatial

[3] http://pangeo.io/.

Consortium (OGC) Sensor Web Enablement (SWE) Common Data Model (CDM) defines important element parameterization (Robin 2011). Datasets must be represented along different predefined dimensions of the data cube, including space, time, and parameter properties. For projection difference issues, OGC recently developed the Discrete Global Grid System (DGGS) to optimize the loss of geospatial data during the reprojection process and seamlessly integrate GIS data from various sources (Stefanakis 2016). Data cube infrastructures also require rapid data access and transfer and real-time processing and analysis. Functionalities for user interactions must be built for various user demands, including file manipulation, data preprocessing, and analysis. These functionalities should also meet the standards of geographical information processing in OGC Web Coverage Services (WCS), geographic information analysis in the OGC Web Coverage Processing Service (WCPS), and format-independent data cube exchange in the OGC Coverage Implementation Schema (CIS).

Cloud computing and big data frameworks could enhance the data cube archive, visualization, and analysis in many ways to meet the needs of big Earth data knowledge mining. In cloud computing, storage is a virtual resource that can be attached and scaled on demand. By leveraging cloud computing and big data frameworks, visualizing data cubes and performing complicated spatiotemporal queries are more effortless than ever before (Zhizhin et al. 2011). One example of data cube visualization in the Earth science domain is the EOD[4] (Earth Observation Data Cube), which enables advanced data access and retrieval capabilities for the European coverage of Landsat-8 and the global coverage of Sentinel2 data. It aims to improve the accessibility of Big Earth data and offers more than 100 TB of Atmosphere, Land and Ocean EO products, demonstrating satellite data in the context of a virtual globe. The ESDC[5] (Earth System Data Cube) is another example of climate data cube visualization and analysis that aims to develop an environment to tap into the full potential of the ESA's Earth observations and integrate with the Biosphere-Atmosphere Virtual Laboratory (BAVL) analysis environment. The use of cloud computing technologies in big data visualization enables a massive amount of end users to explore data online at the same time with very low latency.

Data cube partition and parallel query could be achieved by utilizing distributed big data frameworks, which are faster and easier than traditional noncluster methods. Pagani et al. combined the data cube concept with cloud computing to manage and analyze large Earth datasets and observed better outcomes than traditional file-based approach (2018). Open Data Cube[6] is another example of the utilization of advances in cloud computing, providing free and open technologies to end users without local infrastructure. Thus, developing countries can access data and computing resources to build applications that aid decision making. The Australian Geoscience Data Cube (AGDA) solves similar problems of data sharing. It makes more than three decades of satellite imagery available for the first time, spanning Australia's total land area at

[4]https://eodatacube.eu/.

[5]https://cablab.readthedocs.io.

[6]https://www.opendatacube.org/.

a resolution of 25 square meters with more than 240,000 images that show how Australia's vegetation, land use, water movements, and urban expansion have changed over the past 30 years (NCI).

9.7 Conclusion

The advancement of Digital Earth drives collection of massive data such as transportation data, utility data, hazard data and forest data to monitor the Earth and support decision making. Valuable information extracted from the collected big data can further speed the development of Digital Earth. Digital Earth data continue to grow at a faster speed and with more heterogeneous types, leading to challenges to the lifecycle of data management including storage, processing, analytics, visualization, sharing, and integration. Fortunately, the emerging paradigm of cloud computing brings potential solutions to address these challenges. Compared with traditional computing mechanisms, cloud computing has the advantages of better data processing computing supports. The customizable configuration saves computing resources elastically, and data manipulation with higher security and flexibility offers secure data storage, transfer and sharing. Analytics enabled by cloud computing advance the process by allowing for automatic resource expansion when there are higher requirements.

To manage and analyze big Earth data, a service-oriented, scalable architecture based on cloud computing was introduced in a three-layer architecture: (1) the bottom data storage layer provides physical infrastructure, storage, and file systems; (2) the data query layer supplies data discovery capabilities with proper functionality and interoperability; and (3) the data processing layer supports extensibility, interoperability and scalability based on open source solutions and their variants from Earth science communities. With this architecture, big Earth data can be accessed and analyzed with low time latency or even in real time. The analysis results could be published by a web-based map server (e.g., GeoServer) or web-based notebook (e.g., Zeppelin) for visualization, public access, and collaboration, contributing to advancements in handling big data in Digital Earth to fulfill the requirements of scalability, extensibility and flexibility.

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Yun Li is a Ph.D. candidate majoring in Earth Systems and Geoinformation Sciences at George Mason University. Her research mainly focuses on improving Earth data discovery using machine learning based methods, high performance computing, and spatiotemporal analytics for environmental and climate data.

Manzhu Yu is an Assistant Professor of GIScience at Pennsylvania State University. Her research focuses on spatiotemporal theories and applications, atmospheric modeling, environmental analytics, big data and cloud computing, and the ability of using the above to solve pressing issues in natural hazards and sustainability.

Mengchao Xu is a Ph.D. candidate in Earth Systems and Geoinformation Sciences program from George Mason University. His research mainly focuses on the cloud computing, high performance computing networks, distributed database systems, and precipitation downscaling. He manages a 500-nodes cluster specialized for cloud computing (supported by NASA, NSF and GMU).

Jingchao Yang is a Ph.D. student majoring in Earth Systems and Geoinformation Sciences at George Mason University. He has been contributing to several NSF and NASA funded projects at the NSF Spatiotemporal Innovation Center. His research mainly focuses on the smart city problems with machine- and deep-learning enabled spatiotemporal pattern analysis using multi-sensor (IoT) datasets.

Dexuan Sha is a Ph.D. student in Earth Systems and Geoinformation Sciences at the George Mason University. He researches arctic sea ice and melt pond from high spatial resolution aerial imagery with big spatial–temporal data mining and analysis methodology.

Qian Liu is a Ph.D. student in Geography and Geoinformation Science at George Mason University. Her research mainly focuses on the core areas of precipitation detection and analysis using AI-based methods, and outreaches to environmental and climate science and spatial temporal analytics.

Chaowei Yang is Professor of GIScience at George Mason University, where he established and directs the NSF spatiotemporal innovation center. His academic activities include spatiotemporal computing research, future GIScience leader education, and Geoinformatics outreach.

Chapter 10
Artificial Intelligence

Eric Guérin, Orhun Aydin and Ali Mahdavi-Amiri

Abstract In this chapter, we provide an overview of different artificial intelligence (AI) and machine learning (ML) techniques and discuss how these techniques have been employed in managing geospatial data sets as they pertain to Digital Earth. We introduce statistical ML methods that are frequently used in spatial problems and their applications. We discuss generative models, one of the hottest topics in ML, to illustrate the possibility of generating new data sets that can be used to train data analysis methods or to create new possibilities for Digital Earth such as virtual reality or augmented reality. We finish the chapter with a discussion of deep learning methods that have high predictive power and have shown great promise in data analysis of geospatial data sets provided by Digital Earth.

Keywords Artificial intelligence · Machine learning · Generative models · Statistical data analysis

10.1 Introduction

Earth and its associated data sets are massive. Various forms of geospatial data sets are constantly accumulated and captured by different forms of sensors and devices (Mahdavi-Amiri et al. 2015). Managing such an immense data set is a challenge. As a result, many automated techniques have been designed to process geospatial data sets with minimal human interference. Since manual involvement should be minimal, the machines should be capable of processing data and delivering meaningful information to the users. With advancements in machine learning, processing

E. Guérin
LIRIS, Université de Lyon, Lyon, France

O. Aydin
ESRI, Los Angeles, Los Angeles, USA

University of Southern California, Los Angeles, USA

A. Mahdavi-Amiri (✉)
Department of Computing Science, Simon Fraser University, Burnaby, Canada
e-mail: amahdavi@sfu.ca

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geospatial data sets has significantly improved. In this chapter, we discuss artificial intelligence and machine learning techniques that have been useful to manage and process geospatial data sets. Because the processing of geospatial data can also be a source of knowledge, some methods use existing data to generate and synthesize new data.

We start by discussing some traditional and statistical approaches in machine learning and then present more recent learning techniques employed for geospatial data sets. Traditional methods include predefined models such as linear regression, PCA, SVD, active contour, and SVM, in which the model is fixed and the learning is based on an optimization. We also briefly discuss evolutionary and agent-based methods and autoencoders as traditional methods that can be deep or shallow. We then discuss more recent deep learning techniques, including reinforcement learning, deep convolutional networks and generative models such as variational autoencoders and generative adversarial networks. In this chapter, we describe some applications of these machine learning techniques to handle geospatial data sets that are the main content of Digital Earth. In the future, a dynamic Digital Earth that can use such techniques to work with geospatial datasets is extremely practical. Currently, such methods are sparsely used on very specific Digital Earth data sets. We imagine that a more advanced Digital Earth will use state-of-the-art machine learning techniques much more than they are currently used.

10.2 Traditional and Statistical Machine Learning

Inferring patterns and forming relationships using artificial intelligence require knowledge of some characteristics of the phenomena/system of interest. One of the early approaches to enabling artificial intelligence for complex problems was to create knowledge bases that contain explicit sets of rules and associations, also known as ontology (Gruber 1993). For data pertaining to Earth system modeling, different niche knowledge bases were designed by various authors (McCarthy 1988; Rizzoli and Young 1997). The knowledge base approach to artificial intelligence required expert input to define the rules and associations. In addition, the expert knowledge had to be represented in a "computable form" (Sowa 2000), posing a bottleneck for these approaches. For spatially varying, complex phenomena, ontology representations were defined for Earth's subsystems such as in environmental modeling and planning (Cortés et al. 2001), and ecological reasoning (Rykiel 1989). General spatial and GIS knowledge bases were proposed by various authors (Kuipers 1996; Egenhofer and Mark 1995; Fonseca et al. 2002).

Despite the plethora of niche knowledge bases, knowledge base artificial intelligence requires assertions and ground truths (Lenat 1995), which can conflict with observations (Goodfellow et al. 2016). Numerous attempts to address this limitation have been presented by various authors, such as defining hierarchical (Kuipers 1996), or location/problem-tailored knowledge bases (Rizzoli and Young 1997).

Statistical machine learning alleviates the limitations of the knowledge-based approach to artificial intelligence and discovers rules and patterns from the data directly without explicit supervision (Goodfellow et al. 2016). In the case of statistical learning, patterns and rules from an unknown underlying process are defined for descriptive, predictive and prescriptive analytics.

Applications of statistical learning to understand and forecast natural and human phenomena are evaluated with respect to the components of the general definition of machine learning (Mitchell 1997). Mitchell's (1997) definition is as follows:

> A computer program is said to learn from experience [D] with respect to some class of tasks T and performance measure [Q], if its performance at tasks in T, as measured by [Q], improves with experience [D].

Machine learning methods are broadly grouped into supervised and unsupervised methods. Supervised machine learning methods experience modeled phenomena through so-called labeled training data. Labels in the training data correspond to the target variable to be predicted, either quantitative (regression) or qualitative (classification). Training data consists of predictors and their corresponding predictand. Thus, supervised machine learning methods learn relationships in the data through experiencing input/output pairs.

Unsupervised machine learning methods discover patterns in the data without supervision or explicit rules. Clustering is one of the most common unsupervised machine learning methods for geospatial datasets.

10.2.1 Supervised Learning

Supervised learning aims to define a relationship between r predictor variables, denoted by $X = (X_1, X_2, \ldots, X_r)$, and e predictands, $Y = (Y_1, Y_2, \ldots, Y_e)$. Supervised learning can be posed as a density estimation problem (Hastie et al. 2001):

$$\boldsymbol{P(Y|X) = P(Y, X)/P(X)} \tag{10.1}$$

where $P(Y|X)$ is the conditional probability density of observing the predictand given the predictors, $P(Y, X)$ is the joint probability distribution of the predictand and predictors, and $P(X)$ is the marginal probability distribution of the predictors. Using Mitchell's (1997) description, the performance Q can be quantified using a loss function $\mathcal{L}$ where, for a given method and set of parameters Θ, a location function, $\mu(x)$, is minimized (Hastie et al. 2001) in Eq. 10.2.

$$\boldsymbol{\mu(x) = argmin_{\Theta} E_{Y|X} \mathcal{L}(Y, \Theta)} \tag{10.2}$$

For a given Θ, a supervised machine learning method predicts the values at X as $\hat{y}$. The loss function, $\mathcal{L}$, quantifies the error between $\hat{y}$ and the training data y.

Some examples of supervised machine learning methods as they pertain to geospatial analysis are given in the following subsection.

10.2.1.1 Random Forest

Random forest is a framework for nonparametric estimation in which both classification and regression can be performed (Breiman 2001). It has gained popularity in numerous geospatial applications due to its flexibility in accommodating different types of inputs (categorical or continuous) and its ability to model complex relationships in the data.

Random forest addresses the overfitting limitation of **c**lassification **a**nd **r**egression **t**rees (CART). Random forest uses bootstrap aggregating, also known as bagging, to create subsets of the training data by sampling with replacement to build different CARTs (Breiman 1996). Each of the CARTs that make up the forest predict, or vote, for a given data point of x and the forest returns the majority vote in a classification or the average forest prediction for a regression. The voting scheme of random forest allows for complex relationships to be captured in the data that might not be possible otherwise. A pictorial summary of a random forest classifier for classifying a successful retail store (one) or an unsuccessful one (zero) with respect to its distance to the nearest highway exit and the number of brands it carries is given in Fig. 10.1.

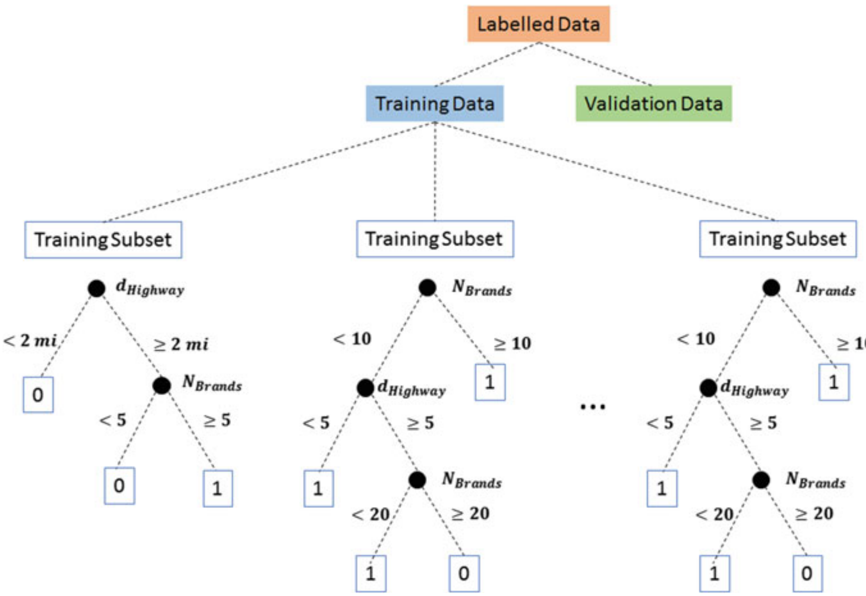


Fig. 10.1 Cartoon representation of a random forest classifier

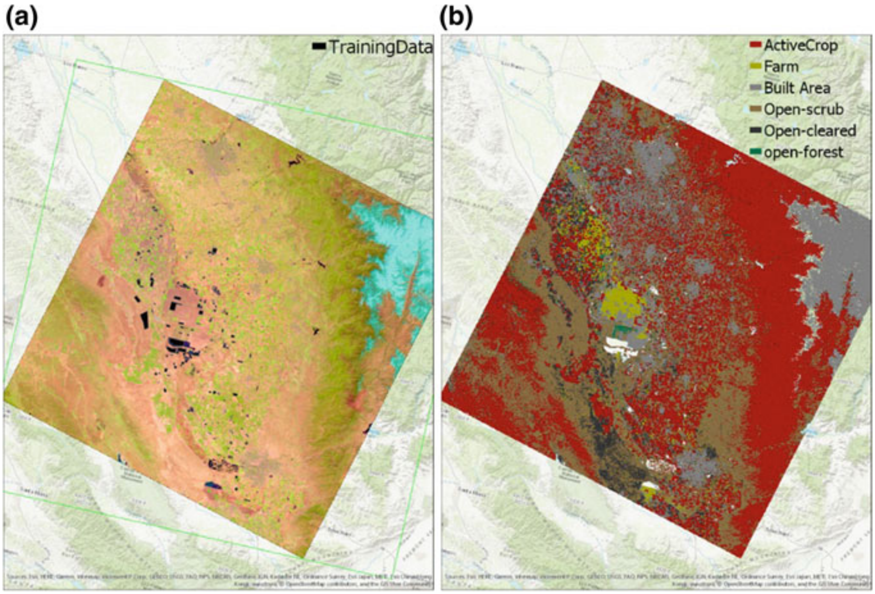


Fig. 10.2 **a** Satellite image over southern California, with training data marked with black polygons **b** classified land coverage map using random forest

Note that every tree experiences different subsets of training data and their structures are different from one another. The voting scheme allows for capturing underlying patterns in the data by defining complex relationships captured in a large ensemble of trees rather than a single tree.

In geospatial problems, various random forest classifiers are used in a wide range of problems, including land cover classification (Gislason et al. 2006) and ecological modeling (Cutler et al. 2007). In land cover classification, random forest speeds up classification of land use by forming a relationship between the satellite image RGB value and the type of land it corresponds to. In this case, the training data consists of tagged locations at which the land cover and RGB values are known. An example of the random forest classifier output for land use classification is given in Fig. 10.2.

In Fig. 10.2, a small number of farms and areas around them were used as training data (marked with black polygons). The training set that consists of 300 farms was used within the random forest classifier to define land use in southern California.

10.2.1.2 Geographically Weighted Regression

Geographically **w**eighted **r**egression (GWR) provides a statistical framework for incorporating spatial dependency within a linear regression system (Fotheringham

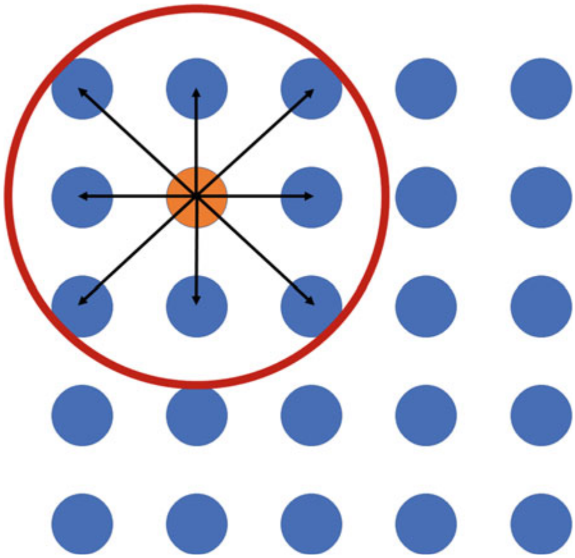


Fig. 10.3 Conceptual depiction of GWR. Regression is performed for the orange point with a red circle defining the neighborhood

et al. 2003). GWR provides spatial extensions to ordinary least squares and generalized linear models (Nelder and Wedderburn 1972) such as geographically weighted logistic regression. GWR is depicted conceptually in Fig. 10.3.

Figure 10.3 illustrates a regression system solved within the neighborhood (red circle) for the location indicated in orange. First, GWR defines a weighting scheme to determine spatial weights for the neighbors, and the predictors $\boldsymbol{X}$ at every location (blue) are weighted with respect to their distance to the location for which the regression is performed (orange). The geographically weighted linear system of equations solved at a point i can be expressed as follows:

$$\hat{\boldsymbol{\beta}}(\boldsymbol{u}_i, \boldsymbol{v}_i) = \left(\mathbf{X}^T \mathbf{W}(\boldsymbol{u}_i, \boldsymbol{v}_i)\mathbf{X}\right)^{-1} \mathbf{X}^T \mathbf{W}(\boldsymbol{u}_i, \boldsymbol{v}_i)\mathbf{Y} \tag{10.3}$$

where $\hat{\boldsymbol{\beta}}(\boldsymbol{u}_i, \boldsymbol{v}_i)$ is the coefficient matrix for the predictors $\mathbf{X}$ at location i. $\mathbf{W}(u_i, v_i)$ is a diagonal weighting matrix that contains geographic weights on its diagonal elements for neighbors inside the neighborhood window (red circle in Fig. 10.3), and $\mathbf{Y}$ contains the variable being predicted. Note that the linear system above is similar to the general linear regression system given in Eq. 10.4.

$$\hat{\boldsymbol{\beta}} = \left(\mathbf{X}^T \mathbf{X}\right)^{-1} \mathbf{X}^T \mathbf{Y} \tag{10.4}$$

where $\hat{\boldsymbol{\beta}}$ is defined globally for the entire dataset. The geographic weights are inversely weighted with respect to the distance. Thus, the weights have large values for neighbors close to the regression location i. Different weighting schemes and neighborhood definitions are possible; the reader is encouraged to explore seminal work on this topic (Fotheringham et al. 2003).

Spatial representation via a weighting scheme can give GWR high predictive power for geospatial datasets in which a strong spatial autocorrelation is observed. The impact of incorporating spatial relationships in the regression model is demonstrated by comparing GWR with a nonspatial supervised machine learning method. In this example, GWR is juxtaposed against a random forest predictor for a problem with strong spatial autocorrelation in the data. Statistical climate downscaling (Wilby and Wigley 1997) was performed with GWR and a random forest regressor. Statistical downscaling calibrates the output of a global circulation model (GCM) to observed climate data such as temperature or precipitation. In this example, climate downscaling for the lower 48 US states; a regression model can be defined between 19 predictors (from GCM) and the observed average temperature. The regression model can be used to predict the average temperature for the entire lower 48 states. A random forest predictor can be trained using the observed average temperature and simulated GCM variables. The GWR model is formed using only 3 of the independent predictors due to the collinearity restriction of GWR. Below are the predicted average temperature profiles.

Note that the average temperature profile estimated in Fig. 10.4a depicts the patterns of temperature change captured in Fig. 10.4b. Even though fewer predictors are used in the GWR than in the random forest regressor, large-scale patterns in the temperature profile changes are captured. The GWR model in Fig. 10.4a was also compared to a random forest regressor model trained using the same three predictors. In that case, the GWR returned a mean-squared error that was 60% of that of the random forest regressor.

10.2.1.3 SVM

Support vector machine (SVM) is a supervised nonparametric statistical learning method (Corinna and Vapnik 1995). In its original form, the method comprises a set of labeled data instances and the SVM attempts to find a hyperplane that separates the dataset into a discrete predefined number of classes as consistently as possible for the training data (see Fig. 10.5) (Vapnik 1979). It is possible to generalize SVM to nonlinear kernels such as radial basis functions to learn and classify data sets with higher complexity (Schölkopf and Smola 2002).

As studied and discussed by Mountrakis et al. (2011), SVMs have been extensively employed in remote sensing and geospatial data analysis due to their ability to use small training data sets, often resulting a higher classification accuracy than the traditional methods (Mantero et al. 2005). For instance, SVM has been used in road extraction from IKONOS imagery by (Huang and Zhang 2009) assessing the influence of the slope/aspect of the terrain on the forest classification accuracy (Huang et al. 2008), a crop classification task (Wilson et al. 2004), and many more factors.

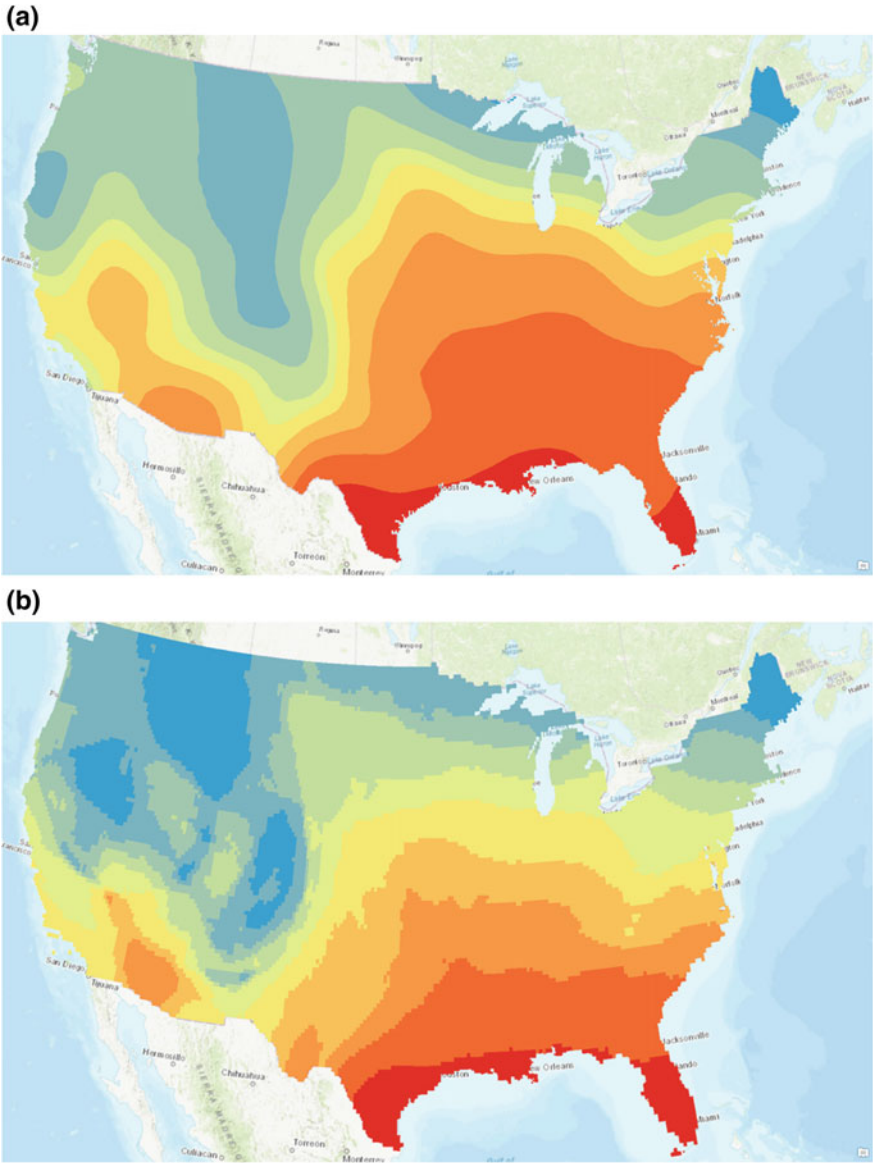


Fig. 10.4 **a** Downscaled temperature profile using GWR **b** downscaled temperature profile using a random forest regressor

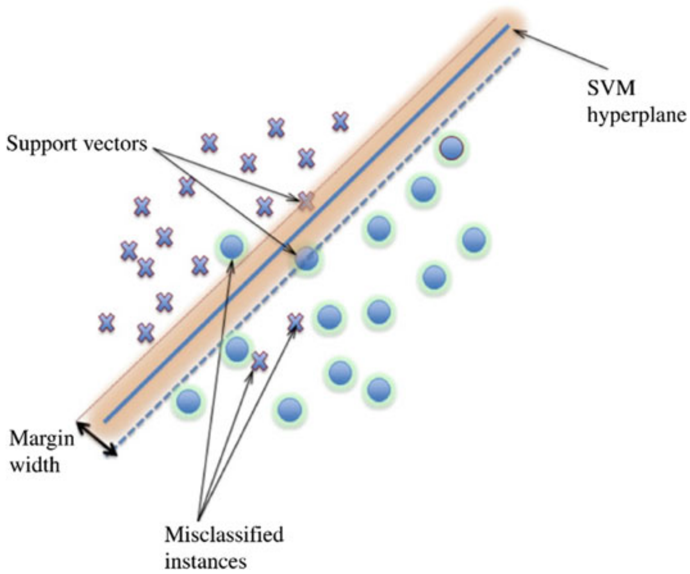


Fig. 10.5 SVM attempts to distinguish two categories of data by a hyperplane. Image from Mountrakis et al. (2011)

10.2.1.4 Active Contours and Active Shapes

Active contours or snakes have been developed with the aim of finding important features in an image by fitting a curve to the edges and lines of an image (Kass et al. 1988). Active contours are a set of energy-minimizing splines that are guided by external forces from the image. Snakes have been used extensively in geospatial image processing to detect features such as roads and buildings.

Active contours were later extended to active shapes to accommodate specific patterns in a set of objects and identify only those that are present in the training data (Cootes et al. 1995). In essence, they are very similar to active contours, but active shapes can only deform and fit the data that is consistent with the training set. Both active shapes and active contours have been extensively used in different applications of remote sensing and geoscience, such as object extraction (Liu et al. 2013), lane detection (Heij et al. 2004), and road extraction (see Fig. 10.6) (Kumar et al. 2017; Laptev 1997).

10.2.2 Unsupervised Learning

Unsupervised learning aims to infer the distribution of $P(X)$ in Eq. 10.1. Unlike supervised learning, $P(Y|X)$ or $P(X, Y)$ is not employed (Hastie et al. 2001). Thus,

Fig. 10.6 Active contours used to extract roads. Image taken form Laptev (1997)

unsupervised learning does not utilize any training dataset that contains information on $P(X, Y)$. One of the most common uses of unsupervised learning in geospatial analysis is in defining clusters and regions. These two terms differ, as clustering refers to defining groups based on value similarity in the data whereas regionalization performs clustering under spatial constraints (Duque et al. 2007). Both of these unsupervised learning approaches have wide applications (Duque et al. 2007; Hastie et al. 2001; Mitchell 1997; von Luxburg 2010). Most clustering and regionalization methods require definition of $\boldsymbol{k}$, the number of clusters to divide $\boldsymbol{X}$ into. There are extensive surveys of clustering and regionalization in the literature for readers to refer to (Duque et al. 2007; Jain et al. 1999).

10.2.2.1 SKATER Algorithm

As discussed in Chap. 8, the K-means algorithm (Macqueen 1967) aims to partition X into k groups and minimize the intergroup dissimilarity with the assumption that minimal intergroup dissimilarity corresponds to distinct groups. K-means seeks to create groups that consist of similar elements, ensuring that dissimilar elements are assigned to different groups. Mathematically:

$$\boldsymbol{\mu}(\boldsymbol{x}) = \boldsymbol{argmin}_{\mathrm{C}} \sum_{i=1}^{k} \sum_{x \in c_i} \left\| \boldsymbol{x} - \bar{\boldsymbol{C}}_{\iota} \right\|^2 \tag{10.4}$$

where $\boldsymbol{C} = \{\boldsymbol{C}_1, \boldsymbol{C}_2, \ldots, \boldsymbol{C}_k\}$ is the group of clusters, with a cluster $\boldsymbol{c_m}$ consisting of a subset of X and $\boldsymbol{c}_1 \cup \boldsymbol{c}_2 \cup \cdots \cup \boldsymbol{c}_k = \boldsymbol{X}$. K-means has various uses in geospatial analysis, including detecting patterns in traffic accidents (Anderson 2009), analyzing landslides (Keefer 2000) and creating labels by clustering topo-climatic data (Burrough et al. 2001).

The SKATER algorithm is a regionalization algorithm that imposes graph-based spatial constraints on the k-means algorithm (Assunção et al. 2006). Unlike Lloyd's algorithm (Lloyd 1982), SKATER only assigns spatially contiguous and similar objects to the same cluster. Regionalization has vast uses in geospatial analysis, including analysis of gerrymandering, healthcare services (Church and Barker 1998) and resource allocation (Or and Pierskalla 1979).

Clustering and regionalization were applied to the same dataset to juxtapose the types of patterns they expose in the data and the resulting understanding gained using these two methods. The average temperature in the United States in June 2012 was used. The resulting clusters and regions are displayed below.

The regionalization and clustering results in Fig. 10.7 show similarities in the overall temperature patterns, which change N-S in the eastern portion of the US and W-E in the western portion. Notably, the k-means result in Fig. 10.7b displays isolated patches whereas the regionalization result has spatially contiguous regions. Due to the constrained optimization scheme to satisfy the spatial constraints, the regions defined by regionalization have a higher variance than those in the k-means result. However, both maps display similarities in the temperature and the extent to which these similarities can be aggregated into homogeneous zones.

10.2.2.2 Autoencoders

Another very useful and common machine learning technique is autoencoders (Rumelhart et al. 1985). In an autoencoder, the data passes through a bottleneck, where the bottleneck is a lower representation of the same data. Autoencoders are made of two neural networks called the encoder and decoder (Fig. 10.8). The encoder receives data D, maps it to a lower space and obtains L; a decoder receives L, maps it back to the same dimension of D and obtains D'. The distance between D and D', which is called the reconstruction loss, should be minimized. A direct application of autoencoders is in compression, in which one can reduce the dimension of D to L and work with L and the decoder instead of the data D in its native resolution. Autoencoders have also been used in geospatial applications to find water bodies (Zhiyin et al. 2015) or denoise satellite images (Liang et al. 2017).

Machine learning techniques are not limited to the list of applications and methods provided here. Several variations of these methods as well as many other standalone techniques have been successfully employed in the Digital Earth, geoscience and remote sensing fields. For a more in-depth and comprehensive study, refer to the work of Lary et al. (2016).

10.2.3 Dimension Reduction

There have been extensive efforts to learn the patterns and forms that data sets contain. It is possible to predict the behavior of a data set and/or compress the data set into a more compact form for transmission, storage, and retrieval. In addition to autoencoders that can be used for dimensionality reduction, one of the easiest methods for compression and dimensionality reduction for a given data set and subsequent prediction of its behavior for unknown data points is *linear regression*.

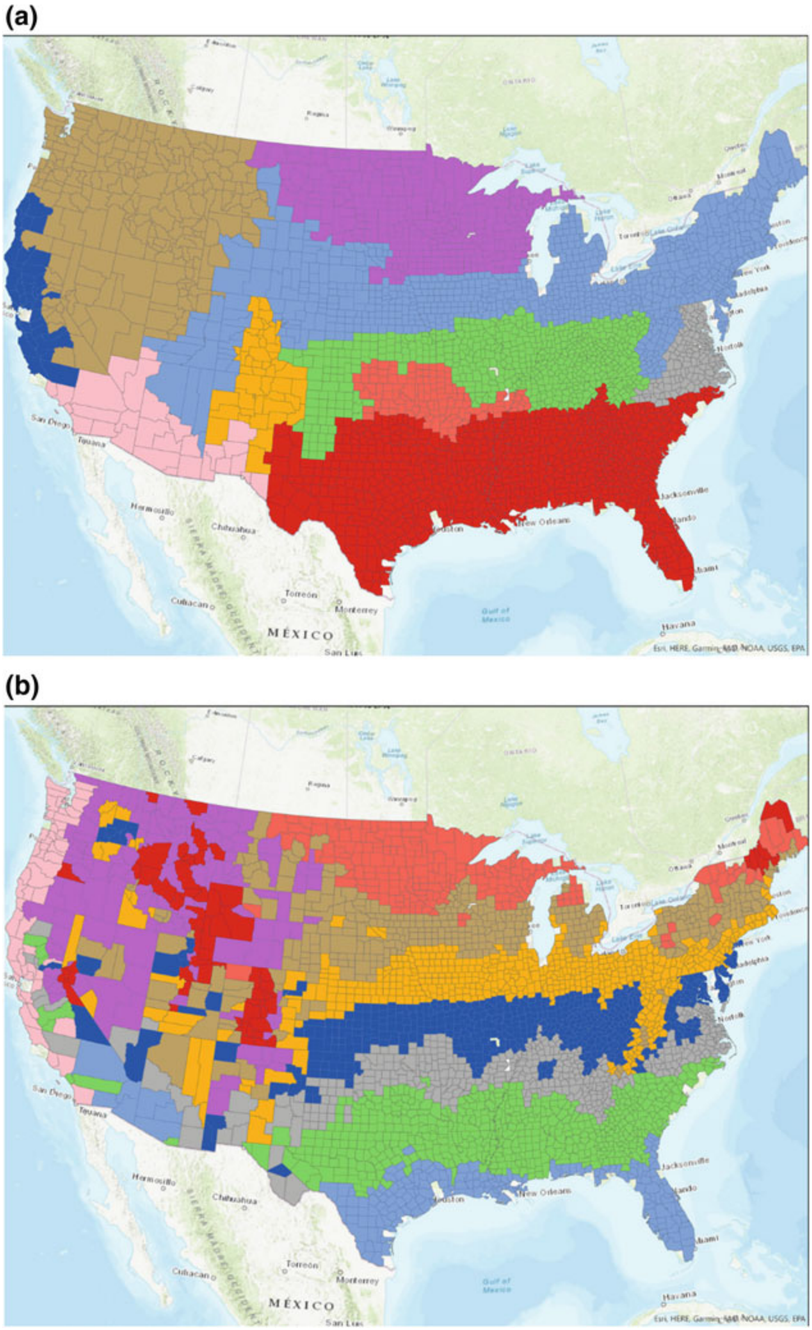


Fig. 10.7 **a** Temperature regions defined by SKATER **b** temperature regions defined by k-means

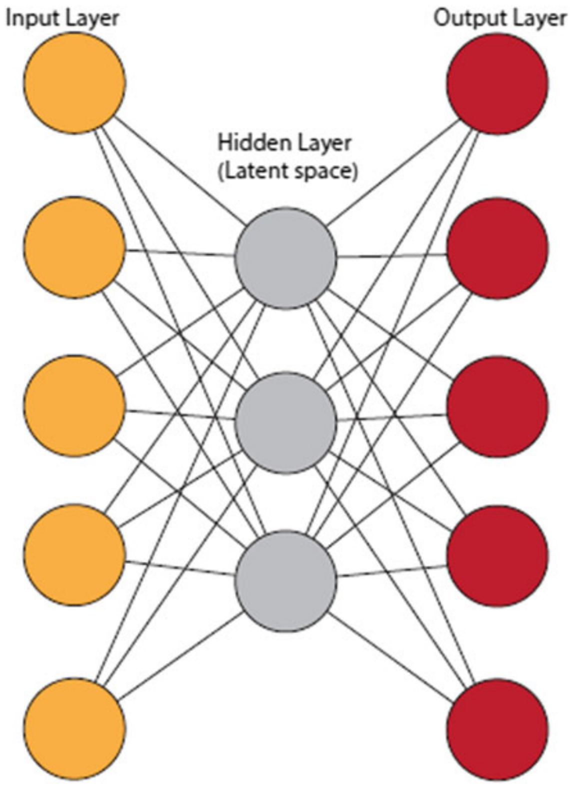


Fig. 10.8 The autoencoder passes the data (yellow neurons) through an encoder to learn a lower dimension (hidden/latent space; gray neurons) representation of the data. The decoder attempts to reconstruct the data (red neurons) as closely as possible to the given data

In the 2D case of this method, the data points attain two coordinates, and the line that best represents these data sets is considered as the model representative of the data. The best representation can have different meanings, including the line that has the smallest least square distance with all the data points. Regression, linear or nonlinear, has been a great tool to analyze spatial data. Belae et al. (2010) provided a survey of regression techniques used to represent and analyze spatial datasets. For Digital Earth platforms, Mahdavi-Amiri et al. (2018) combined regression with a wavelet to transmit quantitative datasets on a discrete global grid system (DGGS).

10.2.3.1 PCA

Another form of linear representation of a data set is principal component analysis (PCA). In this representation, the covariance matrix of the data is initially formed by applying the inner product of a data matrix A in its transpose $\left(Cov = A^T A\right)$. The eigenvectors of the covariance matrix, λ_i, represent the main trends of the data. If we have a data set forming an ellipsoid in 2D, the eigenvectors are the two main axes of the ellipsoid. Figure 10.9 represents PCA in 2D. PCA has been extensively used in

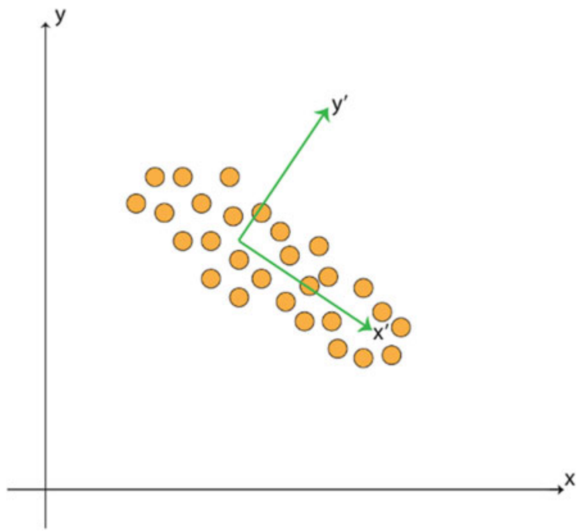


Fig. 10.9 PCA finds the main trends of the data. The data points illustrated in yellow have two main trends x′ and y′ that are the eigenvectors associated with the largest eigenvalues of the covariance of the data

many applications including computer graphics, computer vision, and data science. PCA has been used in different applications related to geospatial data representation and geospatial data analysis (Demšar et al. 2013). For instance, PCA has been successfully used to study drought areas (Gocic and Trajkovic 2014), evaluate water quality (Parinet et al. 2004), and distinguish vegetation (Panda et al. 2009).

10.2.3.2 SVD

Singular value decomposition (SVD) is a decomposition that reveals important information about a matrix. In SVD, a matrix A is decomposed into the form USV^T, in which U and V are two rotation matrices and S is a diagonal scale matrix with values called the singular values, σ_i, of matrix A. There is a direct connection between PCA and SVD because the singular values of the singular value decomposition of data matrix A are the square root of the eigenvalues of the covariance matrix that is found in PCA $\left(\sigma_i = \sqrt{\lambda_i}\right)$. To compress or denoise data, it is possible to zero out small eigenvalues obtained by SVD and keep important portions of the data. SVD has been extensively employed in image processing applications (Sadek 2012). It has also been used in geospatial applications. For instance, Wieland and Dalchow (2009) used SVD to detect landscape forms, and Dvorsky et al. (2009) used SVD to determine the similarity between maps.

10.2.3.3 Evolutionary and Agent-Based Techniques

Evolutionary and Agent-based techniques have also been extensively used to perform analyses of geospatial data sets. Two important algorithms are genetic algorithms (GAs) and ant colony optimization (ACO).

In GAs, a set of random solutions is initially produced and these solutions are considered parents to make a new generation of solutions based on three rules: **Selection** rules that select parents based on their fitness, **Crossover** rules that combine two parents to generate children for the next generation, and **Mutation** rules that apply random changes to parents to form children (Mitchel 1998). GAs have been used in many applications in geospatial data analysis such as road detection (Jeon et al. 2002) and satellite image segmentation (Mohanta and Binapani 2011).

ACO is an optimization technique that works based in an agent-based environment. In this stochastic environment, the ants are agents that walk over a certain solution path and leave a track called a pheromone. Paths with more pheromone are usually more optimal (shortest) than others, and they attract more agents. A classic problem that can be solved by ACO is the travelling salesman problem. ACO has been successfully employed to solve other types of hard problems including those involving geospatial data analysis. For instance, ACO has been used for path planning considering traffic (Hsiao et al. 2004) and road extraction from raster data sets (Maboudi et al. 2017).

10.3 Deep Learning

When a large amount of data is involved and/or a complex model for representing the data is used, it is common to employ deep learning methods (Goodfellow et al. 2016). Digital earth data represents a massive amount of data, for example, high-precision digital elevation models or aerial photography. Because the rules that produce this kind of data are very complex and involve many natural or human processes, it can be difficult to apply standard learning models or algorithms and retain this complexity. Thus, the deep models described in this section are relevant.

10.3.1 Convolutional Networks

Deep learning has been popularized by image processing applications. In this context, the processed data is arranged into a regular grid and is adapted to so-called convolutional layers. Data extracted from Digital Earth can be of this nature by construction. For example, raster data such as digital elevation models or aerial photography images are already arranged into regular grids and can be processed out of the box with convolutional layers. Convolutional neural networks rely on the fact that the same processing can be applied to different parts of the image. Traditional

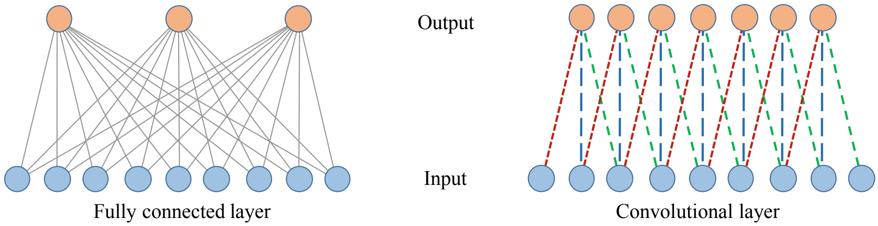


Fig. 10.10 Convolutional layers use fewer coefficients and are spatialized

fully connected schemes for neural network layers use many coefficients that can be spared with convolutional layers and used in other features. Figure 10.10 compares the principle of a convolutional layer to that of a traditionally fully connected layer. Both examples show an input of size 9. While a fully connected layer uses 27 coefficients to produce an output of size 3, the convolutional layer can produce 9 outputs from only 3 different coefficients. This means that the same feature extraction is performed but at different locations, which is relatively close to traditional convolution in the discrete domain.

Recently, a convolutional network was used to infer the super-resolution of a digital elevation model by using aerial photography (Argudo et al. 2018). Figure 10.11 shows the architecture of this network. This work comes from the observation that publicly available high-resolution DEMs (resolution less than 2 m) do not cover the full Earth whereas it is possible to find high-resolution imagery (orthophotos) with good coverage of the Earth. Many applications require a fine resolution for the DEM, and Argudo et al. proposed inserting details into a coarse DEM using inferred information drawn from the high-resolution orthophoto of the same footprint (Fig. 10.12). Basically, the method produces a DEM with 2 m precision from a DEM with 15 m precision and an orthophoto with 1 m precision. To produce this result, a fully convolutional network was used.

In the literature, a full system to automatically infer street addresses from satellite imagery was proposed (Demir et al. 2018a). One step that must be performed is the extraction of roads from the satellite images. This was done using a modified

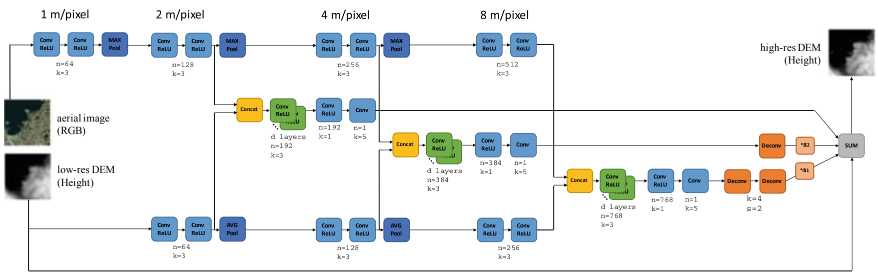


Fig. 10.11 A fully convolutional network was used to infer the high-resolution DEM from its coarse version and the high-resolution orthophoto (courtesy of O. Argudo et al.)

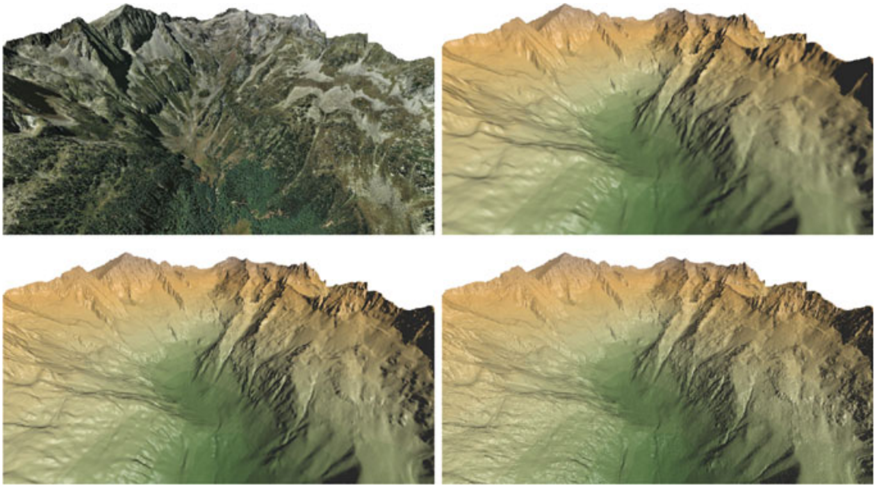


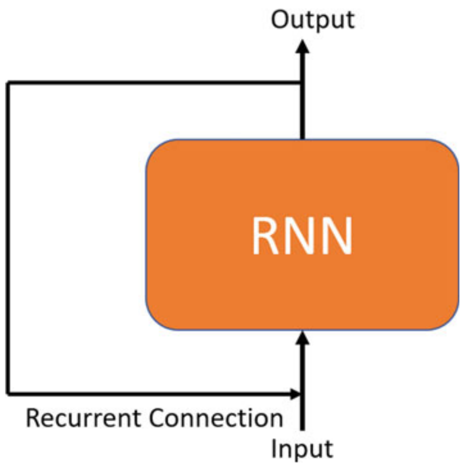
Fig. 10.12 Super-resolution of a 15 m precision DEM (top right) using an orthophoto (top left). Result (bottom left) and the ground truth reference (bottom right) (courtesy of O. Argudo et al.)

version of SegNet, a convolutional network primarily used for image segmentation. In this architecture, the input and output resolutions are identical, and the network consists of several encoder layers that decrease the resolution followed by decoders that increase the resolution. The network is trained using manually labeled 192 × 192 pixel images, in which a binary road mask is associated with each pixel of the image to indicate if the pixel belongs to a road or not. Figure 10.13 shows an example of the results obtained in automatic extraction of the road information compared with the ground truth.

More generally, automatic processing of satellite images with a deep learning approach appears to be very efficient in segmentation and feature extraction. The DeepGlobe project (http://deepglobe.org) aims to challenge authors to use deep learning for three applications: road extraction, building detection and land cover classification (Demir et al. 2018b).

Fig. 10.13 Automatic extraction of the road mask (right) from the satellite image (left), compared with the ground truth road network (center) (courtesy of I. Demir et al.)

Fig. 10.14 The schematic of a recurrent neural network



10.3.2 Recurrent Neural Networks

While convolutional neural networks and dense neural networks work well for static data in which there is no sense of time, a **r**ecurrent **n**eural **n**etwork (RNN) (Jain and Medsker 1999) processes data by iterating through the input elements and maintaining a state that contains information relative to what it has seen until then. An RNN is a neural network with an internal loop (see Fig. 10.14). The state of the RNN is updated between processing independent sequences; therefore, we still consider one data sequence as a single data point in the network. The difference is that this data point is not processed in a single step as opposed to those in dense or convolutional neural networks. In an RNN, the network internally loops over sequence elements until it learns the flow of the data. An RNN is helpful when dealing with a temporal data set. In geospatial data analysis, an RNN has been recently applied in interesting applications such as correction of satellite image classification (Maggiori et al. 2017) and land cover classification (Ienco et al. 2017). Since many types of geospatial data sets such as weather, satellite images, or seasonal animal behavior have timing attached to them, we expect that RNNs will be widely used in the analysis of geospatial data sets in the near future and that Digital Earth will benefit from such networks.

10.3.3 Variational Autoencoder

Deep neural networks are useful to analyze data sets and are also helpful in generating new data sets. It is possible to consider two deep neural networks as the encoder and decoder of an autoencoder and produce a latent space that represents the data. Using only L and an encoder, we can reproduce a lossy representation of D. However, it is not possible to pick a vector in L and expect to reproduce a meaningful result by feeding it to the encoder because the distribution of L is unknown if autoencoders are used. In **v**ariational **a**uto**e**ncoders (VAEs) (Kingma and Welling 2014), in addition to the compression loss, another loss is minimized that forces the L to be a Gaussian distribution. Thus, VAEs can be used as a generative neural network in which one can sample the Gaussian distribution and feed it to the encoder to generate a new shape that does not necessarily belong to the training data set. Although VAEs have potential to generate data and learn low-dimensional data for geospatial data sets, VAEs have not been extensively tested for geospatial data analysis and generation.

10.3.4 Generative Adversarial Networks (GANs)

Similar to VAEs, **g**enerative **a**dversarial **n**etworks (GANs) (Goodfellow et al. 2014) are also generative models. GANs consist of a pair of networks that have two different and adversarial roles. These networks have a convolutional architecture and are often complex to retain the complexity of the underlying models. The first network is a generator that we denote as G, which attempts to generate the best result, for example, an image. Then, the second network takes the image as input and tries to infer if it is a generated image or not. This second network is called a discriminator and we denote it as D. Both G and D are trained alternatively. The objective of G is to fool D whereas D aims to avoid being fooled by G. The strength of this kind of adversarial formalism is that it is equivalent to use of a very complex function to train the generator G (encoded into the discriminator), far more complex than traditional distance would be.

Conditional **G**ANs (cGANs) are GANs with a particular setup in which the discriminator is trained to recognize the matching between an input image A and an output B whereas a traditional GAN only tests the plausibility of the output without any knowledge of the input. The training principle of a cGAN is explained in Fig. 10.15.

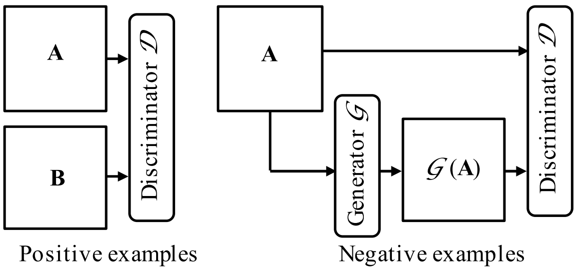


Fig. 10.15 cGAN principle: a training pair (A, B) is used to learn positive examples. For negative examples, only A is used together with the generator to form the pair (A, G(A))

Conditional GANs have recently been used to automatically generate digital elevation models from user sketches (Guérin et al. 2017). The user sketches the river network, the crests and some altitude cues and obtains a plausible terrain that matches the given constraints, based on a training dataset made of sketch/terrain pairs. The method consists of building such a dataset by extracting the sketch from a real-world terrain. The difficulty of this kind of setup is to automatically build a sketch that is compatible with user sketches, i.e., similar to what a user would draw. Building a sketch that is too close to the terrain features will force the user to draw very precisely, which is not relevant in a sketching context but would be useful in a reconstruction process. The digital elevation model must be simplified to produce simpler features. In their work, Guérin et al. propose initially downsampling the digital elevation model and then smoothing it. This coarse digital elevation model is then processed by a flow simulation, from which the skeleton is extracted. The same process is applied to extract ridges. This feature extraction is illustrated in Fig. 10.16.

The training dataset is formed of pairs that describe the matching between the sketch and the terrain. Figure 10.17 gives examples of such pairs. To create a more pliable terrain synthesizer, the sketches randomly include one, two or the three features among the river lines, crest lines and altitude cues.

Figure 10.18 shows examples of outputs produced by the DEM generator from sketches. The results were obtained by using training from a DEM extracted from the NASA SRTM dataset at 1 arc-second from different locations in the United

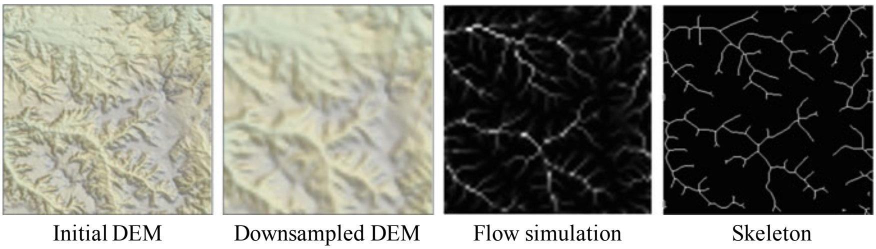


Fig. 10.16 Training database examples

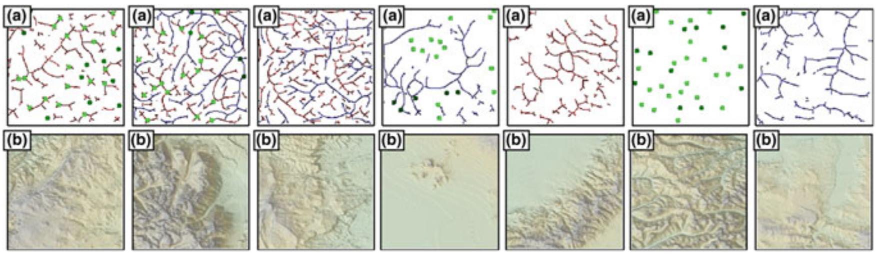


Fig. 10.17 Training database examples. Training pairs are formed by a sketch (**a**) and an associated DEM (**b**). Sketches can feature river lines (blue), crests (red) and altitude cues (green)

Fig. 10.18 Examples of generated digital elevation models from simple sketches. A canyon generated using river and crest lines (left). A volcanic island generated using only crest lines (right)

States. In the same article, the authors proposed the use of the same principle to automatically generate digital elevation models from a single level set sketch. They also described examples of automatic void filling in digital elevation models. Finally, because cGANs can embed very complex models, they used it to mimic an erosion process.

10.3.5 Dictionary-Based Approaches

Approaches based on base function decompositions have intrinsic limitations. Base functions are usually used because they have orthogonality properties that lead to an efficient decomposition. Selecting the base can be difficult because it heavily depends on the nature of the signal. Thus, it can be a viable option to use dictionary-based descriptions. A signal is represented as a linear combination of atoms from a dictionary. Atoms do not need to have special properties such as orthogonality. They are typically chosen directly from the data by picking the most representative signals or by using an optimization. A survey of dictionary-based methods for 3D modeling was conducted by Lescoat et al. (2018). One of the applications of dictionary-based modeling is called sparse modeling, which adds an additional constraint on the number of atoms used to represent the final signal, called *sparsity*.

10.3.5.1 Dictionary Decomposition

Given a dictionary, the decomposition of a signal consists of finding the best atom, i.e., the atom that maximizes the projection. Then, the same process is applied iteratively to the residual until reaching the target sparsity. This process is called matching pursuit and was introduced by Mallat and Zhang (1993). This decomposition algorithm was further improved by Cai and Wang (2011) by introducing the *Orthogonal Matching Pursuit* (OMP) algorithm. The main difference is that the best decomposition of the already-found atoms is recomputed after each new atom is found.

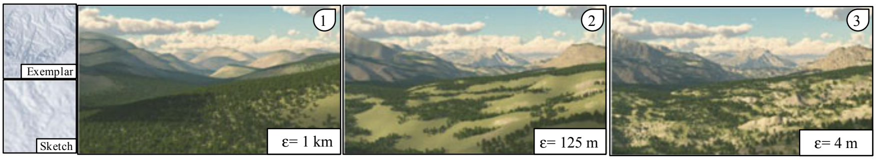


Fig. 10.19 An example of terrain amplification that adds plausible details from a given exemplar using a dictionary-based approach. The original terrain had a precision of 1 km, and successive amplifications by a factor of 4 increase the precision to 4 m

10.3.5.2 Dictionary Optimization

One aim of dictionary based approaches is to find a dictionary that is adapted to a given context or set of signals. This can be done by an optimization process. One goal of this optimization is to minimize the reconstruction error, for example, by computing an L^2 distance between the reconstructed signal and the original. It is common to add a constraint on the type of decomposition, for example, by setting a maximum sparsity. Unfortunately, the optimization problem under this type of constraint is too difficult to solve in an optimal way. Heuristics have been proposed that lead to good results with a relatively low cost. K-SVD is one of these algorithms (Aharon et al. 2006), which consists of iterating between two steps. The first step consists of optimizing the decomposition, which can be done using a standard OMP algorithm. The second step optimizes the dictionary with respect to the previously computed decomposition. The two steps are repeated until a number of iterations is reached or a given error is obtained.

Several applications of sparse modeling with terrains have been proposed by Guérin et al. (2016) and Argudo et al. (2018). The terrain is decomposed into patches that compose input signals. A so-called amplification process is used to introduce plausible details into the terrain by mapping between low-resolution and hi-resolution atoms. The dictionary is drawn from an exemplar terrain at high resolution and automatically transformed into low resolution by a trivial downsampling process. The amplification algorithm simply decomposes the patches from a given terrain in the low-resolution dictionary and uses the corresponding high-resolution atoms to reconstruct it. Because the dictionary has been extracted from real terrain, the added details are plausible and realistic, as shown in Fig. 10.19.

10.3.6 Reinforcement Learning

Reinforcement **l**earning (RL) is a powerful learning method in dynamic environments (Sutton and Barto 1998). In RL, there is usually an agent in an environment and the agent receives rewards based on its actions. The final goal is to learn how to take actions to maximize the rewards. At any time t, an environment is defined by states S_t in which an agent can take action A_t and change the environment state to S_{t+1}. When

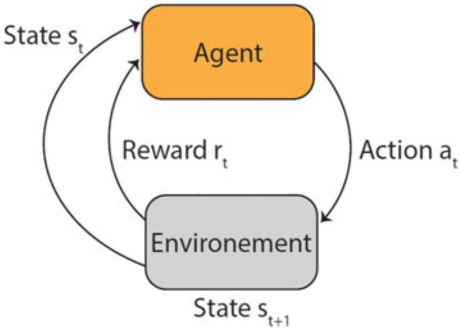


Fig. 10.20 An agent receives state s_t, performs an action and receives reward r_t from the environment. The state of the environment changes to s_(t+1). This process continues until a terminal state is achieved

the agent takes action A_t, the environment receives a reward r_t. These iterations continue until the environment reaches a terminal state (Fig. 10.20). Examples of applications that RL can be extremely useful for are games or robot locomotion in which more points and more stable states are the rewards of the game and locomotion environments, respectively.

RL has also been used in applications in GIS and geospatial data analysis. For instance, RL has been used to model land cover changes (Bone and Dragicevic 2009). With recent advances in RL and the growth of computational power, we expect that RL will receive more attention from the GIS and Digital Earth communities. For instance, one application of RL can be to simulate the behavior of endangered species in different simulated environments.

10.4 Discussion

In the past, machine learning has seen hypes and winter seasons. It started with symbolic AI in the 1960s, which claimed the ability to make machines with intelligence comparable to an average human being in less than a decade. However, people soon realized that they were far from reaching that point. In the 1980s, with the rise of *expert systems*, similar hype was seen in the area of machine learning, followed by a winter season due to the lack of generality of expert systems and their high maintenance costs (Chollet 2017). Recently, deep learning methods became popular again and showed great success in different areas of computer science including geospatial analysis, which is an important portion of Digital Earth platforms. Deep learning will likely continue to grow and be applied more in this field, especially because of the availability of computational power and big data sets that help create more powerful models. However, deep learning cannot solve all problems. For instance, current deep learning models are unable to solve problems that require reasoning or long-term planning (Chollet 2017). Deep learning models work extremely well in mapping an input to a desired output with very little human-level knowledge about the input or output and their effect on industry and science will probably remain for a very long time. There is plenty of discussion about the future of deep learning and AI, notably by its great pioneers such as Lecun et al. (2015) and in the European perspective on AI (Craglia et al. 2018).

Artificial intelligence and particularly machine learning and deep learning have great potential to contribute to the generation, analysis, and management of geospatial data sets. Digital Earth should benefit from such opportunities, as a place holder to represent such data sets and a platform to analyze them. Since Digital Earth is constantly receiving geospatial data sets, a successful Digital Earth should use reliable, fast, and comprehensive techniques to manage and make use of such data. Deep Learning techniques show promise in these directions. However, there are still issues in their use in Digital Earth platforms that must be addressed. In the following sections, we discuss some of these issues.

10.4.1 Reproducibility

If a technique such as a deep neural network produces particular results, such results should be reproduceable by others. Placing the code on GitHub and providing free access to data sets have been helpful for this issue. However, there are still some issues, especially when the data are owned by a company or the network was designed by an industrial team. In particular neural network architectures, randomness can be included, usually to improve the training. When this randomness is also present in the operational network, it can disrupt the reproducibility of results.

10.4.2 Ownership and Fairness

Ownership of artifacts provided by machine learning techniques is also heavily under question. If a person with almost no knowledge about a network takes information from available sources, modifies a few parameters, takes data from an available source and produces something unique or obtains a certain analysis, who is the owner of such results? The data owner, developer of the network, or the person who combined these ingredients? In more serious scenarios, who is at fault when a system that works based on machine learning techniques makes a catastrophic mistake or performs a discriminatory action that may involve racism or sexism? Another question is whether data sets and computation power are available to everyone, i.e., do we have "data democratization"? Fortunately, the wealth of free access data sets and code bases along with cheap computational power such as Amazon Web Services (AWS) have resolved some of these issues but we are still far from perfect.

10.4.3 Accountability

Due to the nature of some algorithms involved in machine learning, it usually cannot be used in contexts where accountability is a strong constraint. This is especially the case with deep neural networks where a lot of information is hidden in the layers, which can lead to unexpected and unwanted results. Conversely, traditional machine learning methods such as linear regressions or PCA are very reliable even if they are limited in terms of applications. Reasonably, one could consider using deep learning methods only when traditional methods fail or are lacking.

10.5 Conclusion

In conclusion, we provided a sampling of artificial intelligence techniques and their applications in geospatial data generation, analysis, and management. We discussed how AI can be beneficial for generating new terrain data sets, identifying roads and analyzing various geospatial data sets such as satellite imagery. AI techniques and deep learning methods appear very promising. Extensive research on these topics will likely make them even more suitable for use in different domains including geospatial analysis and Digital Earth. However, these techniques are unfortunately standalone and have not been integrated into a Digital Earth platform that makes use of such techniques. Appropriate artificial intelligence techniques should be meticulously included in Digital Earth, considering their pros and cons including fairness and bias to provide interactive, comprehensive and meaningful analysis to users.

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Eric Guérin is Assistant Professor at INSA de Lyon, France. He received an engineering degree from INSA de Lyon in 1998 and a Ph.D. in Computer Science from Université Claude Bernard Lyon 1 in 2002. His research interests include procedural modeling of virtual worlds, natural phenomena and machine learning. He is head of the LIRIS/Geomod team since 2015.

Orhun Aydin is a researcher in Environmental Systems Research Institute and assistant professor in Spatial Sciences Institute at U.S.C. Prior to joining ESRI and USC, he obtained a Ph.D. and M.Sc. in Geostatistics from Stanford University. Orhun's research pertains to modelling, exploring and forecasting spatial and spatio-temporal phenomena and their applications for Earth Systems.

Ali Mahdavi-Amiri is a University Research Associate at Computing Science department in Simon Fraser University. His research interests are in Computer Graphics with specialty in Geometric Modeling, Geospatial Modeling and Visualization, Digital Fabrication, and Machine Learning. Ali has received several awards including NSERC Postdoctoral Fellowship, Graduate Achievement Award, Michael A. J. Sweeney Award, and Teaching Excellence Award.

Chapter 11
Internet of Things

Carlos Granell, Andreas Kamilaris, Alexander Kotsev, Frank O. Ostermann and Sergio Trilles

Abstract Digital Earth was born with the aim of replicating the real world within the digital world. Many efforts have been made to observe and sense the Earth, both from space (remote sensing) and by using in situ sensors. Focusing on the latter, advances in Digital Earth have established vital bridges to exploit these sensors and their networks by taking location as a key element. The current era of connectivity envisions that everything is connected to everything. The concept of the Internet of Things (IoT) emerged as a holistic proposal to enable an ecosystem of varied, heterogeneous networked objects and devices to speak to and interact with each other. To make the IoT ecosystem a reality, it is necessary to understand the electronic components, communication protocols, real-time analysis techniques, and the location of the objects and devices. The IoT ecosystem and the Digital Earth (DE) jointly form interrelated infrastructures for addressing today's pressing issues and complex challenges. In this chapter, we explore the synergies and frictions in establishing an efficient and permanent collaboration between the two infrastructures, in order to adequately address multidisciplinary and increasingly complex real-world problems. Although there are still some pending issues, the identified synergies generate optimism for a true collaboration between the Internet of Things and the Digital Earth.

Keywords Internet of Things · Geospatial standards · Smart scenarios

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C. Granell · S. Trilles (✉)
Institute of New Imaging Technologies, Universitat Jaume I, Castelló de la Plana, Spain
e-mail: strilles@uji.es

A. Kamilaris
Department of Computer Science, University of Twente, Enschede, The Netherlands

A. Kotsev
European Commission, Joint Research Centre, Ispra, Italy

F. O. Ostermann
Faculty of Geographic Information Science and Earth Observation (ITC), Department of Geo-Information Processing, University of Twente, Enschede, The Netherlands

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11.1 Introduction

According to Jayavardhana (Gubbi et al. 2013), the term Internet of Things (IoT) was first coined by Kevin Ashton in 1999 in the context of supply chain management. Empowered by the latest advances in Information and Communication Technology (ICT), the IoT is revolutionizing the world, opening new possibilities and offering solutions that were unthinkable even only a few years ago. The concept of the IoT is highly multidisciplinary because it brings together a wide variety of technologies, protocols, applications, scenarios, and disciplines (Atzori et al. 2010; Gubbi et al. 2013). The International Telecommunication Union (ITU) Standardisation Sector defines it as '*a global **infrastructure** for the information society, enabling advanced services by interconnecting* (*physical and virtual*) *Things based on existing and evolving interoperable information and communication technologies*' (International Telecommunication Union 2018). As an infrastructure, the IoT can be seen as a broader system involving data, resources, standards and communication protocols as well as theoretical studies.

The pace of IoT development seems quite fast, with continuous proposals of new approaches, applications, and use case scenarios, increasing the presence of IoT in multiple and varied applications, and aspects of daily life. To date, smart devices constitute the IoT's most visible form, applied in a wide range of scenarios and sectors such as cities, industry, commerce, agriculture, home, and mobility. Although we are far from the 200 trillion smart devices as predicted by 2020 (Intel, n.d.), significant progress has been made in this direction. Estimates suggest that there will be 26 smart devices per person in 2020, 40.2% of which will be located in the business environment (termed Industry 4.0).

According to the Forbes analyst Daniel Newman (Newman 2017), the IoT is one of the most rapidly evolving trends today, especially in three development lines: the analytics arena, the development of edge computing, and the deployment of 5G networks. As 5G technology is progressively implemented and deployed (Shafi et al. 2017), the current analysis platforms will need adaptation in order to analyze effectively the large amount of data flows acquired, produced by IoT devices with increasingly more powerful built-in sensors and emerging real-time analysis functions, empowered even more by the rapid emergence and (parallel) development of edge computing (Shi et al. 2016).

Edge computing is a recent paradigm motivated by bandwidth limitations between the producer (smart objects) and consumer parts (cloud server), as well as the need for improved performance in computing and consumer smart objects. The main feature of edge computing is that data can be processed locally in smart devices rather than being sent to the cloud for further processing.

Like the IoT, Digital Earth (DE) also entails an **infrastructure**. Al Gore, at his famous speech in 1998 (Gore 1998), introduced the concept of a DE with the vision of extending the real Earth with a digital/virtual replica or counterpart. Over the last two decades, many geographic phenomena and observations have been converted to digital data to be used, analyzed, and visualized using digital tools such as virtual globes (Butler 2006). In this chapter, we use the term DE to refer to a network infrastructure that allows for the discovery, access, analysis, and processing of spatially referenced data. For more details on DE, we refer the reader to Schade et al. (2013). In particular, Schade et al. describe the origins and evolving concepts of terms such as DE, Geographic Information Infrastructures and Spatial Data Infrastructures, together with their theoretical and technical features.

This chapter takes a technological perspective focusing on the description of the current relationships between DE and the IoT, identifying ongoing efforts, potential synergies and bridges, as well as existing limitations and barriers that prevent both infrastructures from collaborating and communicating in practical terms. Instead of operating in parallel, scientists and researchers need the IoT and DE to work jointly by establishing an efficient and permanent collaboration to adequately address the multi-disciplinary nature and growing complexity of the pressing problems that characterize modern science.

The rest of the chapter is divided into five sections. In Sect. 11.2, we provide an overview of the most frequent definitions of the IoT, describe our working definitions throughout this chapter, and briefly review related work in the interplay of the IoT and the DE. In Sect. 11.3, we analyze the existing interplay between both infrastructures in the context of the main, high-level functions of DE. Then, an overview of relevant case studies across several smart scenarios in which the symbiosis of the IoT and DE could lead to beneficial results is provided in Sect. 11.4. Afterwards, Sect. 11.5 analyses the frictions and possible synergies today and in the future. Finally, concluding remarks and emerging trends for the immediate future are provided in Sect. 11.6.

11.2 Definitions and status quo of the IoT

This section defines the current state of the IoT with respect to the concept of the DE. The first subsection examines the different definitions of a ‘Thing’, adopted by standardization organizations, followed by our working definition for this chapter. The last subsection describes related works in which interaction between IoT and DE is the main goal.

11.2.1 One Concept, Many Definitions

The concept of a ‘Thing’ may seem generic. A ‘Thing’ can be characterized as a network object or entity that can connect to the Internet directly or through a network gateway. This exemplifies a network-centric perspective of the IoT in which a variety of interrelated ‘Things’ are able to communicate with each other to deliver new applications and services (Atzori et al. 2010). In contrast to the network-centric vision focusing on the communication technologies being used, the IoT can be seen from a purely Thing-centric perspective in which the services associated with Things are pivotal. These services are expected to manage large amounts of data captured by smart objects or 'Things' as a result of interacting with the environment.

Regardless of the vision, the definition of the term 'Thing' is extensive and includes a wide variety of physical elements. Examples of these elements include: (i) personal objects such as smartphones, smart watches or bands; (ii) ordinary objects and appliances in our daily lives such as refrigerators, lights, cars, and windows; (iii) other identifiable objects equipped with Radio-frequency identification (RFID) tags, Near-field communication (NFC), or Quick Response (QR) codes; and (iv) objects equipped with small microcontrollers.

Because of the heterogeneity of the technology and hardware, there is no single, unified definition of the term 'Thing'. Different international standardization bodies and organizations have suggested a definition, resulting in multiple interpretations of the concepts of Things and the IoT, which sometimes differ only slightly. Consequently, each stakeholder group may have a particular view of what the IoT and Things are, as demonstrated below by the definitions of some internationally renowned organizations.

The World Wide Web Consortium (W3C), an international organization whose aim is the collaborative development of Web standards, defines a 'Thing' as '*the abstraction of a physical or virtual entity that needs to be represented in IoT applications. This entity can be a device, a logical component of a device, a local hardware component, or even a logical entity such as a location* (*e.g., room or building*)' (Kajimoto et al. 2017).

The Institute of Electrical and Electronics Engineers (IEEE), a global professional engineering organization whose mission is to foster technological innovations and excellence for the benefit of humanity, defines a 'Thing' as a device with programmable capabilities. In contrast to the W3C's definition, the IEEE's definition takes a more practical engineering view of Things, driven by two defining features: (i) Things have the ability to communicate technologically, and (ii) Things have the ability to connect to or integrate in an already connected environment. This networking capability can be based on microcontrollers such as Arduino, Raspberry Pi, BeagleBone and PCDuino, among others.

The European Research Cluster on the Internet of Things (IERC) describes Things as '*physical and virtual things with identities, physical attributes, and virtual personalities and smart user interfaces, and are seamlessly integrated into the information network.*' (IERC 2014). Similarly, considering that Things belong to a network, the ITU introduces the term *infrastructure* and defines the IoT as "*a global infrastructure for the information society, enabling advanced services by interconnecting* (*physical and virtual*) *things based on existing and evolving interoperable information and communication technologies*" (ITU-T 2012). In addition, the ITU recognizes three interdependent dimensions that characterize Things (Fig. 11.1). This indicates the versatility of the IoT in application domains that differ in terms of the requirements and user needs.

The Internet Engineering Task Force (IETF), an open international community of network designers, researchers, and operators concerned with the evolution of the

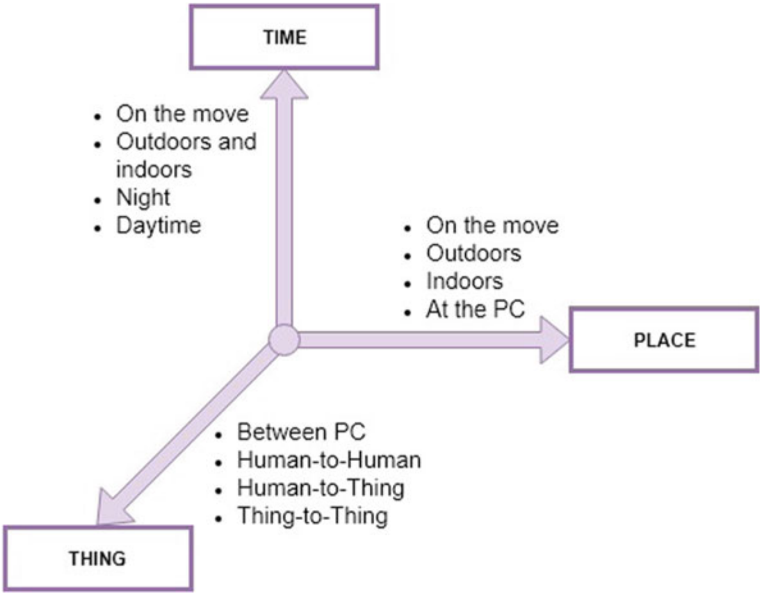

Fig. 11.1 Dimensions of the IoT (inspired in ITU-T 2012)

IoT, takes a broad perspective of Things in the context of the IoT, contemplating that "*'things' are very varied such as computers, sensors, people, actuators, refrigerators, TVs, vehicles, mobile phones, clothes, food, medicines, books,* etc. *These things are classified into three scopes: people, machines* (*for example, sensor, actuator,* etc.) *and information* (*for example, clothes, food, medicine, books,* etc.). *These 'things' should be identified at least by one unique way of identification for the capability of addressing and communicating with each other and verifying their identities. In here, if the 'thing' is identified, we call it the 'object'*" (Minerva et al. 2015).

Finally, the Organisation for the Advancement of Structured Information Standards (OASIS), a nonprofit consortium that drives the development, convergence and adoption of open standards for the global information society, describes the IoT as a '*system where the Internet is connected to the physical world* via *ubiquitous sensors*' (Cosgrove-Sacks 2014). OASIS focuses on the ubiquity of sensors, as they exist in '*every mobile, every auto, every door, every room, every part, on every parts list, every sensor in every device in every bed, chair or bracelet in every home, office, building or hospital room in every city and village on Earth*'.

In Fig. 11.2 we categorize the aforementioned IoT definitions based on physical, virtual and location considerations. The definitions reveal that these institutions and organizations consider the IoT from a physical point of view. In addition to the physical view, three organizations (ITU, IERC and W3C) add a virtual connotation to the definition of a 'Thing'. Only the W3C definition acknowledges explicitly location as a defining element of the IoT.

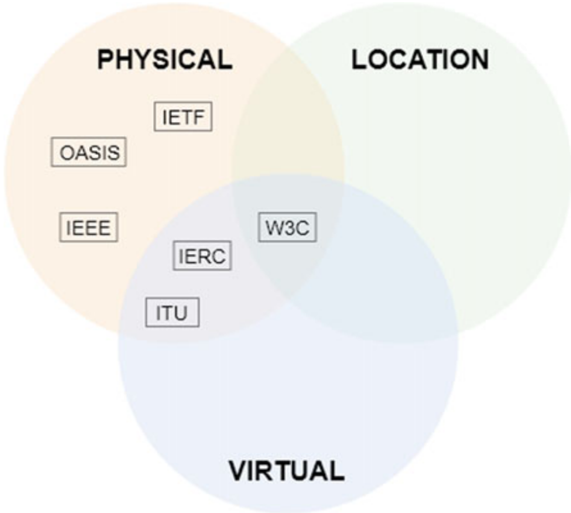

Fig. 11.2 Classification of IoT definitions

11.2.2 Our Definition

After analyzing the different definitions of internationally renowned institutions and standardization organizations, we propose our interpretation of the term ‘Thing’ that will be used throughout the rest of the chapter. This definition aims to (i) relate the IoT to DE, and (ii) be as broad as possible.

From our perspective, three main features characterize a ‘Thing’: (i) networked communication; (ii) programmability (data processing and storage); and (iii) sensing and/or actuating capabilities. From a DE perspective, the third feature plays a more prominent role. The sensing and/or actuating capabilities permit an IoT device or node to interact with its environment. This environment is closely related to the location feature, since all Things will intrinsically have this feature as a property, which increases in importance when the ‘Thing’ has a mobile component. Contrary to most of the definitions above, we consider a Thing’s location as a crucial characteristic because it impacts how a ‘Thing’ can communicate and how it can interact with its environment. However, we argue that the physical point of view can be understood to include location implicitly, as a physical sensor is located somewhere in the physical world.

11.2.3 Early Works on the Interplay Between DE and the IoT

As noted above, this chapter explores potential bridges between the IoT and DE for the development of applications and services that take advantage of the benefits of both infrastructures to effectively address complex research issues. In this context, we briefly summarize studies related to this objective.

In 1999, Gross predicted that electronic devices would populate the Earth and have the ability to capture different types of information, forming an 'electronic skin' (Gross 1999). These devices would be able to communicate through the Internet, and include meteorological or pollution sensors, cameras, blood pressure sensors or microphones, among others. The imagined 'electronic skin' could be in contact with what was happening in different scenarios and places on Earth, in the atmosphere, cities, houses, or even in ourselves.

Gross' vision is gradually becoming a reality. There is great variability in the form, size and purpose of sensors in wireless networks. Such Wireless Sensor Networks (WSN) enable distributed communication and data sharing between sensor network nodes. From this perspective, WSN form a subset of the IoT and, as such, the IoT can be seen as the logical next step of WSN in a progression that is still evolving in terms of the sophistication, variability in functionality, flexibility and integration with other infrastructures and network protocols (e.g., the Internet Protocol).

The IoT gained popularity between 2008 and 2013 (Fig. 11.3), and all organizations concerned with WSN began to focus on the IoT. The matured technology of WSN was applied to IoT developments, and DE organizations were not an exception. The field of sensors and sensor networks has been the object of study from multiple and varied angles, including the geospatial community, especially the Open Geospatial Consortium (OGC). The OGC started to transfer improvements made in the definition and application of standards and specifications in the field of WSN to the IoT.

The most significant OGC contribution concerning sensors and WSN has been the Sensor Web Enablement (SWE) standards suite (see Sect. 11.2.4 below). SWE enables the discovery and access of sensors and associated observational data through standard protocols and application programming interfaces (API) (Botts et al. 2008). The SWE standards have been applied directly to many application domains in DE.

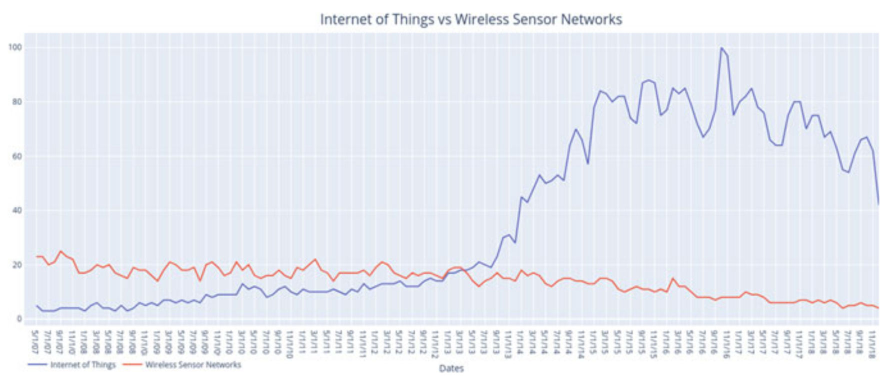

Fig. 11.3 Search volume on wireless sensor networks (red) and the Internet of Things (blue). *Source* Google Trends

The shared goal was to observe a particular phenomenon, for example, to predict emergency warnings or fire alarms or alerts when an event is triggered (Wang and Yuan 2010). For example, SWE has been widely applied to different Earth Observation (EO) application domains, with disaster management being one of the most important and well-developed. One of the early applications was the use of sensor web techniques to monitor natural and man-made hazards such as fires (Trilles et al. 2014; Jirka et al. 2009; Brakenridge et al. 2003), floods (Brakenridge et al. 2003), and volcanic eruptions (Song et al. 2008).

In parallel with the concept of WSN, Ashton (2009) noted that the term IoT was first used in his work entitled "I made at Procter & Gamble" in 1999. Back then, the IoT was associated with the use of RFID technology. However, the term WSN was not yet the focus of much interest, as shown in Fig. 11.3.

Some studies explored the connection between the IoT and DE concepts. Li and his colleagues studied the impact of the IoT on DE and analyzed the transition to Smart Earth (Li et al. 2014). The concept was introduced in 2009 during a panel discussion with the U.S. president and U.S. business leaders. In that panel, IBM's CEO Sam Palmisano requested that countries should invest in a new generation of smart infrastructure, with crucial use of sensors, suggesting the concept of 'Smart Earth' as a name. Subsequent governments showed interest in adopting this type of technology, and are making huge investments in researching and developing smart devices (e.g., the 'Array of Things' in Chicago, https://arrayofthings.github.io).

The primary objective of a 'Smart Earth' is to make full use of ICT and the IoT, and apply them in different fields (Bakker and Ritts 2018). In a 'Smart Earth', IoT devices are placed in all possible locations of our daily life, as long as our privacy can be respected. Through the combination of the IoT, DE, and cloud computing, globally deployed physical objects and sensors can be accessible online. The idea of a 'Smart Earth' is ambitious and includes remote sensing, GIS and network technology in combination with DE platforms (see Chap. 2 in this book featuring "Digital Earth Platforms"). The goal is to enable sustainable social development, which is a visionary step that is still utopian today, towards the establishment of a global information infrastructure to support UN Sustainable Development Goals (see Chap. 13 "Digital Earth for Sustainable Development Goals in this book,").

The work by Van der Zee and Scholten (2014) highlighted the importance of location in the concept of the IoT. The authors noted that space and time can play a role as 'glue', to enable an efficient connection between smart devices; therefore, geospatial sciences should have an active presence in the development of IoT architecture. In their study, Van der Zee and Scholten described a set of technologies related to the geospatial domain and big data analysis that could be combined with the IoT. The authors concluded that these technologies were already available for application in the field of the IoT and recommended their immediate use. However, the authors also identified the lack of IT professionals with knowledge in geospatial sciences as the main obstacle in massive uptake of the IoT for geo-related applications. They proposed to address this limitation through a gradual incorporation of core geospatial skills and competences into IT curricula.

Our aim in this chapter is to move beyond the initial steps and thoughts presented in Van der Zee and Scholten (2014), where the status quo of the IoT and DE was described five years ago. We focus on the 'current status quo' by outlining emerging technology trends that can be crucial for establishing real connections between DE and the IoT, and investigate developments during the last five years in particular. Even though development has been gradual and incremental, and not rapid and revolutionary (i.e. from a GIScience perspective), new requirements and technology trends have appeared and the IoT has become a topic that is undoubtedly gaining increasing traction.

11.2.4 IoT Standards Initiatives from DE

As noted above, the IoT ecosystem has been very diverse for several years (Atzori et al. 2010), and its diversity has been increasing. It is comprised of heterogeneous devices, protocols and architectural approaches. A plethora of international initiatives are put in place to unify and streamline aspects associated with the design and implementation of IoT infrastructures. The current standardization initiatives address aspects related to discoverability, data transmission, device processing and tasking.

The growing number of interconnected devices, combined with the increasing importance of the use of the IoT in almost any aspect of human life, tend to increase the need and importance of mature, well-established and -implemented standards. The diversity of different standardization initiatives provides designers and developers with a broad range of opportunities that do not necessarily complement each other. There are multiple ways of reaching the same destination, i.e., there is no single solution to be adopted. Here, we provide a short overview of selected IoT standards that play an important role within the context of DE. The SWE suite of standards is described in more detail in Chap. 8 of this book.

From the geospatial perspective, the OGC coordinates different standardization initiatives. This consortium is comprised of more than 525-member organizations from governmental, commercial, non-governmental, academic and research institutions. The primary objective of the OGC is to develop open standards that include a geospatial component. These standards are developed through a consensus-based process and are openly available to streamline the exchange of geospatial data. OGC standards are used in a wide variety of domains, including geosciences and the environment, defense and intelligence, emergency and disaster management, and public services, among others.

Over a decade ago, well before the IoT became mainstream, the OGC developed the SWE suite of standards for spatio-temporal observation data (Botts et al. 2008). SWE outlines a set of specifications related to sensors and proposes data models and Web service interfaces that can act as a bridge between sensors and users, allowing the sensors and their measurements to be accessible and controllable through the Web (Sheth 2018). The SWE suite, although initially designed for sensors, can easily be applied to any type of spatio-temporal data flow (including heterogeneous types of smart devices with an observation capability). It offers a set of specifications in an open standard schema using extensible markup language (XML) and web services. It enables (i) finding sensors and sensor data; (ii) describing sensor systems and data; (iii) recovering real-time and historical sensor observations; (iv) adding simulations and recovering simulation results; (v) reporting results and alerts; and (vi) full web control.

SWE (depicted in Fig. 11.4) is organized through several interdependent standards that include the Sensor Model Language (SensorML) (Botts and Robin 2007), Observations and Measurements (O&M) (Cox 2003), Sensor Observation Service (SOS), Transducer Markup Language (TransducerML, deprecated) (Havens 2007), Sensor Planning Service (SPS) (Simonis 2007), Sensor Alert Service (SAS) (Simonis 2006) and Sensor Event Service (SES) (Echterhoff and Everding 2008). In this work, only the first three specifications are shown in detail (i.e. SensorML, O&M, SOS), as they are the most widely used in the IoT context today.

SensorML provides the ability to define a sensor in a structured manner. The standard specifies how to find, process and record sensor observations so that a data model and XML schema can be established to control sensors through the Web. SensorML defines a standard schema describing any type of sensor, stationary or dynamic, in situ or remote, active or passive. The PUCK protocol (O'Reilly 2010) is an addition to the SensorML standard that provides a low-level protocol to retrieve sensor drivers, and metadata documents, encoded according to SensorML.

The O&M standard, initially developed by the OGC, is also adopted as an International Organization for Standardization (ISO) standard (ISO 2011). It provides a model for representing and exchanging sensor observations. The standard is encoded

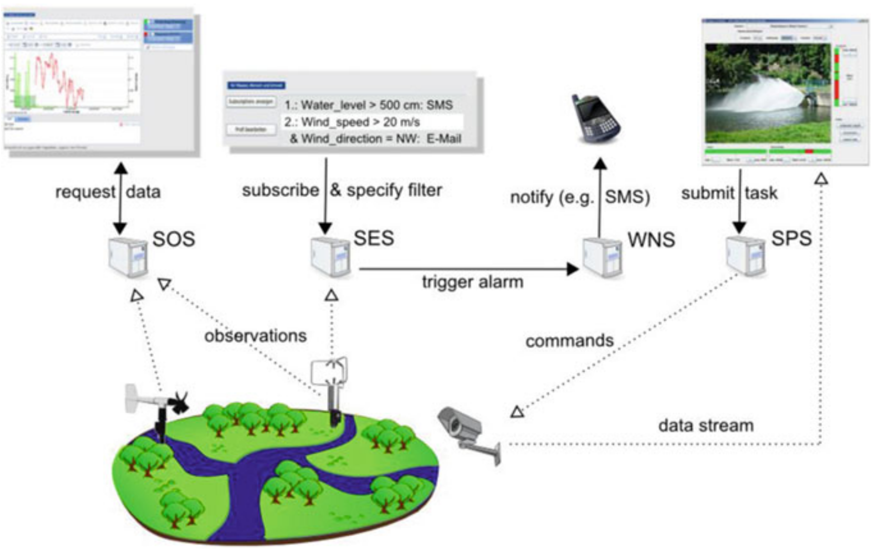

Fig. 11.4 The sensor web enablement suite of standards. *Source* Bröring et al. (2011)

using an XML/JSON data model, which describes the relationship between different aspects of the data capture process. The O&M schema defines both observations and phenomena. In addition, it can be extended to better support metadata.

Finally, the SOS provides an interoperable means for serving observations via a Web interface and is the primary service model of the SWE suite. The current version of the standard introduces a modular structure. The base module provides three mandatory operations. The first, “GetCapabilities”, offers a spatial and temporal description of the observations that have been stored, as well as a list of the sensors and their available features. The “DescribeSensor” operation is used to return a sensor description using SensorML. The “GetObservation” operation provides access to the actual spatio-temporal data encoded in accordance with the O&M standard.

All the standards described above were conceptualized and adopted several years ago within a completely different technological landscape. The rapid growth of the IoT and the emergence of new technologies (e.g. remote sensing, 4G/5G communication, machine-to-machine and machine-to-human interactions) brought new challenges such as (i) the need for lightweight data encoding, (ii) the need for higher bandwidth for data exchange, and (iii) the issue of constrained devices with little or no computational capabilities, such as RFID tags and QR codes (Kotsev et al. 2018). These challenges acted as a driver for the OGC and led to adoption of new standards that better fit the IoT.

The SensorThings API (Liang et al. 2016), designed to follow the paradigm of the Web of Things (WoT) (Guinard et al. 2010), offers access to data through standard web protocols and is based on the O&M conceptual data model. The main features of the standard are (i) a RESTful interface, (ii) the use of lightweight and efficient JSON encoding, (iii) adoption of the OASIS OData URL pattern (OData) and query options, and (iv) support for the ISO message queuing telemetry transport (MQTT) messaging protocol to offer real-time connections.

The SensorThings API data model (shown in Fig. 11.5) is divided into two parts (profiles), namely, the ‘Sensing’ profile and the ‘Tasking’ profile. The former enables IoT devices and applications to CREATE, READ, UPDATE, and DELETE (through the standard web operations HTTP POST, GET, PATCH, and DELETE) IoT data and metadata by invoking a SensorThings API service. In addition, the tasking profile provides a standardized approach for controlling IoT devices through the “ACT” capability, which is revisited in the next section. Each ‘Thing’ has a Location (or some Historical Locations) in space and time. A collection of Observations grouped by the same Observed Property and Sensor is called a Datastream. An Observation is an event performed by a Sensor that produces a value of an Observed Property of the Feature of Interest.

From a spatial analysis perspective (De Smith et al. 2018), many raster- and vector-based operators and techniques have been developed over the last decades and have been shown to be successful in many varied applications. Substantial progress has been made to bring geospatial workflows—i.e., a combination of the above spatial operations to accomplish a sophisticated analytical process—to the cloud and distributed computing environments (e.g., Granell et al. 2010; Granell 2014; Yue et al. 2016), expanding the field of the Geoprocessing Web (Zhao et al. 2012) to the

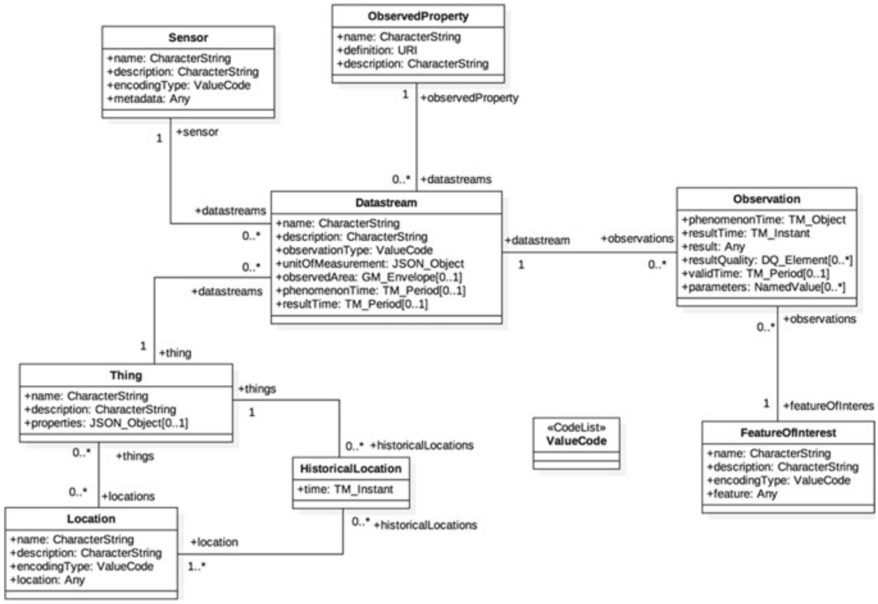

Fig. 11.5 The SensorThings API data model. Each thing has a location (or some historical locations) in space and time. A collection of observations grouped by the same observed property and sensor is called a datastream. An observation is an event performed by a sensor that produces a value of an observed property of the feature of interest. *Source* OGC SensorThings API (http://docs.opengeospatial.org/is/15-078r6/15-078r6.html)

Digital Earth (Hofer et al. 2018). The OGC Web Processing Service (WPS) (OGC 2005), a service interface for exposing and executing processes of any granularity on the Web, enables sharing and integration of spatial data processing capabilities on the Web, including polygon area calculation, routing services, or entire environmental models (e.g., Díaz et al. 2008; Granell et al. 2010). The geoprocessing capabilities in DE are extensively covered in other chapters, e.g., Chap. 5, and our interest lies solely in the relationship between the WPS and the IoT (see Sect. 11.3.2).

11.3 Interplay Between the IoT and DE

One of the aims of this chapter is the identification of potential bridges between the IoT and DE. This overview is partly speculative since we tried to identify potential paths for collaboration between both infrastructures, which may or may not lead to successful linkages in the future. To support our claims in Sect. 11.4, we identify the current situation, i.e., the state of the art of the IoT's and DE's technological substrate. In this section, we highlight new technological developments and emerging trends that are or may become crucial in the coming years that were not present or not sufficiently developed at the time of Van der Zee and Scholten (2014).

Along the lines of the topics described in Sect. 11.2.3, the traditional focus of DE embraces the following high-level functions (Lü et al. 2019): (i) discovery and acquisition of spatial information, (ii) understanding of spatial objects and their relationships (e.g., GIS analysis, spatial statistics), and (iii) determination of the spatio-temporal behavior and simulation rules (e.g., simulations, predictions). These functions help categorize and restrict the discussion in terms of the current technological substrate. However, we should interpret and contextualize these high-level functions of DE from the viewpoint of the IoT.

First, the acquisition of spatial information is a crucial function in the IoT because Things and smart devices observe and sense their environment to collect observational measurements. Through the lens of the IoT, the discoverability of Things and the communication of gathered spatial data become extremely relevant for data acquisition. Of the two main capabilities of Things (see Sect. 11.2.2), the ability to **observe and sense**, is a fundamental mechanism to provide input observational data for DE.

Second, spatial statistics and spatial analysis are well-established geospatial methods for exploring spatial patterns, relationships and distributions (De Smith et al. 2018; Worboys and Duckham 2004). Analytical methods are fundamental building blocks in DE, although recent trends in real-time analysis and edge computing promise to move much of the analytical power to devices (i.e., edge and fog computing) so that gathered data can be immediately processed directly on the smart devices. This trend suggests that analytical improvements in the IoT will also play an important role in DE.

Third, predictive modeling and simulations are required to explore both physical and social dynamic geographic phenomena to better understand the evolution, changes and dynamics of the phenomena from a spatio-temporal perspective, to gain new insights and scientific knowledge to support informed decision-making processes. Understanding spatiotemporal behaviors makes sense from the DE point of view, to aid in the assembly of a detailed yet broad perspective of the complex, multidimensional relationships that occur in the real world. We recognize that prediction and simulation activities are typically associated with DE and that advances in the IoT might contribute to this area, but we see this hypothetical scenario occurring in the mid- to long-term, well beyond the time frame of the speculative exercise in Sect. 11.4. Since research on the IoT and DE with respect to predictive modeling and simulations is still in its infancy, we do not cover it in this chapter.

As a result of the previous functions, new scientific knowledge is generated that is necessary for taking informed and insightful actions, often ‘acting’ over the environment. In terms of **acting**, the second main capability of Things, new knowledge can trigger actions at least at two different levels in the context of the IoT: first, self-calibration of a sensor and/or Thing, similar to adjusting the lens in a human eye to sharpen the image, e.g., changing the sampling frequency; and second, providing a reflex similar to a reaction to pain without thinking, e.g., by opening a valve or level in the case of imminent flooding. However, this view would mean a priori that

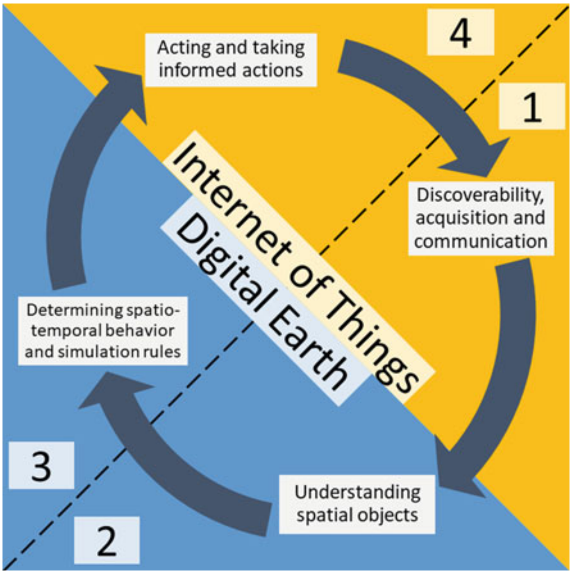

Fig. 11.6 IoT and DE workflow according to the higher cognitive functions in DE

the acting in IoT and Things do not contribute sufficiently to the higher (cognitive) functions of DE such as spatial analysis, predictive modeling and simulation, but the results of higher cognitive functions in DE may impact the acting behavior of Things and the IoT. In addition, we add a fourth function related to the ability of Things to act and take informed actions, depending on the insights and knowledge produced in the analysis, simulations, and predictions in DE.

Figure 11.6 reflects the existing and potential roles of each infrastructure in relation to the four functions: (i) discoverability, acquisition, and communication of spatial information, (ii) understanding of spatial objects and their relationships, (iii) determining spatio-temporal behavior and simulation rules, and (iv) acting and taking informed actions. We argue that the IoT infrastructure is important in (i) and (iv) whereas DE is more relevant in (ii) and (iii). For (i), the IoT can enhance DE by acquiring data streams from new sources, at a fine scale and high frequency. For (ii), it is plausible that both infrastructures progressively collaborate in a symbiotic manner per use case. From a broader perspective, it can reasonably be argued that DE includes IoT and encompasses the IoT life cycle in a broader ecosystem. Although GIS methods and analysis have traditionally taken a predominant role in DE, the role of the IoT will most likely increase in the future given the close relation between the IoT and the nascent edge-fog-cloud computational paradigms that enable IoT-based analytical processes to be conducted at different scales. This is a partial view, as we focus on the relationship between DE and the IoT. For example, remote-sensing satellite imagery, LIDAR and UAV were intentionally omitted even though they are key spatial data sources (i.e., the first function) for DE. We acknowledge the fuzziness of the boundary between both infrastructures and pay special attention to the interplay between DE and the IoT in Fig. 11.6, demonstrating how collaboration and integration is starting to happen while frictions and barriers are becoming more visible.

In the following sections, we identify for all but the third function the current technological substrate.

11.3.1 Discoverability, Acquisition and Communication of Spatial Information

Discoverability of Things. An important objective in IoT research is the discovery of devices and their services and/or the data they produce. The absence of standardized discovery methods for the WoT (Zhou et al. 2016) led to the development of online global sensor directories and collections such as Xively (https://xively.com), SenseWeb (Grosky et al. 2007), SemSOS (Pschorr et al. 2010) and the SWE discovery framework (Jirka et al. 2009). A key feature of these online directories/registries is that they provide open Web APIs supporting the development of third-party applications. The main drawback is that they are centralized, with a single point of failure. Decentralized approaches have also been proposed, such as IrisNet (Gibbons et al. 2003), which uses a hierarchical architecture for a worldwide sensor Web. G-Sense (Perez et al. 2010) is a peer-to-peer (P2P) system for global sensing and monitoring. These approaches, although more robust and scalable, do not effectively solve the problem of sensor discovery as they still require sensor registration to dedicated gateways and servers, which need to maintain a hierarchical or P2P structure among them.

Approaches towards real-time discovery of physical entities include Snoogle (Wang et al. 2008) and Dyser (Elahi et al. 2009). Snoogle is an information retrieval system for WSNs, but it cannot scale for the World Wide Web. Dyser requires an additional Internet infrastructure such as sensor gateways to work. Moreover, utilization of the domain name system (DNS) as a scalable, pervasive, global metadata repository for embedded devices and its extension for supporting location-based discovery of Web-enabled physical entities were proposed (Kamilaris et al. 2014; Kamilaris and Pitsillides 2012). However, this technique requires changes in the existing Internet infrastructure. It is possible to exploit web crawling for discovery of linked data endpoints, and through them the discovery of WoT devices and services was examined in WOTS2E (Kamilaris et al. 2016) as well as in SPITFIRE (Pfisterer et al. 2011).

While the approaches described above are mainly targeted at ‘professional’ users, there is demand for a simple and easy means for the general public to access IoT data. Experts can use a plethora of different service interfaces and tools to discover and utilize data from IoT devices, as implemented by the SmartEmissions platform (Grothe et al. 2016). Nonexpert users typically only search for IoT devices and their data through mainstream search engines such as Google and Bing. Ensuring the discoverability of devices and the data they produce is being investigated for geospatial data in general (see Portele et al. 2016 for further details). A similar approach might be adopted for the IoT, considering its higher complexity due to the high temporal (and spatial) resolution of the data produced by Things.

Spatial acquisition with Things. Some examples of geospatial standards to encode sensor metadata and observations were introduced in Sect. 11.2.4, and the SensorML standard is one of the most important. SensorML describes sensor metadata in a comprehensive way, providing a useful mechanism to discover sensors and associated observations. This standard specifies information about a sensor such as its sensor operator, tasking services, location, phenomena, and history of the sensor. Thus, it can be used by discovery services to fill their search indexes.

Following the SWE framework, there are two different search types (Jirka et al. 2009): *sensor instance discovery* and *sensor service discovery*. The first type finds individual sensors (devices) or sensor networks, and the second type refers to services that interact with the sensor (through sensing or tasking). Jirka et al. (2009) define three different criteria to identify both annotated search types:

- The Thematic criterion covers the kind of phenomena that a sensor observes, such as temperature, humidity, or rainfall.
- The Spatial criterion refers to the location where the sensor is deployed.
- The Temporal criterion is the time period during which the observations are generated.

This classification was defined from a conventional sensor point of view. The inclusion of current IoT devices with the ability to act leaves the previous criteria incomplete, as some IoT devices act as well as observe. Therefore, the definition of the thematic criterion requires extension to include an IoT device's capability to act, for example, to turn on/off a light or activate/deactivate an air conditioner.

In addition to the three shared criteria, Jirka et al. (2009) defined two criteria that focused exclusively on the *sensor instance discovery* type of search: sensor properties and sensor identification. The sensor properties are based on a specific state of the sensor, for example to find all *online* sensors. The sensor identification refers to the unique id used to identify unambiguously a sensor. Regarding the *sensor service discovery type of search*, two additional criteria were defined: functionality and usage restrictions. The first refers to the functionalities of the associate service such as available operations for data access, alerting or tasking, among others. The second criterion on usage restrictions is related to the permissions and restrictions to access the service functionalities.

Two different aspects are vital for the successful discovery of a sensor: metadata and semantics. As for all spatial data, metadata is essential to describe and discover a sensor or a network of sensors. SensorML was created for this purpose and can define a sensor in a well-known manner to add flexibility and allow for the use of any type of sensor. The Sensor Instance Registry (SIR) defines operations for handling sensor metadata and allows for sensor discovery. The above criteria, both common and specific for each type of search, are closely related to the metadata aspect for the discovery of sensor instances and services.

Semantics is the other pillar in a powerful and effective discovery service. Semantic rules can aid in locating sensors related to the same phenomena or discovery of all sensors that are related to the same thematic aspect. This semantic view can be extrapolated to link sensors with places to retrieve sensors or observations associated with place names. The Sensor Observable Registry (SOR) offers a primary interface to explore this kind of relationship between phenomena and sensors.

Unfortunately, the support of semantics is a weakness in the SWE standards. To solve this issue, an initiative from World Wide Web Consortium (W3C) was created to integrate and align sensors with semantic web technologies and Linked Data. This contribution was led by the W3C Semantic Sensor Network Incubator Group (SSN-XG) that proposed an ontology called Semantic Sensor Network (SSN) to address the semantic gap in sensor-related OGC standards (Compton et al. 2012). The main fields of this ontology are sensors (e.g., location, type), properties (e.g., precision, resolution, and unit), and measurements (values).

Despite the great advances that SSN brought, it does not currently support all the possibilities that the IoT offers since SSN was designed before the mainstream adoption of the IoT. New ontologies have been launched to cover this gap. One example is how the Internet of Things Ontology (IoT-O). IoT-O adds some missing concepts relevant to the IoT such as Thing, Actuator, and Actuation (Seydoux et al. 2016). Similarity, the Sensor, Observation, Sample, and Actuator (SOSA) ontology is a follow-up to SSN. It is the result of a joint effort of the W3C and OGC that builds on the lessons learned from SSN to provide a better representation of the IoT and alignment with OGC-related specifications (Janowicz et al. 2018).

Communication with Things. The advances in IoT connectivity solutions such as Bluetooth, ZigBee, Wi-Fi and 3-5G (Palatella et al. 2016) combined with decreases in the price and energy consumption of IoT components have led to a huge deployment of smart devices using IP-connectivity worldwide, increasing the frequency of communication to the point that they are perceived as always connected. As outlined above, these devices can offer two different capabilities, observing (sensing) and acting. A decade ago, sensor networks were only able to capture and send data, similar to a simple data logger. In recent years, the ability to establish two-way communication between Things and the cloud has added the feature that Things can (re)act. Consequently, new protocols that enable machine-to-machine (M2 M) communication have been developed, with the goal of providing efficient and transparent two-way communication channels between smart devices. Examples of such TCP/IP-based protocols are the advanced message queuing protocol (AMQP), MQTT, and the simple/streaming text oriented messaging protocol (STOMP). These communication protocols are adapted to the requirements of IoT devices that are constrained concerning their performance and energy efficiency.

11.3.2 Spatial Understanding of Objects and Their Relationships

Spatial analysis of Things. There are many more smart devices (Things) around today than five years ago. Smart devices now produce massive volumes of data, i.e., flows of data with strong temporal and spatial features. Therefore, spatial analytical methods such as proximity, area, volume, and trajectory are of vital importance in analyzing processes of Things. However, the variety of data sources related to the IoT has posed new analytical challenges, especially in the design and provision of a new class of analytical tools capable of handling real-time temporally and spatially referenced data from a plethora of heterogeneous smart devices (Trilles et al. 2017). Despite the existence of tools capable of analyzing temporal data in real time, the same does not appear to be true for the spatial component. Space (location and orientation for all Things, size and shape for larger Things such as cars) plays an indispensable role in the IoT, as Things-generated data have spatial properties and are spatially related to each other. Promising initiatives and platforms have recently emerged with the aim of performing spatio-temporal analysis in real-time, such as Microsoft Streaminsight, the Oracle Spatial Database with the Oracle Complex Event Processing engine, and the GeoEvent processor module as an extension of the ArcGIS Server environment (ArcGIS Server, n.d.).

Despite these notable efforts, spatial support for the real-time analysis of IoT data is still in its infancy. As Van der Zee and Scholten (2014) noted, any IoT architecture should consider the geospatial component. Location provides a kind of 'glue' that efficiently connects smart devices. The authors proposed storing the location of each 'Thing' and other geographic-related features such as orientation, size, and shape. However, the ability to handle and analyze the location of Things in near real time is still limited with existing analytical platforms, despite its opportunities (McCullough et al. 2011; Rodríguez-Pupo et al. 2017).

Furthermore, spatio-temporally located Things have the potential to significantly improve advanced geospatial analysis, as Kamilaris and Ostermann (2018) describe in their review on the potential role of geospatial analysis in the IoT field. In short, Kamilaris and Ostermann suggest network analysis and monitoring, surface interpolation, and data mining and clustering as spatial analysis techniques and methods that would especially benefit from an increasing number of mobile or stationary sensor Things. However, as the authors noted, these advanced analytical applications have been scarcely exploited to date.

Geospatial standards for Things. Despite some remarkable exceptions such as prototype systems to analyze data from air quality sensor networks (Trilles et al. 2015b), real-time, geospatial analysis approaches and tools have not been sufficiently developed to offer standardized procedures through uniform interfaces that can be widely consumed and integrated in DE applications. DE has traditionally considered sensors as a fundamental pillar to collect information to support and realize strategies or policies at a higher level. As described in Sect. 11.2, the SWE suite was the initial step in offering a standardized specification that would fulfil the requirements demanded by the IoT from the DE perspective. For example, the SOS specification requires handling large XML documents, which is problematic in a typical scenario in the IoT where memory capacity and connectivity are limiting factors.

Although the core of the SWE suite has served to cover the required functionality of the IoT, the complexity of the data models in some of the specifications (Tamayo et al. 2011; Trilles et al. 2014) and the appearance of new requirements such as the ability to work in real time and to act have reduced the applicability and integration of the SWE suite in the scope of the IoT. In an effort to bridge the gaps between SOS and the IoT, new extensions or approaches attempt to make the SOS interfaces more suitable for IoT devices. These approaches include SOSLite (Pradilla et al. 2015), TinySOS (Jazayeri et al. 2012) and SOS over CoAP (Pradilla et al. 2016).

Another crucial feature for the analysis functionality of the IoT and Things is the ability to specify and perform real-time and asynchronous notifications and communications. In this regard, the GeoMQTT protocol based on the MQTT protocol allows for adding spatial notification and data streaming between publish/subscribe instances (Herle and Blankenbach 2018). Following the original approach of the MQTT channels, the authors proposed the concept of GeoPipes to distribute instances and enable the sharing of geospatial data streams in a standardized manner.

Laska et al. (2018) proposed a real-time stream processing pipeline that allows for spatiotemporal data stream integration from IoT devices. A data integration layer allows for geospatial subscriptions using the GeoMQTT. Tools such as Apache Kafka and Storm are used to transfer and apply map matching algorithms to IoT data with spatiotemporal components. For example, these algorithms were used to analyze traffic congestion for a recent route optimization using IoT Things with Global Navigation Satellite System (GNSS) receivers in buses.

Another study (Rieke et al. 2018) took an additional step to bridge the DE and IoT realms by arguing for the need to establish event-driven architectures as a natural evolution of the predominantly static Spatial Data Infrastructures (SDI). The authors identify a series of interdependent issues that need to be addressed in the coming years to take full advantage of the uptake of eventing in GIScience (and DE). The issues relate to the (i) inconsistencies between classic data access methods that are based on a request-response pattern, and event-driven approaches where a publish-subscribe pattern prevails, (ii) heterogeneous approaches for defining event patterns, (iii) multiple standards and limited support in software tools, (iv) the integration of devices in an SDI and the data they produce, and (v) the lack of semantic interoperability of geospatial events.

11.3.3 Taking Informed Actions and Acting Over the Environment (ACT)

As shown in the defined IoT lifecycle (Fig. 11.6), to act means to take or perform actions (over the environment) depending on the results obtained in previous functions. Bélissent (2010) noted that this feature can make the management of public services in a city, education, health, safety, mobility or disaster management more aware, interactive and efficient.

IoT devices have been traditionally suitable for use as input sources for Decision Support Systems (DSSs) in a multitude of application domains and use case scenarios such as disaster management, cities, mobility, and safety. In this chapter, we focus on Spatial Decision Support Systems (SDSSs), which are defined as interactive systems designed to support decision making related with spatial planning problems. SDSSs have evolved to more complex architectures and communication models, from systems deployed on the cloud operating with data from the WSN (or IoT data sources) to a shift in the computing paradigm in which the actual computation is implemented at three different levels: edge, fog, and cloud (Fig. 11.7). In this new setting, both the computation and decisions are made closer to the producers of the data (*Things*).

The 'Edge' is the layer that covers the smart devices and their users, providing local computing capacity within Things. The 'Fog' layer is hierarchical, aggregating a variable number of edge layers. In addition to computing, the fog layer has other functionalities such as networking, storage, control, and data processing, possibly using data produced by the edge layer and data from other sources. As a result, data contextualization is more important in the fog layer to make sense of different data sources than the typical single data stream in an edge layer. The 'Cloud' layer on top performs the final analysis to extract information and create knowledge to be

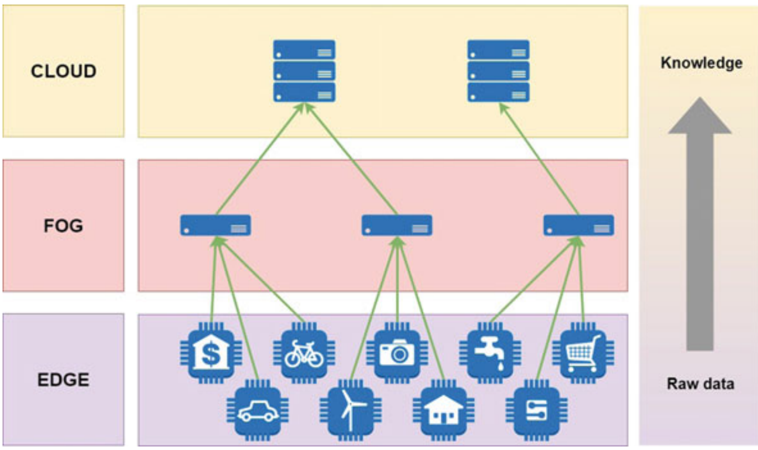

Fig. 11.7 Three-layer IoT architecture

transferred for decision support actions. This implies an increased level of contextualization and complexity in the analysis process than in the previous (lower) layers, at the cost of losing capacity for real-time analysis.

Given the edge-fog-cloud layered architecture, the introduction of geospatial concepts and spatial analysis in the fog layer could allow for decision-making processes without a human in the loop based entirely on the semantics of the spatial-temporal dimensions in the incoming data. In recent years, many efforts have been made to move the analysis from the cloud to the fog layer, with the aim of reducing latency in the analysis once the data are received in the fog layer (Barik et al. 2016).

Although data usually flow from the edge to the cloud layer (sensing capability), devices with the ability to act (tasking) also require information to perform their operations. The tasking capability allows for other devices or users to actuate devices via the Internet so that these 'controlling' devices or users can easily control them to execute tasks remotely. Autonomous Things would be previously programmed to act without establishing a connection. While the sensing capability allows for users to continuously monitor the status of devices and the environmental properties they capture, the tasking capability can help users make adjustments accordingly by controlling devices remotely.

In general, combining the sensing and tasking capabilities of IoT devices enables users to create various automatic and efficient tasks and applications. These kinds of applications are called "physical mashup" applications (Guinard et al. 2010). A simple, domestic example is the activation of an air conditioning system depending on the position and behavior of the user, through an application that uses a GNSS sensor. In this example, the air conditioning device provides an interface to turn on/off (tasking) the system to establish a comfortable temperature. To facilitate this kind of mashup of sensing and tasking capabilities, a uniform (interoperable) interface for users or applications to enable access and communication is a critical requirement.

The tasking feature was initially conceived in the SPS specification of the SWE suite. SPS offers a standardized interface for tasking sensors and sensor systems and defines interfaces to expose sensor observations and metadata. For example, a sensor network can be set up to measure air pollution in 5-min intervals or a satellite can be tasked to remotely sense a specific region on the surface of the globe (De Longueville et al. 2010). This standard offers operations such as GetFeasibility, which can be used in advance to verify whether the execution of a task is feasible for a certain sensor, and the DescribeResultAccess operation to determine the access points to collected data. The SPS interface also offers functionality for managing submitted tasks, including convenient operations for retrieving the status of a task, updating tasks or cancelling them.

A next step is the tasking profile of the SensorThing API, which is a follow-up, improved profile of the SPS (Simonis 2007). The SensorThing API (see Sect. 11.2) defines two different profiles, Sensing and Tasking. The Tasking profile is based on the SPS standard and enables interoperable submission of tasks to control sensors and actuators. The main difference between SPS and the SensorThings API is that the former offers task operations over sensors and the latter also includes tasks on actuators. Although the first version of the SensorThing API did not include the

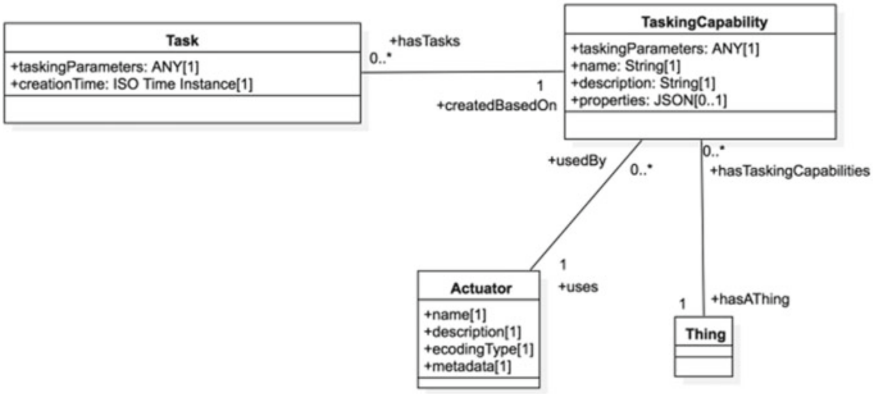

Fig. 11.8 The SensorThings API tasking entities. *Source* OGC SensorThings API (http://docs.opengeospatial.org/is/15-078r6/15-078r6.html)

Tasking profile, a new candidate standard illustrates the potential of the SPS standard, duly adopted and aligned with the requirements of the SensorThings specification (Liang and Khalafbeigi 2018). This new specification called Tasking Core defines three new entities, *TaskCapability*, *Task,* and *Actuator* (Fig. 11.8).

The *TaskingCapability* entity describes all supported tasks for each Thing and how they can be used. This entity is defined by four properties: name, description, taskingParameters, and properties. The second entity, *Task*, is a list of performed tasks that are defined by a set of tasking parameters (commands executed) and creation time. The last entity is the *Actuator* and defines a type of transducer that converts a signal to a real-world action or phenomenon. This entity is comprises a name, description, encoding type of metadata and metadata.

11.4 Case Studies on Smart Scenarios

In this section, we show how the IoT and DE work hand-in-hand in real-world scenarios based on the latest technology initiatives to relate the IoT and DE described in the previous section. Kamilaris and Ostermann (2018) provide an extensive overview of work at the nexus of geospatial analysis and the Internet of Things; here, we provide a selection of case studies in various domain applications, with a special focus on the relationship between DE and the IoT.

In the context of applications for environmental monitoring and resource management in cities, recent examples of IoT applications include an Arduino-based sensor platform in Seoul to measure variations in the physical-chemical parameters in water streams (Jo and Baloch 2017). The sensor platform is powered by solar energy and transmitted sensor readings every second via Bluetooth for three years. Although the case study in Jo and Baloch (2017) relies on a single sensor station and the clustering analysis of the raw data focuses uniquely on the temporal dimension, the paper shows the potential of Arduino-based sensing modules for environmental sensing applications in smart city applications. To improve solid waste management, Tao and Xiang (2010) developed an information platform to support recycling. The main technologies were RFID and GPS to track and check waste flows between collection, transport, and processing facilities. Lee et al. (2015) examined the role of the IoT in an industrial service provision scenario (fleet management) and Fazio and Puliafito (2015) use the example of road conditions to showcase a cloud-based architecture for sensor and data discovery. They distinguish two scenarios of data- or device-driven search, and develop the system architecture based on the OGC SWE suite and the extensible messaging and presence protocol (XMPP).

Reducing the required energy consumption remains an important objective for IoT devices. Ayele et al. (2018) proposed a dual radio approach for wildlife monitoring systems. They combine Bluetooth low energy for intraherd monitoring with LoRa for low-power wide-area networks to communicate between herd clusters and a monitoring server. The proposed architecture promises significant advantages in reducing power consumption while maintaining low latency.

Improving traffic management is another promising IoT application area. In 2006, Lee et al. proposed the use of cars as a mobile vehicular sensor network and for data exchange in “smart mobs”. More recently envisioned solutions include parking management and smart traffic lights as part of a cognitive road management system that handles different types of traffic efficiently (Miz and Hahanov 2014). Jing et al. (2018) examined the combination of GNSS localization and RFID tagging for infrastructure asset management with promising results. Additionally, the city of Aarhus in Denmark deployed traffic sensors across major roads in the city, and the information was used by the CityPulse project to provide context-aware recommendations to users for route planning (Puiu et al. 2016).

Noise pollution is a frequent problem in dense urban areas, and because urban morphology makes noise distribution modeling difficult, it has attracted participatory sensing approaches. Wireless acoustic sensor networks are another option. Segura Garcia et al. (2016) presented a case study in the small city of Algemesi (Spain), where a network of 78 inexpensive sensor nodes based on Raspberry PIs collected sufficient data for a subsequent highly accurate spatial interpolation.

Okasenen et al. (2015) harnessed movement data from mobile sports tracking applications in urban areas to produce heat maps of cyclists commuting through the city of Helsinki. Mobile phones could be considered IoT sensor devices in participatory sensing-based models for mining spatial information of urban emergency events, as demonstrated by Xu et al. (2016). In addition, van Setten et al. (2004) supported the COMPASS tourist mobile application with context-aware recommendations and route planning. Mobile phones were also used for crowdsourcing-based disaster relief during the Haitian earthquake (Zook et al. 2010), where people used the camera and GPS of their phones to send information from the field to the authorities to map the landscape of the disaster and assess the overall damage.

University campuses present an interesting environment for smart city approaches because the visitors are usually more tech-savvy than the average population, the network coverage is good, and the geographic boundaries allow for a comparatively crisp delineation of the study area. Cecchinel et al. (2014) presented a system architecture for a smart campus case where the four requirements of sensor heterogeneity, reconfiguration capability, scalability, and data as a service were handled via a middleware in the Amazon Web Services (AWS) cloud, with Arduino Uno and Raspberry Pi sensors for bridging. Another case study at a university campus examined the impact of nearby weather and pollution sensors on the everyday decision-making of the students (Kamilaris and Pitsillides 2014). Trilles et al. (2015a) presented a sensorized platform proposal that adheres to the principles of the IoT and the WoT. They use the SensorThings API to avoid interoperability issues. An environmental WSN in a Smart Campus scenario was developed as a proof of concept.

However, smart approaches with IoT technology are not limited to smart city applications. Sawant et al. (2014) presented a low-cost automated weather station system for agriculture that uses Raspberry Pi systems at its core and SWE to transmit data. The sensor readings were also broadcast on a dedicated Twitter account. The system has been extended with additional components such as a web-based client (Sawant et al. 2017). The environmental impact of agriculture was studied by Kamilaris et al. (2018) in the region of Catalonia, Spain. In their study, sensors measuring nitrates and data from the mobile phones of farmers in the region were used. Fang et al. (2014) presented a holistic approach to environmental monitoring and management through an integrated information system that collects data on the regional climate for the city of Xinjiang from various sources including IoT sensors, and related it with ecological response variables such as the primary production and leaf area index. For environmental monitoring, the AirSensEUR project established an affordable open software/hardware multisensor platform, which can monitor air pollution at low concentration levels to create maps of pollution levels in different areas (Kotsev et al. 2016).

A crucial component of any DE system and application is monitoring shifting surface conditions such as erosion on sandy beaches. Pozzebon et al. (2018) presented an Arduino-based system to measure the height of sandy beaches and dunes in real-time. The sensor network uses the ZigBee standard to transmit data, with a GPRS transmitter for sending sensor readings to a MySQL database. Another example is the monitoring of landslides in mountainous areas. Benoit et al. (2015) tested a successful cheap wireless sensor network using XBee for communication and GPS for localization. A thematically related case study is the use of small and inexpensive sensors for monitoring and early-warning systems for floods caused by melting snow in the Quergou River basin (China), as reported by Fang et al. (2015). In addition, changing climate conditions make reliable and efficient management of storm water surges in urban areas important. Rettig et al. (2016) designed and tested a geospatial sensor network for this task, built using common, off-the-shelf components.

With respect to the provision and reception of cultural heritage and cultural services, Chianese et al. (2017) proposed and tested a system that combines business intelligence, Big Data, and IoT data collection to analyze visitor interests and behaviors in a museum. Although IoT devices were only part of the approach, measuring visitor proximity to artworks, their integrated use with other technologies and platforms showcases the strength of a multisensory DE approach.

11.5 Frictions and Synergies Between the IoT and DE

Based on the current technological substrate that provides the initial steps to establish connections between the IoT and DE according to the three cognitive functions (Sect. 11.3), and the presentation of selected case studies (Sect. 11.4), in this section, we (i) carry out a speculative exercise to discuss the main existing limitations and frictions that prevent the IoT and DE from working closer together and (ii) suggest future ways to establish effective communication channels between the two infrastructures.

Before going into detail, it is necessary to establish a fundamental assumption that influences any discussion related to the frictions and synergies between the IoT and DE: the diverging speeds of development of DE and the IoT. New technology and disruptive breakthroughs generally challenge the status quo in any sector, and adopting such improvements can enable more rapid developments and new applications. However, the rapid growth of the IoT field has produced a vast variety of IoT devices and protocols and, consequently, the landscape of IoT-related standards, protocols and specifications is fragmented. For example, a large portion of 'Things' were not originally designed to connect to the Internet; they were later adapted to establish Internet connections by adding connectivity chips via microcontrollers (e.g., Arduino, Raspberry Pi) or through tags (QR Code or RFID). As a result, many different ways to connect hardware and software to enable Internet connectivity were developed and established with no clearly agreed upon consensus and consequently resulted in a lack of interoperability. This example illustrates the great variety and complexity of the IoT universe, where the exponential growth of the IoT is due to the rapid decrease in the size, cost, and energy requirements of sensors, and the ubiquity of network coverage for wireless Internet connections, leading to many standardization efforts following diverging paths. In addition, DE has been traditionally characterized by a slow adaptation of new improvements (López 2011), and thus, the recent technological developments **have not evolved at the same speed in DE as in the IoT**. Noting this fundamental friction, we identify other potential frictions and synergies, which may be considered two sides of one coin, and organize the discussion according to the cognitive functions defined in Sect. 11.3.

11.5.1 Discoverability, Acquisition and Communication of Spatial Information

A direct result of the fragmented standardization context noted above is the **absence of well-accepted global protocols for the discovery of Things**, which also occurs to some extent in DE. Search and discovery is crucial for geo-locating nearby, local, and/or relevant real-world devices and services, a vital step in exploiting sensor data and services to create more advanced knowledge. Early efforts in this direction are discussed in Sect. 11.3.1, but we are still far from a complete solution to this difficult problem, which must be addressed along with the challenges of better description of devices and services and the semantics of the data involved, especially from a geospatial point of view.

Therefore, it remains an open issue to build an IoT-DE ecosystem in a way that will be compatible with standardized IoT reference models and architectures to enable the discovery of relevant sensors (or Things) and related services. Although there are many different scenarios and solutions, several common features can be extracted to find synergies between both infrastructures: the modularity and interoperability of IoT components, open models and architectures, flexible service compositions, integrated security solutions, and semantic data integration. There is an intensified effort regarding the development of architectural frameworks and solutions such as the IEEE or ITU-T models, as well as other related works and approaches developed under the auspices of IETF, W3C, or OASIS. From a DE point of view, associated services for sensor devices and instances are the cornerstone to enable seamless communication and interoperability between the IoT and DE. There are different options such as the SWE and SensorThings API, the latter of which is especially relevant for the establishment of potential solid bridges between the IoT and DE concerning common data models for better data acquisition and unified interfaces for enhanced sensor and service discovery. Some research works have already made substantial progress. Jara et al. (2014) presented a comprehensive framework and architecture to enable discovery over a wide range of technologies and protocols, including legacy systems, and Wang et al. (2015) implemented annotations with an ontology-based semantic service model, SPARQL queries, and geographic indexing to enable sensor discovery in an experimental study, which delivered faster and more accurate responses than other tested approaches.

11.5.2 Spatial Understanding of Objects and Their Relationships

A friction between DE and the IoT is related to the way geographical features are modeled. Traditional GIS data models conceptually abstract the real-world objects into core geometric elements such as points, lines, polygons, and volumes, implemented as raster data models, vector data models, or a combination. These data models were designed to perform spatial analyses such as distance computations and topological operations. Despite these great achievements, GIS (and DE) data models were not designed to cope with the richness and complexity of the interactions between the physical, natural, and social actors that naturally occur in the environment in the way that the IoT potentially can. As noted above, smart devices and Things can 'sense' the environment in a way that was unimaginable before, and, consequently, the streams of rich and finer data acquired by **IoT devices do not fit well with the "coarse-grained" vector/raster data models** widely used in DE applications and systems, as these spatial structures were not intended to handle data with such a high spatio-temporal resolution.

The lack of suitable data models to efficiently manage data at high spatio-temporal resolution highlights **the need for new tools to process data coming from Things and smart devices** in which the modeling of geospatial features has not yet been fully resolved. Moreover, real-time data is often a defining feature in the IoT, as IoT devices and Things can produce data at a high frequency (e.g., data streams), which requires methods for real-time analysis. Therefore, the lack of new algorithms and implementations for real-time computation and processing streams of spatially referenced data sets is a clear limitation. Although some tools can run geospatial queries of stored data, they do not offer ways to analyze data from IoT devices and sensor nodes in real-time (Nittel 2015).

Unlike the IoT, any changes in the DE arena have been more gradual and less frenetic. However, some notable changes indicate the way forward to consolidate potential bridges between DE and the IoT in the midterm and long term. For example, in a Digital Earth Nervous System (De Longueville et al. 2010), **Things could perform basic geospatial operations on sub-networks of Things**, providing processed information for the higher-level elements of a DE. Geometric measurements and basic geospatial analysis are application areas in which Things have been used more widely in recent years (Kamilaris and Ostermann 2018). Similarly, an often overlooked component of IoT applications are the gateway nodes that connect the sensor devices to the wider network. In addition to a simple routing function, these gateways can perform other tasks including exploratory analysis (clustering, event-detection) of incoming data. Rahmani et al. (2018) examined the use of smart gateways in an e-health system that monitors several individual physiological parameters, demonstrating the potential benefits of (spatial) analysis executed directly on smart gateways in the context of DE-related applications such as precision agriculture, environmental monitoring, and disaster management.

The status quo of services for spatial analysis and geoprocessing on the Web is mainly driven by the WPS standard specification (Sect. 11.2.4). However, Herle and Blankenbach (2018) argued that the current WPS standard is not well suited to handle the large amounts of real-time streaming data expected from massive IoT sensor networks. Building on previous work, they extended the WPS with the GeoPipes concept using the GeoMQTT protocol for communication, implementing several smaller proofs-of-concept for application cases such as inverse distance weighting with a sliding window and trajectory data mining. In addition, Armstrong et al. (2018) presented an IoT + CyberGIS system to detect radiation risk and propose that new approaches are needed to integrate the IoT and geospatial analysis and support the fourth scientific paradigm of data-intensive discovery (Hey et al. 2009).

11.5.3 *Taking Informed Actions and Acting Over the Environment*

In the initial stages of DE, it was thought that sensors could only capture what is happening in the physical environment, i.e., sensors as mere data loggers. The data collected by these sensors are transferred from bottom to top until reaching the SDI repositories. In this sense, the IoT is much more complex because, in addition the feature of acting on the physical environment, the IoT supports communication between devices in the same layer (edge) and complex strategies to determine solutions to real, large problems can be developed. As mentioned above, DE should be adapted to the possibilities that the IoT devices can offer to enrich the capabilities of the current SDIs.

The previously noted heterogeneity problem of connecting IoT devices implies different hardware specifications across the multiple IoT devices. This variety of hardware means that the abovementioned standards cannot work at a low level. This is why the standards mainly define web service interfaces, and connectors or adapters (hub approach) are required to control IoT nodes. Similar to the hub approach, the Sensor Interface Descriptor (SID) solution is a declarative model based on the Sensor ML standard for describing device capabilities (Broering and Below 2010), sensor metadata, sensor commands, and device protocols. In terms of the tasking capability, the SID describes device protocols with the Open Systems Interconnection (OSI) model using an XML schema and thus understanding and adapting the SID may be costly for IoT device manufacturers.

An opportunity that DE can offer the IoT is a global vision on the in situ data that the IoT collects, with the aim of establishing strategies to perform actions in a coordinated manner among the IoT nodes, taking advantage of the ability to act. To conclude, the following Table 11.1 summarizes the frictions and synergies between the IoT and DE.

11.6 Conclusion and Outlook for the Future of the IoT in Support of DE

The concept of combining sensors organized in networks to monitor the environment has been around for decades, and DE has contributed to its expansion. The confluence of new technologies has created a new reality that offers millions of new possibilities, led by the IoT revolution that promises to create a newly interconnected "smart" world (or Earth). After the massive deployment of a ubiquitous array of IoT devices and the

Table 11.1 Detected frictions and synergies between the IoT and DE

	Discoverability, acquisition and communication of spatial information	Understanding spatial objects and their relationships	Taking informed actions and acting over the environment
Frictions	– Absence of well-accepted global protocols for the discovery of Things	– IoT devices do not fit well with coarser vector/raster data models – Lack of tools to process data from Things	– DE has traditionally considered sensors as collectors, with data flowing from bottom to top. – GIS standards must be adapted for each hardware specification
Synergies	– Different standardized IoT models and architectures such as SWE and SensorThings API	– Things can perform basic geospatial operations – Some initiatives have adapted GIS processing standards to support IoT data	– DE provides a global view to establish IoT node strategies to act

impact it made, the world cannot give up being 'online'. Today, the IoT has enabled millions of relationships between objects and Things, so that objects, people, and their environment are more tightly intertwined than ever. Despite the great advances achieved in recent years, like all disruptive innovations, the IoT presents a series of challenges that should be treated as a priority in the coming years, especially in the areas of security, interoperability and standards, privacy, and legal issues. DE can also play a crucial role in handling some of these challenges.

The IoT and DE dichotomy presents various challenges that should be addressed in the near future to create a more beneficial union for both parties: The first challenge is to activate mechanisms to streamline the adaptation of new IoT functionalities from DE. Traditionally, DE is characterized by its comparative inertia to adopt new approaches that imply improvements in terms of performance or usability. Examples include the slow adoption of more flexible interfaces such as the RESTful web interface or data formats that are more suitable for exchange such as JSON in sensor standards such as the SOS specification (Tamayo et al. 2011). The tradeoffs between standardization and disruptive innovation in DE should be carefully discussed by all involved actors to fuel rapid, innovative developments in DE like those in the IoT field. Although the standardization process is key to establishing permanent links between the two infrastructures, it should not slow down innovative changes and technical developments, and standards should be seen as a means to filter out and embrace changes that prove to be useful, effective and valuable for improvement of the IoT-DE ecosystem.

When a technological field grows exponentially, it often leads to heterogeneity and variety in the short term. Within the IoT, this is partly due to the impact that the continuous development and improvement of hardware technology has on IoT devices. Therefore, another challenge to be addressed is the heterogeneity of IoT devices. Although the OGC specifications have helped in the service connection and data/service access levels, the IoT still presents a wide variety of different hardware developments and implementations, most of which are disconnected from the DE infrastructure, and therefore remain invisible for DE applications. The development of ad hoc adapters is one way, at least until a standards consensus is reached in the IoT field, to allow for interaction with the variety of hardware specifications of IoT devices and Things and foster connections between the two infrastructures. This is not an optimal solution since the integration of IoT devices is a challenging and difficult task, but it helps discern the connections and adaptors that may eventually become candidates for standardization bodies.

Throughout this chapter, we revisited many tools that are capable of analyzing spatially referenced data collected by IoT devices. However, the quantity and quality of tools that handle the temporal dimension of data in real time far exceeds those that deal with the spatial dimension. An additional barrier is the large-scale variance in the data models between IoT devices and the decision-making systems that are typically established in DE. Optimal spatial models to handle scale variations can be useful to analyze the information received from IoT devices and obtain a more high-level vision that can be interpreted by decision makers and policy makers. Therefore, investment in the research and development of better tools to spatially analyze IoT data in real time on the edge, fog and cloud scales is a priority in the IoT-DE ecosystem roadmap.

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Carlos Granell currently holds a 5 year Ramón y Cajal post-doctoral fellowship at the Universitat Jaume I of Castellón, Spain. His interests lie in multi-disciplinary application of GIS (Science/Systems), spatial analysis & visualization of streams of sensor- and/or user-generated geographic content, reproducibility research practices, and finding synergies between citizen science projects, education and dissemination of science.

Andreas Kamilaris is an Assistant Professor at the Computer Science department of the University of Twente, the Netherlands and the leader of the SuPerWorld research laboratory at the Research Centre on Interactive Media, Smart Systems and Emerging Technologies (RISE), in Nicosia Cyprus. Andreas has published more than 60 research papers, has received several awards and has co-founded three start-ups. His research interests include geospatial analysis, Internet/Web of Things, machine learning and smart ecosystems.

Alexander Kotsev is a scientific project officer at the European Commission's Joint Research Centre. He holds a Ph.D. in Geographic Information Science from the University of Sofia. His research interests include data analysis, sensor web, open source technology and architectures for knowledge management.

Frank O. Ostermann is an Assistant Professor at the faculty ITC at the University of Twente (Netherlands). His research focuses on handling novel sources of geoinformation from citizens and small in-situ sensors. He received his Ph.D. from the University of Zurich (Switzerland), and worked as a post-doctoral researcher at the European Commission's Joint Research Center.

Sergio Trilles received his Ph.D. in Integration of Geospatial Information from the Jaume I University in 2015. He had the opportunity to work four months as researcher in the Digital Earth and Reference Data Unit of the European Commission's Joint Research Centre (JRC). Currently he is a postdoc researcher at the GEOTEC group.

Chapter 12
Social Media and Social Awareness

Xinyue Ye, Bo Zhao, Thien Huu Nguyen and Shaohua Wang

Abstract The human behaviors and interactions on social media have maintained themselves as highly dynamic real-time social systems representing individual social awareness at fine spatial, temporal, and digital resolutions. In this chapter, we introduce the opportunities and challenges that human dynamics-centered social media bring to Digital Earth. We review the information diffusion of social media, the multi-faced implications of social media, and some real-world cases. Social media, on one hand, has facilitated the prediction of human dynamics in a wide spectrum of aspects, including public health, emergency response, decision making, and social equity promotion, and will also bring unintended challenges for Digital Earth, such as rumors and location spoofing on the other. Considering the multifaceted implications, this chapter calls for GIScientists to raise their awareness of the complex impacts of social media, to model the geographies of social media, and to understand ourselves as a unique species living both on the Earth and in Digital Earth.

Keywords Social media · Human dynamics · Social awareness · Location spoofing

12.1 Introduction: Electronic Footprints on Digital Earth

Geo-positioning system-enabled instruments can record and reveal personal awareness at fine spatial, temporal, and digital resolutions (Siła-Nowicka et al. 2016; Li et al. 2017; Ye and Liu 2019). With an exponential growth, human dynamics data are retrieved from location-aware devices, leading to a revolutionary research agenda regarding what happens where and when in the everyday lives of people in both real and virtual worlds (Batty 2013; Yao et al. 2019). Many location-based social media

X. Ye (✉) · S. Wang
College of Computing, New Jersey Institute of Technology, Newark, USA
e-mail: xye@njit.edu

B. Zhao
Department of Geography, University of Washington, Seattle, USA

T. H. Nguyen
Department of Computer and Information Science, University of Oregon, Eugene, USA

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(LBSM) instances have been gaining popularity, fostering the emergence of fine-grained georeferenced social media content through these personalized devices (Liu et al. 2018a, b). The proliferation of LBSM enables researchers and practitioners to efficiently track a large and growing number of human action and interaction records over time and space to develop insights and enhance decision-making process from individual to global levels. The patterns and trends produced by LBSM can identify the movement of active social media users and aid in inferring demographics and related infrastructures. The collected data on users' physical and virtual activities facilitate the in-depth understanding of human dynamics from various aspects (Barabasi 2005; Shaw et al. 2016). The large volumes of such user-generated locational and contextual information are especially beneficial to studies relevant to the evolution of population size and human settlement structure as well as highly topical subjects such as traffic and epidemiological forecasting. For instance, real-time customer shopping behaviors might be rapidly identified by searching specific keywords in tweets, which allows for urban researchers and business analysts to monitor the fine-scale dynamics of economic geography and market outcome (Ye and He 2016). This new data landscape might not directly provide an ultimate solution to long-standing social or economic issues, but can increasingly shed light on many societal characteristics that are otherwise difficult to discover using traditional questionnaires or surveys.

Human actions and interactions in the digital form as well as frequent status updates can manifest themselves as highly dynamic real-time social systems, which enable the government to formulate appropriate policies for the relevant groups and targeted communities (Shi et al. 2018; Wang and Ye 2018). The electronic footprints and perceptions left by social media users and derivatives of complicated social networks can be utilized to enhance the design of location-based services (Ye and Lee 2016). Hence, the increasing demands in mapping and analyzing social media data call for more innovative conceptual and technological advances in visual and computational methods. These research challenges and opportunities can facilitate a paradigm shift in the broader social science disciplines in this new form of data landscape. Social media messages can depict the interconnected patterns and relationships between cyberspace and physical space, and can also be distributed instantly to a large number of users globally, who may belong to different virtual communities (Shelton et al. 2015).

Geographic information has traditionally been spread by governments or industries in a top-down manner; but its broadcast is much faster through social media than official agencies. The dramatic transition towards bottom-up digital dissemination has challenged these official or professional processes. Individuals can utilize the power of volunteered geographic information to minimize the difference and/or quality between experts and nonexperts in the context of generating a large collection of user-described features and numerous georeferenced citizen observations on socio-economic phenomena. With social media platforms becoming increasingly location-enabled, users can share geo-tagged information about their own lives and, as a result, rich content about large populations can be aggregated for social and behavioral studies (Sui and Goodchild 2011). Such a practice facilitates the policy transition from long-term to short-term action with a new perspective of understanding, visualizing, and analyzing human dynamics (Batty 2013).

The use of LBSM content represents a significant methodological advancement in social sciences and humanities research, providing rich content regarding human-environment interaction with locational estimation in ubiquitous/pervasive computing. It can efficiently assist place-based policy interventions in a timely fashion. Prompt and rigorous detection of emerging social and economic events calls for more robust algorithms to support such unprecedented research efforts in both qualitative and quantitative analyses. However, challenges and difficulties remain in processing user-generated messages to derive effective and high-quality information, considering the complex syntax and context embedded in social media messages. Additionally, if data analytics cannot be effectively conducted, the expected results could lose value for decision makers. These issues must be addressed to realize the potential of social media analytics.

Considering the above-mentioned issues, the remainder of this chapter is organized as follows. Section 12.2 describes the multifaceted implications of social media. Regarding social media, the unprecedented opportunities to predict human dynamics are introduced in Sect. 12.3, while multiple challenges are listed in Sect. 12.4. Then, the implications of these opportunities and challenges are further discussed in Sect. 12.5, followed by a conclusion in Sect. 12.6.

12.2 Multifaceted Implications of Social Media

Value systems are fundamental to anything we do. Today, the rapid proliferation of social media has greatly affected us and almost every aspect of human society. Confronted with this complicated and unstoppable interaction, we employ value structures to holistically discover the implications of social media, especially the unintended but vital ones. McLuhan's (1975) law of media is frequently utilized to capture the social consequences of various media. Tuan (2003) also proposed the psychology of power to unveil the internal logic of human's perceptions of places, and Ihde (1990) contemplated how technology mediates between human beings and the world from a phenomenological perspective.

Among these value structures, we employ Ihde's amplification-reduction structure to investigate the opportunities and challenges brought by social media. This structure reveals how technology (including social media) amplify and simultaneously reduce a certain human experience. The amplified and reduced experiences are intertwined and interrelated. More significantly, the amplified human experience is obvious whereas the reduced human experience is undiscoverable and easily ignored. Though Ihde only suggested applying this structure to the human experience, it can also be applied to understand the social implications of the investigating object. Through this structure, the opportunities and challenges of the social implications can be revealed. For example, during the 2008 Olympic Games, social media was touted as a tool of freedom to enable the general public to express their concerns about the air pollution issues in major Chinese cities. If we acknowledge the promotion of free speech as the opportunities brought about by social media, the hidden challenges can be revealed through this value structure—social media can also be used as a tool of surveillance by big brother to control the discussion on air pollution as well as a medium of advertisement by private companies to sell relevant products (e.g., masks) to prevent air pollution-related symptoms. The implications of social media are multifaceted. Therefore, the value structure can be applied to examine the impacts of social media on the rapidly evolving Digital Earth. In the following sections, we discuss the opportunities provided by social media as well as the potential challenges.

12.3 Opportunities: Human Dynamics Prediction

As a newly chartered territory for human activities, social media has resulted in tremendous electronic footprints. Such footprints represent a large number of the population and can be used to predict human dynamics on the ground via the relationships between the spread of information, user characteristics, and message contents. In this section, we discuss how social media can be used for different aspects of human society, including public health, emergency response, decision making, and social equity promotion.

12.3.1 Public Health

Social media platforms can be used to mitigate the spread of pandemics and associated anxiety. Scholars have used sentiment analysis and spatial analysis to examine how social media communication conveys information about contagious and infectious diseases and alerts the public, through identifying, tracking, and visualizing the behavioral patterns of users (Zadeh et al. 2019). For instance, Ye et al. (2018a, b) explored public health-related rumors during disease outbreaks and evaluate how such media framing sets the tone negatively, affecting the quality of disease outbreak detection and prediction, using the diffusion of Ebola rumors in social media networks as a case study. Sharma et al. (2017) find that the inaccurate Facebook posts are more popular than those with accurate and relevant information about the Zika virus. Villar and Marsh (2018) studied the impact of social media health communication of Ebola and Zika, concluding that the effect relies on users' attitudes and trust towards authorities and the media. Average citizens and ordinary social media users have very limited knowledge regarding the accuracy and relevancy of infectious diseases spreading over time and across space as well as concerning complications. As a force in health communication, social media data could be utilized to define a temporal extent of the infection and to populate a spatial database of reported occurrences of the disease. Additionally, social media data can be used to track and predict the emergence and spread of infectious diseases and distribution across various spatial and temporal scales. As a self-reported volunteered information platform and useful surveillance tool, social media feeds outperform those from official or government outlets in timeliness. They can also aid in gaining insights into the opinions and perceptions of the public.

12.3.2 Emergency Response

The use of massive computer-mediated communication in emergency response and disaster management has captured considerable interest from both the general public and decision makers. Social media enables fast interpersonal communication during crises through information dissemination, early warnings, environmental awareness, and public participation in disaster-affected areas, allowing for emergency workers to respond more speedily and capably (Hashimoto and Ohama 2014; Finch et al. 2016). As Yin et al. (2012) argue, "this growing use of social media during crises offers new information sources from which the right authorities can enhance emergency situation awareness. Survivors in the impacted areas can report on-the-ground information about what they are seeing, hearing, and experiencing during natural disasters. People from surrounding areas can provide nearly real-time observations about disaster scenes, such as aerial images and photos." Moreover, since social media users can access information posted by official agencies through following their accounts, organizations and agencies can leverage social media as a platform to post authoritative situational announcements and communicate with the public in emergency situations and to potentially retrieve and verify on-the-ground information using the public as the information source (Wang et al. 2016). Palen et al. (2009) examined the consequences of digital communication and information sharing on emergency response in the context of the Virginia Tech massacre. Chen et al. (2016) proposed real-time geo-tagged tweet collection and recording in a distributed geodatabase as well as real-time data redistribution using a Web GIS application. This system was applied to a hypothetical mass evacuation using tweets from Hurricane Joaquin in 2015.

12.3.3 Decision Making

As a new kind of user-generated geospatial information, social media data could be invaluable to political agenda-setting that needs to be aware of location-based topic distribution. For example, the data could help political strategists analyze the tweets of residents or voters in a given geographical area. Politicians can gauge people's reactions by monitoring the communication among Twitter accounts regarding policy issues. Ye et al. (2017) employed voting tweets regarding a water bond in California to highlight place-based situational awareness. Convention and visitors' bureaus may focus on ‘hot button’ issues in certain places within their cities or regions. These data could provide operational indicators about places that are most visited or preferred by visitors, which can inform the marketing strategies relevant to these locations. Local governments could analyze social media messages to determine whether a proposed construction project would be favored by the public or if other proposed projects would be perceived positively by their constituents. Ye et al. (2018a, b) examined how the Multilevel Model of Meme Diffusion (M3D) captures the debates regarding death penalty abolishment across space. At the intracity scale, Liu et al. (2018a, b) assessed the utility efficiency of subway stations in a Chinese city by matching the capacity of train services and the travel needs using social media data. Deng et al. (2018) analyzed how geotagged tweets are associated with hourly electric consumption at the building level, given the assumption that tweeting behavior is highly related to human activities.

12.3.4 Social Equity Promotion

Most social media platforms such as Twitter, Facebook, or Instagram are designed for the general public; few are dedicated to specific groups (e.g., LGBTQ, photographers, natural disaster victims, etc.). An in-depth analysis and visualization of the specific groups can promote social equity among different groups. Social awareness of where they are is the first and foremost step in enabling local residents and governments to recognize the necessity to treat these underrepresented populations equally. For example, Jack’d, a dedicated gay social networking app, enables its users to communicate online with those who are physically nearby. Through collecting online locational information from Jack’d, a 3D distribution of the gay community in Beijing were visualized (Zhao et al. 2017). By overlapping this distribution with landmarks such as major roads, university campuses, shopping malls and gay-friendly places (e.g., gay bars, gay saunas, gay-friendly gyms, gay-friendly parks and public restrooms attracting gay activities, etc.), the characteristics of this underrepresented group’s distribution can be revealed. Gay people in Beijing primarily concentrate in the northwestern and eastern parts of the city. The northwestern area is the center for higher education, with several famous universities. In the eastern area of Beijing, the area from Sanlitun to Worker’s stadium is acknowledged as a recreation center for LGBT people. To the south, a few famous gay-friendly residential communities are surrounded by gay saunas; to the east, there are several high-end residential communities and shopping malls in the Guomao and Sihui subdistricts. This 3D distribution reveals a hot spot of gay activities in the Tongzhou district. This may result from the relatively low house rent and convenient accessibility to Chaoyang and other local urban centers for hangouts. Through this 3D distribution of the gay community’s electronic footprint, the local public health agencies can provide corresponding services for the gay community and organize more targeted activities as an effective means to promote social equity.

12.4 Challenges: Fake Electronic Footprints

In addition to those obvious opportunities in human dynamics prediction, challenges inherently in social media are often ignored. As Chun et al. (2019) argue, “uncertainty and context pose fundamental challenges in GIScience and geographic research. Geospatial data are imbued with errors (e.g., measurement and sampling) and various types of uncertainty that often obfuscate any understanding of the effects of contextual or environmental influences on human behaviors and experiences.” Although social media has been touted as a platform to authentically present human trajectories and their mobilities, rumors, spoofings and privacy concerns, not limited to the physical world, are also exist on Digital Earth. In this sense, We cannot immediately treat social media messages as accurate and credible without considering the above-mentioned issues.

12.4.1 Rumors

The unmoderated nature of social media user’s posting behavior might lead to the accumulation of invalidated and unverified information and news involving speculation and uncertainty regarding social events (Ye et al. 2018a, b). Jones et al. (2017) found those who relying on social media for updates of a campus lockdown tend to suffer from greater distress due to their increased exposure to conflicting content in social media channels. Rumors are considered messages or forms of interaction among people about certain events that may not be true. As a nonprofessional medium, social media platforms can spread rumors. However, some information from reliable sources can minimize rumor propagation, lowering the level of anxiety in the virtual community. Zubiaga et al. (2018) noted that the openness of social media platforms also enables the study of user behavior on sharing and discussing both long-standing and newly emerging rumors based on natural language processing and data mining methods, especially for four components: rumor detection, rumor tracking, rumor stance classification, and rumor veracity classification.

12.4.2 Location Spoofing

Location spoofing is a deliberate geographic practice to disguise one’s actual location with inconsistent locational information (Zhao and Sui 2017). It facilitates the spoofer to virtually travel to places of interest for various purposes. For smartphones, the spoofing mechanism can be divided into three steps, (1) blocking the positioning service of a smartphone to acquire the actual locational information, (2) generating inconsistent locational information, and (3) transmitting it to an operating LBSM app (e.g., Twitter, Facebook, Pokémon Go, etc.) on a smartphone (Zhao and Zhang

2018). As a result, the LBSM app mistakes the fake location as where the operating smartphone really is. Specifically, the positioning service relies on a hybrid approach that integrates three major positioning techniques: built-in GPS, surrounding WiFi network triangulation, and cellular tower network triangulation. For these three techniques, the more accurate, the higher priority in deciding the final result. In practice, the fundamental function of location spoofing is to downgrade the accuracy of the positioning technique or totally block the positioning function. There are three common location spoofing techniques, in terms of falsifying the MAC addresses of surrounding WiFi routers, spoofing GPS signals in the environment, and mocking in-transit locational information. The last method is predominantly adopted by dedicated mobile android apps for location spoofing. Such apps enable users to virtually visit a place other than the actual location. An example is presented below to clarify this.

In reaction to the 2009 presidential election in Iran, the government of Iran regularly monitors all activities on social networks (Ansari 2012). During the campaign, social network sites were suddenly blocked, and online political activity became the target of harsh criticism and reprisals from the government. To prevent this surveillance and protect online protestors, many internationally based Green Movement supporters spread disinformation over Twitter to mislead local police. Foreign supporters who were not in Iran decided to set their online locations to Tehran to protect those who were tweeting from Tehran. This strategy may have helped some Iranian opposition leaders avoid persecution, but also made it impossible to understand the real impacts of Twitter on the protest.

12.4.3 Privacy Abuse

When users share content and their data on social media, there is a risk that such content and data are collected and exploited in a way that is not expected by the users. This poses a serious challenge in terms of privacy for user data and calls for the responsibility of the network administrators, researchers and users to preserve privacy in social networks. Two broad classes of privacy issues in social networks—user-user privacy and user-third party privacy—are discussed below.

In social media, one user might share content about another user or party. Although this mechanism helps spread the content over the networks efficiently, it inherently presents a tremendous risk for privacy violation. For instance, your friends might share a picture you posted, showing you were in a restaurant with another friend. The picture sharing might be done without your consent and accidentally reveal your location, private information that you do not want to share beyond your friend list. To prevent such privacy breaches, social media administrators have implemented mechanisms for users to make complaints and request that the content be removed from the networks. However, before the content can be reviewed and revoked, it might have caused some detrimental consequences for the users. It would be more effective if such content dissemination was validated at the very beginning. Addressing the user-user privacy issue requires collaboration among scientists from different disciplines, including computer scientists, GIScientists, and psychologists. For example, Kekulluoglu et al. (2017) studied a hybrid negotiation architecture with a reciprocity mechanism to mimic the social responsibility in reality, and a credit system was used to encourage agents/users to respect other's privacy in social media.

Regarding user-third party privacy, content and data generated by social media users might be collected by different third parties for various purposes, potentially causing serious data leaks and violating the privacy of users. A retailer might retrieve user profiles and posts to deliver appropriate ads to the users or an upstart voter-profiling company could exploit such information to characterize the personalities of users and influence their voting decisions (e.g., the recent Facebook privacy crisis and data leak with Cambridge Analytica on American elections described in Rosenberg et al. (2018)). Another example is researchers who query user data to infer various user characteristics (e.g., depression, drug abuse) (Choudhury et al. 2013). While such inferences can provide valuable insights into different social problems and support monitoring systems for social issues, the leaks of such inferred information for specific users can cause biases and affect the users' ability to participate in social activities (e.g., jobs, school admission). Consequently, it is important to develop technological strategies to ensure privacy in user data-related activities in social media. The Future of Privacy Forum and DataGuidance (2018) delivered the report "Comparing privacy laws: GDPR v. CCPA." This report compares the European Union's General Data Protection Regulation (GDPR) effective on May 25, 2018, and the California Consumer Privacy Act of 2018 (CCPA) scheduled to be in effect on January 1, 2020. Both laws would also fundamentally influence social media platforms in collecting/sharing/employing users' data online and offline.

12.5 From Awareness to Action

A close scrutiny of the opportunities and challenges would raise our awareness of the potential capacity of social media in understanding human dynamics. As Yang et al. (2016, p. 61) argued, "the convergence of social media and GIS provides an opportunity to reconcile space-based GIS and place-based social media." Driven by this awareness, GIScientists should take actions to model the geographies of social media, propose innovative approaches to location spoofing screening and connect the virtual world in social media with the real word to better explain social media phenomena.

12.5.1 Modeling the Geographies of Social Media

Tracking and predicting the diffusion of social media information from a neighborhood to a global scale raises a series of questions such as where and when certain topics will be discussed and become popular. Sui and Goodchild (2011) suggested two hypotheses to test the nature of social media message diffusion such as geo-tagged hashtags spread through Twitter. The spatial influence model states that the spatially nearby locations tend to be impacted in the near future, and the community affinity influence model asserts that such dissemination would occur between functionally connected places. However, the reality is usually a combination of these two models. Such predictions will be useful for policymakers to estimate the spatial and functional influence of economic downturns facilitated by supply-chain networks. The community affinities are expected to enhance the prediction power of purely spatial models.

12.5.2 Detecting Location Spoofing Through Geographic Knowledge

If we examine location spoofing from the traditional standard of scientific data, it is highly unlikely that such "fake" information is generated by environmental uncertainties, measurement uncertainties, or limited knowledge about measurement (Zhang and Goodchild 2002). Today, location spoofing cannot simply be treated as fake data, as these data are associated with complicated generative motivations from different stakeholders, governments, local business or average social media users. To identify location spoofing, it is necessary to determine the motivations why the author produces that location, and then judge whether it is spoofed or not.

Therefore, we must seek appropriate solutions to the positioning inconsistency and the motivations for spoofing. Usually, self-reporting (e.g., survey, questionnaire) or observations can qualitatively collect and interpret human motivations that trigger the generation of positional inconsistency. However, in practice, it is difficult to measure the real motivation: admittedly, the survey or questionnaire participants might not report their true intentions of location spoofing due to the fear of being recognized as location spoofers or rumormongers.

The positioning inconsistency in spoofing can be quantitatively detected. Theoretically, any spoofing detection is supposed to unveil a certain underlying positioning inconsistency. As Goodchild (2013) indicated, a geospatial accuracy model interprets how a world is constructed geographically. In this sense, spoofing detection is meant to detect scenarios that do not follow the way in which the world is geographically constructed. One crucial theoretical framework to build up the geographic truth is Hägerstrand's Time Geography (1970). This analytical framework conceptualizes the trajectory of each individual as a life path, which is restricted by several predefined human behavioral constraints in space and time. Meanwhile, a series of analytical tools to measure human dynamics are provided by Time Geography, such as space-time path, prism, and cube. Zhao and Sui (2017) provided a Bayesian time geographic estimation approach to determine the places that an examined user is unlikely to appear. Time-geographic density estimation (TGDE) was used to model the human appearance in a region over time. TGDE can convert trajectories (e.g., a time sequence of historical geo-tags from an individual) to a visiting probability distribution of spatial positions over time. This model can effectively convey the behavioral constraints and describe where and when an individual is more likely to visit. A location with a lower probability value is more likely to be spoofed. Moreover, with the rise of deep learning such as long short-term memory, LSTM (Greff et al. 2017), it is worth investigating application of deep learning techniques in detecting fake location information. For example, given a set of sequenced historical geo-tags of an individual, LSTM can be used to model the sequential information and build deep learning-based classification methods.

12.5.3 Connecting Social Media with the Real World

In social media, people share their thoughts and emotions about events in the real world. Such events might be explicitly mentioned or implicitly referred to in their posts. For instance, some social media posts might explicitly include a link to a news article they would like to discuss whereas other posts might express the users' attitude on some events without citing those events. In many inference problems for social media data (e.g., sentiment analysis, opinion mining), it is crucial to determine the corresponding realistic events to fully understand and explain the trends and phenomena in social media (i.e., connecting social media with the real world). One example is that social media posts concerning implicit events where the absence of the implied events would clearly impede accurate analysis of the posts.

To model the real world, we can resort to public information resources such as news articles and public knowledge resources such as Wikipedia and Freebase (Bollacker et al. 2008). These resources cover a wide range of events across various aspects of life. They are also updated with new events in almost real time due to the recent advances in publication technologies, promoting these public information resources as a digital counterpart of the real world. Consequently, we can connect social media data with the real word via the reflected world of public information resources. The major technical challenges to accomplish this connection involve the ability to autonomously extract events from those public resources (e.g., news articles) and the capacity to link the information in social media to the appropriate detected events. Such challenges would require a deep analysis of the semantics of the information presented in both (e.g., the posts in social media and the events in public resources) to identify the events and connections with high accuracy. Fortunately, deep semantic understanding of such information is being actively investigated in artificial intelligence research, including natural language processing, computer vision, graph modeling and machine learning. For instance, many recent studies have shown that events in news articles can be effectively curated using deep learning techniques, a branch of machine learning that is capable of automatically inducing the underlying representations for data to achieve high extraction performance (Nguyen et al. 2016; Nguyen and Grishman 2018; Nguyen and Nguyen 2019). As these event extraction techniques can also recognize the time and locations at which the events occur, they can be beneficial for GIScientists in geographical research of populations on social media and the real world. In addition, deep learning might also present effective solutions for the problem of linking social media data with realistic events due to its recently demonstrated capacity for embedding and representation learning for various problems. Once converged, such advances in these fields of computer science might eventually offer an opportunity to connect the virtual world and real world by solving the aforementioned technical challenges.

Finally, the realistic events from public information resources enable novel semantic-based solutions to combat the problems of rumors or fake news in social media. An important property of the public resources discussed in this section is that they generally capture trustful information/events, as such information is verified by the media administrators for accuracy and correctness. This is one reason why news articles are usually slower than social media in presenting the information to the public. Consequently, if the social media information can be accurately linked and compared with the information/events in the trustful information sources, novel detection and tracking techniques can be proposed to prevent rumors and fact-check the information spread over social media. Artificial intelligence research can provide the fundamental technologies to tackle these problems, as demonstrated in recent research in natural language processing and deep learning (i.e., Yin and Roth 2018).

12.6 Conclusion

As a crucial platform for human dynamics and activities, social media content can be mined in multiple approaches to determine how individuals connect and share information as well as purposefully move across scales and resolutions (Croitoru et al. 2013; Miller et al. 2019). When social media activities are attached with locational information, these online human activities can generate tremendous electronic footprints on Digital Earth. Especially when merging with other digital overlays of authoritative data through multisource data fusion, such as land use, urban planning, and natural resources data, powerful interoperation and prediction that require both electronic footprints and digital overlays on Digital Earth become feasible with the optimal weights for combination (De Albuquerque et al. 2015; Lin et al. 2019). These digital overlays serve as the socioenvironmental context within which the geosocial media dynamics and events occur and evolve, calling for scientific cross-fertilization of many separate domains toward an integrated science of human dynamics.

In this chapter, we introduce the opportunities and challenges that human dynamics-centered social media bring to Digital Earth. We review the information diffusion of social media, the multifaced implications of social media, and some real-world cases. Social media will facilitate the prediction of human dynamics in a wide spectrum of aspects, including public health, emergency response, decision making and social equity promotion. Social media will also bring unintended challenges for Digital Earth, such as rumors and fake location spoofing. Considering the multifaceted implications, this chapter calls for GIScientists to raise their awareness of the complex impacts of social media and urges them to model the geographies of social media as well as filter fake locations through geographic knowledge, targeting a more robust geosocial knowledge discovery. Social media will continue to evolve, along with the development of human society. Social media has become a crucial part of human activities on Digital Earth. Any effort that ignores the importance of social media will bring the effort into question. Therefore, the study of social media provides new data sources and data collection methods about real-world activities and happenings, and social media help us in profoundly understanding ourselves as a unique species living both on the Earth and in Digital Earth.

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Xinyue Ye is an Associate Professor in the College of Computing at New Jersey Institute of Technology where he directs Urban Informatics & Spatial Computing lab. He develops and implements new methods on spatiotemporal-social network analysis/modelling/simulation for different application domains such as economic development, disaster response, land use, public health, and urban crime.

Bo Zhao is an Assistant Professor in the Department of Geography at University of Washington. His research interests are on the social implications of geospatial technologies, the study of different spoofing phenomena in geography towards a post-truth reflection on the value of geospatial technologies, the geovisualization and geo-narrative of the coupled human and natural system.

Thien Huu Nguyen is an Assistant Professor in the Department of Computer and Information Science at University of Oregon. His research explores mechanisms to understand human languages for computers so that computers can perform cognitive language-related tasks for us.

Shaohua Wang is an Assistant Professor in the College of Computing at New Jersey Institute of Technology where he directs Software Engineering lab. His research spans the study of software engineering from system, empirical, and machine learning perspectives.

Part II
Digital Earth for Multi-domain Applications

Chapter 13
Digital Earth for Sustainable Development Goals

Graciela Metternicht, Norman Mueller and Richard Lucas

Abstract Sustainable development is nothing new, but it has proven notoriously difficult to implement in practice. The 2030 Agenda for Sustainable Development, with 17 goals, 169 targets and 232 associated indicators, was approved at the 2015 UN General Assembly and addresses the economic, social and environmental pillars of development, aspiring to attain by 2030 a sustainable future that balances equitable prosperity within planetary boundaries. While the goals are universal (i.e., applicable to both developing and developed countries), it is left to individual countries to establish national Sustainable Development Goal (SDG) targets according to their own priorities and level of ambition in terms of the scale and pace of transformation aspired to.

Keywords Sustainable development goals · Digital Earth · Earth Observation · Big Earth data · Indicators · Land cover classification

13.1 Fundamentals of Digital Earth for the Sustainable Development Goals

The Digital Earth (DE) exists in parallel to the physical Earth along with some translating elements between them (Sudmanns et al. 2019). Chapter 1 describes the origin, evolution and main elements of Digital Earth, and the links between Digital Earth, Big Data (Chap. 9) and big Earth data. Guo (2017) argues that, from the perspective of big data, big Earth data inherits big data's 'Vs' (volume, velocity and

G. Metternicht (✉)
School of Biological, Earth and Environmental Sciences, The University of New South Wales, High Street, Kensington, NSW 2052, Australia
e-mail: g.metternicht@unsw.edu.au

N. Mueller
Geoscience Australia/Digital Earth Australia (DEA), GPO Box 378, Canberra, ACT 2601, Australia

R. Lucas
Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, Ceredigion, Wales SY233DB, UK

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variety) and, in this context, DE can be considered to be big Earth data. Furthermore, as big Earth data research focuses on synthesis of systematic observations of the Earth, as well as data-intensive methods for studying Earth system models, based on the premise of increased knowledge discovery (Chap. 1), Digital Earth can support countries in their implementation of the 2030 Agenda for Sustainable Development.

Through analysis of recent literature and a case study, this chapter collects and presents evidence of the potential and limitations of Digital Earth for systematic generation of information and knowledge for use in measuring progress towards the Sustainable Development Goals (SDGs). We frame the analysis and discussion around priorities for implementation (ICSU, ISSU 2015), including:

(a) the design of SDG indicator metrics at national levels and how Digital Earth, through the Analysis Ready Data (ARD) concept, can contribute to that end
(b) harmonized national metrics for SDG implementation, including for baseline determination and target setting
(c) setting up monitoring platforms for tracking progress towards the SDGs
(d) knowledge needs for assessing implementation of actions and strategies towards achieving set SDG targets
(e) governance and institutional arrangements, including multi-stakeholder participation.

The remainder of the chapter is structured as follows. Section 13.2 identifies the information needs of countries for the implementation of the SDGs, including for the SDG Global Indicator Framework (GIF). Section 13.3 summarizes the findings of recent research and practice on the use of Digital Earth (including Earth Observation[1] and social sensing) in support of the SDGs. Section 13.4 presents a national case study of multi-stakeholder engagement in the operationalization of the Indicator Framework of the Sustainable Development Goals with Earth Observations. The chapter closes (Sect. 13.5) with an outlook on the prospects of Digital Earth and big Earth Data in relation to the SDGs.

13.2 Information and Knowledge Relevant to National Implementation of the SDGs

The SDGs provide a coherent, evidence-based framework for development planning and programming at a national level (Allen et al. 2017a). The goals and targets essentially set the desired destination for development through to 2030 and provide a framework for monitoring progress. This section introduces the metrics agreed for monitoring and reporting of the SDGs, and broadly identifies data and information requirements for their implementation.

[1]The Earth Observation data in this chapter refers to the definition provided by Nativi et al. (2019).

13.2.1 How the SDGs Are Monitored and Reported

The Global Indicator Framework (GIF) was established in March 2016 to monitor progress towards achieving the SDGs (UN Statistical Commission 2016). The SDG indicators have been grouped into three different tiers according to the level of data availability and methodological development. Of the 232 SDG indicators that make up the GIF, as of March 2019, 101 are classified as being Tier I. This means that the indicator is conceptually clear, has an internationally established methodology and standards, and the data are regularly compiled for at least 50% of participating countries. The remaining indicators are Tier II (94 indicators), which are conceptually clear but for which the data are not regularly produced by participating countries, or Tier III (34 indicators), for which no internationally established methodology or standards are yet available. Six indicators are determined as having several tiers (Inter-Agency and Expert Group on Sustainable Development Goals 2019). Hence, three years after the adoption of the GIF, less than half (44%) of the SDG indicators can be confidently populated.

It is worth noting that the SDG indicators are essentially **performance metrics** and, as such, are reported regularly at *national levels* through National Voluntary Reports (NVRs) (UNGA 2015, paras. 79 and 84), and annually at the *global level*. The latter is undertaken by the UN Secretary General to inform the High-Level Political Forum based on a selection of indicators from the GIF for which data are available, as mandated by the General Assembly (UNGA 2015, para. 83). For Tier I and II indicators, the availability of data at national levels may not necessarily align with the global tier classification, and countries can create their own tier classification for implementation.

13.2.2 Information Needs for Implementation of the SDGs

Recent research (Allen et al. 2018, 2019) has identified challenges for implementing the SDGs that, in turn, influence information and knowledge needs.

(a) The comprehensiveness of scope makes prioritization essential.
(b) The goals are integrated, with very complex feedback and dynamics. This is a significant change from prior narrow, linear approaches to development.
(c) The SDG targets have complex trade-offs and synergies, and conflict can emerge from the interactions between targets and goals (Lusseau and Mancini 2019; Nilsson et al. 2016; Le Blanc 2015; Allen et al. 2019).
(d) Currently, there is a weak conceptual understanding of these interlinkages, which limits the ability to respond with coherent policy and management across sectors (Allen et al. 2018; Spangenberg 2017).

Challenges related to aspects of target-setting are that the system of SDGs is not coherent, but rather a network of interlinked targets and a reflection of the political mapping of development priorities rather than a reflection of how the Earth System works (Le Blanc 2015). Furthermore, the SDGs do not reflect the cause–effect relationships that are needed to understand how the achievement of one target could impact on the other targets. Hence, national implementation of the SDGs requires more than information on performance metrics. For example, timely data in support of policy formulation and targeted interventions may be of much greater importance for countries aiming to advance the implementation of the SDGs according to their national circumstances than simply providing a metric around an agreed global indicator. Furthermore, implementation of the SDGs at national levels also requires determining a baseline for 2015, deciding on targets for 2030, as well as a system for tracking the progress towards the set targets, monitoring the performance of decisions (actions, policies and strategies) and reporting advances using the GIF.

Building an evidence-based framework for national implementation, monitoring and reporting of the SDGs requires government agencies (including National Statistics Offices) to address the what, why and how of data and information provision (Fig. 13.1).

(a) What is happening requires baseline assessment of indicators related to SDG targets, identifying priorities (e.g., what SDG targets or goals a country is lagging behind) and the identification of data and information gaps needed for such assessment, as summarized in Allen et al. (2017b).
(b) Why it is happening (e.g. drivers of and pressures leading to (un)sustainable development) relates to the need for systems analysis of interlinkages between SDG targets, understanding of cause–effect relationships, feedbacks and dynamics, and the identification of leverage points for actions and strategies to accomplish the transformational changes that the SDGs aim for.
(c) How to accomplish changes, demands that countries answering the above questions also understand how data and information are to be obtained and integrated.

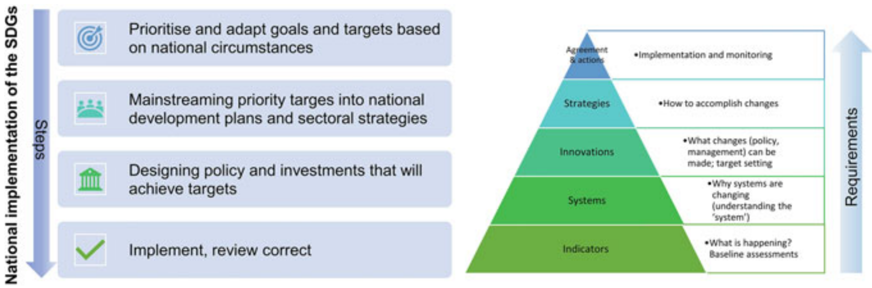

Fig. 13.1 National implementation of the SDGs requires evidence-based approaches for monitoring and reporting. As implementation will largely rely upon national action, government actions, through their policy, planning, regulatory and expenditure functions—i.e. the 'plan, do, check, act' planning cycle are central to the delivery

13.3 State of the Art for the SDGs in DE

Whether 3Vs, 5Vs (including volatility and veracity, as suggested by Hammer et al. 2017) or 6Vs (including volatility, veracity and value: Fig. 13.2), big data may offer new cost-effective or efficient ways of compiling indicators, improving timeliness, and compiling linkable datasets, and also open the way for cross-cutting analyses that may help with better understanding of the causation and identification of relevant and coherent policy interventions (see Fig. 13.1).

When adopting the SDGs, the United Nations (UN) Assembly recognized the contribution that could be made by Earth Observation (EO) and geospatial information (i.e., big Earth data) in supporting and tracking progress towards the SDGs (UNGA 2015, para. 76). Analysis and interpretation of big Earth data, including Earth Observation, have much to offer the SDGs and other multi-lateral environmental agreements (Sudmanns et al. 2019). However, MacFeely (2019) makes a case for the challenges that big data face (legal, technical and ethical) concerning their use in compiling SDG indicators. National statistical offices, government agencies and UN agencies, which are the custodians of specific SDGs tasked with implementing the

Fig. 13.2 The 6Vs of big data for official statistics. Modified from Hammer et al. (2017)

GIF, face concerns about whether big data are representative and stable enough to be used consistently for compiling the SDG indicators and also their operationalization. For example, in the Big Data Project Inventory compiled by the UN Global Working Group on Big Data, 34 national statistical offices from around the world registered 109 separate big data projects and their potential contribution to the SDG implementation. Most data projects focus on goals 3, 8, 11 and, with a lesser emphasis, goals 2, 15 and 16. Though promising, most projects have not yet moved beyond the planning stage, and others are dealing with legal issues related to data protection (MacFeely 2019). Specific to the EO community are challenges for consistently and systematically turning satellite and other remote sensing data into valuable global information layers in support of effective implementation of the SDGs.

In late 2018, the Committee on Earth Observation Satellites (CEOS) compiled a report on the potential of satellite EO for the SDGs (Paganini et al. 2018), and their findings suggest that EO data has a role to play in quantifying around 40 of the 169 Targets, and around 30 of the 232 Indicators. The CEOS argues that there is an unrealized potential for EO data to contribute to the Indicator Framework, with only a third of its data being routinely exploited today. This is based on the premise that only 12 out of the 30 indicators identified are listed as Tier I.

Moreover, the report points to the importance of EO in relation to Goal 6 (Clean water and sanitation), Goal 11 (Sustainable cities), Goal 14 (Life below water), and Goal 15 (Life on land). Most of the perceived contribution of EO towards these goals has been around the provision of information in relation to the mapping of land cover, land productivity, above ground biomass, soil moisture content, and water extent or quality characteristics, as well as air quality and pollution parameters (Table 13.1). A 2016 compilation of the Group on Earth Observation (GEO) appraised the potential of EO and geospatial information for informing all SDGs, although the document was vague in terms of specific contributions to SDG targets and indicators. A subsequent joint GEO-CEOS report (CEOS-GEO EO4SDG 2017) further investigated the potential of big Earth Data (EO and geo-information) for supporting countries in the implementation of the 2030 Agenda for Sustainable Development, arguing that it could contribute to the implementation of 29 indicators (through direct measurement or indirect support) and 71 targets of 16 goals (but not all indicators of these targets). By referencing national-scale satellite datasets (e.g. Terra/Aqua MODIS, Landsat, and Sentinel), Metternicht et al. (2018) concluded that EO satellite-derived information tends to have a more indirect contribution to the SDG targets and indicators (i.e. use as proxies). Using data available from the Australian Terrestrial Ecosystem Research Network platform (TERN), the study ascertained that EO-derived information was most relevant to Goal targets 15, 14, 13, 11, 6, 3, 2 and 1, and, to a lesser extent, Goal 9 (Fig. 13.3).

The potential of EO to support the SDG indicator framework appears in the biosphere cluster (Fig. 13.4) and to a lesser the SDG indicators related to society and the economy. This concurs with the argument of Plag and Jules-Plag (2019) that very few indicators can currently be quantified based on information extracted from EO alone because of the strong focus of the SDGs on human needs and the bias toward social and economic information and the built environment. Traditional

Table 13.1 Summary of research that shows the contribution of big Earth Data towards the SDGs

SDG	Supported targets									Supported indicators				
1	1.4	1.5								1.4.2				
2	2.3	2.4	2.c							2.4.1				
3	3.3	3.4	3.9	3.d						3.9.1				
4														
5	5.a									5.a.1				
6	6.1	6.3	6.4	6.5	6.6	6.a	6.b			6.3.1	6.3.2	6.4.2	6.5.1	
7	7.2	7.3	7.a	7.b						7.1.1				
8	8.4													

(continued)

Table 13.1 (continued)

SDG	Supported targets									Supported indicators				
9	9.1	9.2	9.3	9.4	9.5	9.a				9.1.1	9.4.1			
10	10.6	10.7	10.a											
11	11.1	11.3	11.4	11.5	11.6	11.7	11.b	11.c		11.3.1	11.6.2	11.7.1		
12	12.2	12.4	12.8	12.a	12.b					12.1.1				
13	13.1	13.2	13.3	13.b						13.1.1				
14	14.1	14.2	14.3	14.4	14.6	14.7	14.1			14.3.1	14.4.1	14.5.1		
15	15.1	15.2	15.3	15.4	15.5	15.7	15.8	15.9		15.1.1	15.2.1	15.3.1	15.4.1	15.4.2
16	16.8													
17	17.2	17.3	17.6	17.7	17.8	17.9	17.16	17.17	17.18	17.6.1	17.18.1			

From Paganini et al. (2018)

Product	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Forest Cover						T6.6								T14.1	T15.1, T15.3, T15.2		
Woody extent *															T15.1,T15.4, T15.8		
Fractional cover	T1.5/1.5.4		T3.9 / 3.d			T6.6					T11.3, T11.7		T13.1, T13.3	T14.1	T15.3, T15.1, T15.2		
Presistent Green Vegetation Fraction						T6.6								T14.1	T15.3, T15.1, T15.2		
Foliage Projective Cover						T6.6								T14.1	T15.3, T15.1, T15.2		
Seasonal Fractional Cover			T3.9 / 3.d											T14.1	T15.1,T15.3,T 15.4,T15.5		
Seasonal Ground Cover														T14.1	T15.1, T15.2, T15.3, T15.4		
Seasonal Persistent Green Cover			T3.9 / 3.d											T14.1	T15.2		
Biomass		T2.3, T2.4	T3d			T6.6								T14.1	T15.1,T15.4, T15.8		
Vegetation height and structure															T15.1,T15.4, T15.8		
Phenology		T2.4, T2a	T3d												T15.1,T15.2		
Leaf Area Index			T3d			T6.6					T11.3, T11.7		T13.1, T13.3		T15.1,T15.2, T15.3,15.5		
Gross Primary Productivity	T1.5/1.5.4	T2.3, T2.4	T3d										T13.1, T13.3		T15.3, T15.1, T15.2		
fPAR			T3d			T6.6									T15.1,T15.2, T15.3,15.5		
Active Crop Mapping*		T2.3, T2.4, T2.a											T13.1, T13.3				
Grassland curing			T3d												T15.1		
Water Prevalence	T1.5/1.5.4					T6.4, T6.6							T13.1, T13.3				
Land surface temperature	T1.5/1.5.4										T11.7			T14.1			
Thermal Anomalies	T1.5/1.5.4												T13.1, T13.3				
Burnt area & day of burn	T1.5/1.5.4												T13.1, T13.3				
NRT Burnt Area	T1.5/1.5.4												T13.1, T13.3				
Fire patchniess (sub-pixel)	T1.5/1.5.4												T13.1, T13.3				
Annual Fire Scars	T1.5/1.5.4												T13.1, T13.3				
Total Land Cover (Land Condition Index)			T3.9 / 3.d										T13.1, T13.3	T14.1, T14.2	T15.1, T15.3		
Dynamic Land Cover Map		T2.3, T2.4, T2a	T3d			T6.6			T9.1		T11.3, T11.7			T14.1, T14.2	T15.1, T15.3		
Ecosystem Disturbance Index	T6.6		T3d			T6.6									T15.1,T15.4,T 15.5,15.8,15. 9		
Surface Reflectance			T3d			T6.6								T14.1	T15.3,T15.1		
NDVI			T3d			T6.6					T11.3, T11.7		T13.1, T13.3		T15.1,T15.2, T15.3,15.5		
EVI			T3d			T6.6					T11.3, T11.7		T13.1, T13.3		T15.1,T15.2, T15.3,15.5		

TERN Landscape governance as good practice of 'means of implementation'

Fig. 13.3 SDG targets that TERN Auscover products contribute to are listed in the table; the table cells are color-coded according to whether the contribution is more direct (green) or more indirect (yellow) (Metternicht et al. 2018)

EO techniques are designed for extracting information on environmental variables, with only a few being related to the built environment and associated infrastructure (e.g., built-up areas and roads). Hence, there are limitations on the possibility of EO *alone* producing reliable metrics for SDG indicators (see Table 13.1); however, approaches underpinned by big Earth data do have some potential, as evidenced in recent research by Kussul et al. (2019), Foody et al. (2019), Freire et al. (2018), and Corbane et al. (2017). Specifically:

- meta-optimization of EO with external data-intensive infrastructure has led to improved mapping of built-up areas in support of the global human settlement layer (Corbane et al. 2017)
- national mapping of SDG indicators 15.1.1, 15.3.1 and 2.4.1 has been achieved through synergy of in situ and multi-resolution satellite data (Kussul et al. 2019)
- big Earth Data (global census data and satellite-derived built-up area maps) has enabled enhanced mapping of population distribution along coastlines (Freire et al. 2018)
- EO and machine learning have enabled mapping of sites associated with slavery, in support of SDG target 8.7 ("*take immediate and effective measures to eradicate forced labour, end modern slavery and human trafficking and secure the prohibition and elimination of the worst forms of child labour*") (Foody et al. 2019).

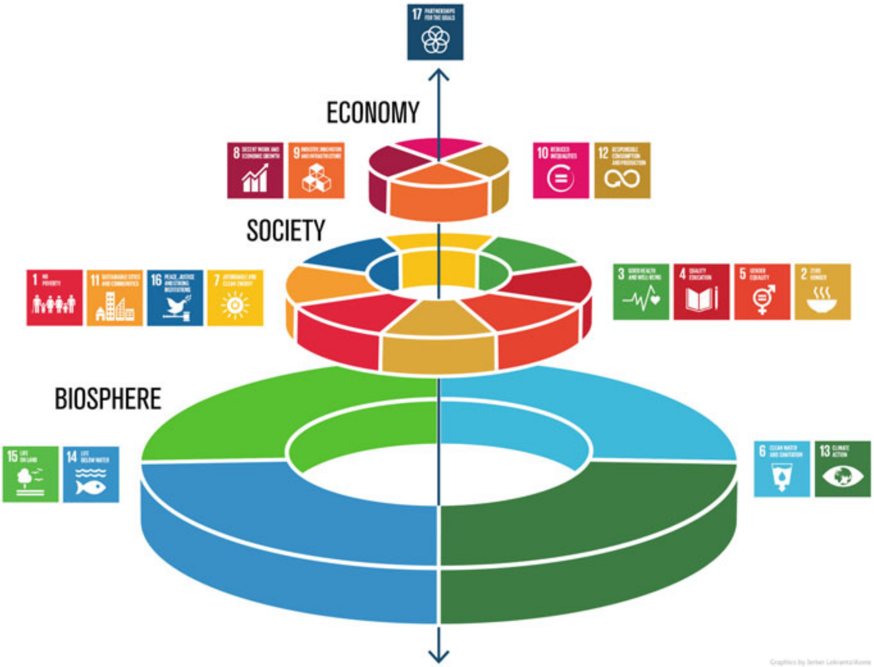

Fig. 13.4 Clustering of the SDGs that relate to the biosphere (earth life supporting system), society and economy. *Illustration* Azote for Stockholm Resilience Centre, Stockholm University

In summary, EO data does not directly deliver the SDG indicators agreed by the Inter-Agency and Expert Group (IAEG) on SDGs; rather, it provides a diversity of spatio-temporal information that can then be related to the indicator framework. For example, directly observed indicators can be specific biophysical aspects of entities (e.g., land cover status and type) that provide evidence for monitoring advances towards SDG targets. As an example, changes in land-cover states can be an indication of land improvement or land degradation in SDG target 15.3. Indirect cues derived from EO data can provide evidence for SDG domains related to human health, cities and infrastructure, ecosystem health and so on (Paganini et al. 2018; Sudmanns et al. 2019). Few studies, however, refer to specific SDG indicator metrics; many papers and reports highlight the potential of Earth Observation for targets and goals but fall short of being specific regarding the operationalization of Digital Earth for the SDG target or indicator.

For the full information potential of big EO data in support of the SDGs to be realized, approaches are needed that broaden the use of EO beyond specialized scientific communities and that support decision makers with the knowledge required by systematically analyzing all available observations by converting them into meaningful geophysical variables. Data Cubes (see Chap. 21) apply the concept of satellite ARD and are facilitating access to large spatio-temporal data (Giuliani et al. 2017). This enables the coupling of EO with other big data such as demographic, economic, climatic, or administrative data, which are needed to make indicators and analysis more relevant and targeted to the SDGs. Furthermore, some of the proposed SDG targets relate to the so-called 'means of implementation', namely technology transfer and capacity building (i.e. SDG17; SDG targets 13.1, 1.3.3 and 16.8). In this regard, Digital Earth and EO infrastructure, as currently offered by Australia's TERN Landscape initiative (TERN 2017) and other major international and national systems for big Earth data (e.g. Google Earth Engine, Amazon Web Services, Earth Server, Earth Observation Data Centre, Copernicus Data and Exploitation Platform-Deutschland, United States Geological Survey Earth Explorer, Swiss Data Cube, Digital Earth Australia, Chinese Academy of Sciences Earth, and GEO*Essential* of the Group on Earth Observations), could serve as 'methodological frameworks' and examples of good practice for cross-institutional governance models, thus indirectly contributing to progress towards these targets.

The case study presented hereafter is an example of how EO can be a promising complement to traditional national statistics. Digital Earth Australia (DEA) aligns with the current trends in EO of having open data policies and using cloud computing and data cubes for improving big Earth data integration and analysis, thereby strengthening environmental data and indicators (Dhu et al. 2017). In particular, this case shows how the analysis capabilities of DEA (see Chap. 21 for infrastructure) can be used to draw together and effectively link data from multiple domains in support of the implementation of the 2030 Agenda for Sustainable Development in Australia.

13.4 Case Study of Australia: Operationalizing the Indicator Framework of the SDGs Through DE and a Participatory Process

In July 2018, Australia produced its first Voluntary National Review (VNR) of the SDGs (Australian Government 2018). Australia's consideration of the SDG Indicators has been a whole-government exercise. The Australian Bureau of Statistics (ABS) undertook a data-mapping exercise for the SDGs, in conjunction with lead agencies, exploring both ABS and other government-held data sources to identify those germane to supporting monitoring and reporting on the SDGs. A Reporting Platform[2] was created to: (a) house identified Australian government datasets relevant to the development of the country's SDG indicator framework; (b) assist in identifying new datasets; and (c) refine the SDG indicators, particularly as the move from a Tier III to a Tier I or II occurs and where additional datasets may be needed. An inter-agency governance agreement assigned the responsibility for following up and completing additional data sets to individual agencies (particularly those that hold datasets relevant to the SDG indicator framework).

[2] https://www.sdgdata.gov.au/.

For the first VNR, a total of 118 indicators were reported online using data drawn from a national indicator dataset. For 57 indicators, potential data sources were identified. However, further analysis is needed to ensure the data are suitable for reporting and are comparable to the globally agreed methodology for each UN SDG indicator. 12 indicators were not reported either because the indicator was not relevant to Australia or because no suitable Australian government data source exists for the indicator. Another 57 were not considered because, at the time of reporting, a globally agreed methodology for these UN SDG indicators is lacking (i.e., Tier III). Therefore, Australia did not investigate potential data sources. In summary, the first Australian VNR took a narrative approach, addressing each of the SDGs, though no baseline was created. Targets were not specified and Australia had complete and relevant datasets for only half of the SDG indicators. The Australian government has acknowledged that EO technology can help progress towards the completion of datasets and, in tandem, inform decision-makers about performance against SDG targets and indicators (Australia Government 2018).

In this regard, EO-derived information could help in setting baselines against which SDG targets could be set and, in turn, measure progress against agreed goals—aspects that the first VNR did not tackle. Germane to this point is the DEA initiative led by Geoscience Australia, which has enabled the compilation, analysis and interpretation of decades of satellite sensor (largely Landsat) data into information and insights about Australia's terrestrial and marine ecosystems using ARD standards (Dhu et al. 2017; Lewis et al. 2016). Building on the DEA infrastructure (see Chap. 21), Geoscience Australia is leading an inter-institutional initiative to produce reliable, standardized, continental-scale maps of land cover and land-cover dynamics across Australia at 25 m spatial resolution using multi-scale time series of Landsat and Copernicus Sentinel datasets. This approach builds on the Earth Observation Data for Ecosystem Monitoring (EODESM; Lucas and Mitchell 2017), which is fully described in Lucas et al. (2019a) and which provides multi-scale and temporal land-cover and evidence-based change maps by integrating environmental variables retrieved from EO data and utilizing the framework of the Food and Agriculture Organisation (FAO) Land Cover Classification System (LCCS; Version 2, Di Gregorio 2016). The approach is based on the requirement for information about land cover and its change over time, as both are essential input metrics to several SDG targets (Fig. 13.3) and indicators (e.g. 6.6, 11.3.1, 15.2.1, 15.3.1). This information is also useful to other national and international reporting requirements on the state of the environment (e.g. United Nations Convention to Combat Desertification, Aichi Targets, and the Paris Agreement).

13.4.1 DEA to Map Land Cover and Dynamics Over Time

The DEA land cover product has been optimized for high-performance computing within the Open Data Cube (ODC) framework and is generating continental maps of land-cover datasets from environmental variables (thematic and continuous), with a focus on those that are generated at a national level within DEA's ODC environment (Lucas et al. 2019a) and for multiple points in time. These include the vegetation cover fraction of the Joint Remote Sensing Research Program (Gill et al. 2017), Water Observations from Space (WOfS) (Mueller et al. 2016), surface reflectance Median Absolute Deviation (MAD) (Roberts et al. 2018), and national mangrove distribution (Lymburner et al. 2019) (Fig. 13.5). Additional layers generated through DEA are also used (e.g., the InterTidal Elevation Model (ITEM) of Sagar et al. (2017). The mapping is undertaken at 25 m resolution and the initial focus has been on generating land-cover classifications according to the LCCS Level 3 taxonomy, which differentiates 8 classes relating to aquatic and terrestrial (semi) natural vegetation, cultivated and managed terrestrial and aquatic vegetation, artificial and natural (bare) surfaces, and natural and artificial water bodies (Fig. 13.5 and Table 13.2). More detailed classifications are being generated at what is termed Level 4 (e.g., vegetation canopy cover and height, and water hydroperiod), which are further described using

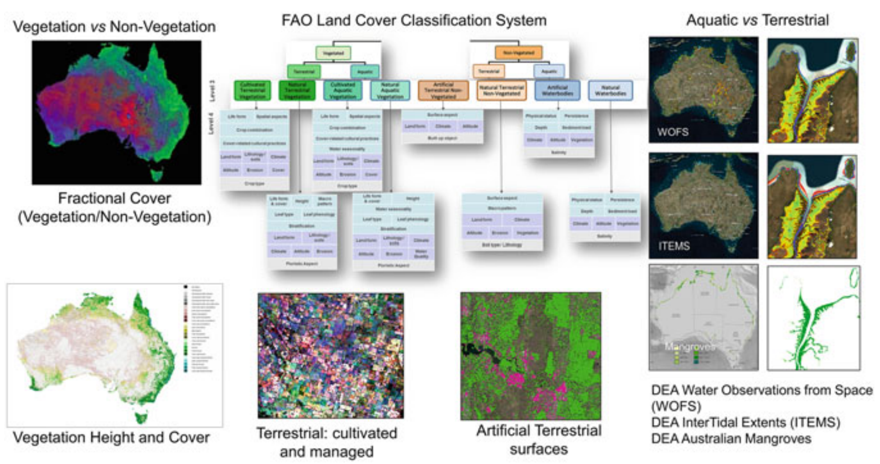

Fig. 13.5 Examples of data inputs for the application of the FAO LCCS level 3 within Digital Earth Australia used to produce standardized land cover maps at 25 m resolution

Table 13.2 Level 3 FAO land-cover classification (FAO LCCS) classes

Class name	Acronym
Cultivated terrestrial vegetation	CTV
Natural terrestrial vegetation	NTV
Cultivated aquatic vegetation	CAV
Natural aquatic vegetation	NAV
Artificial terrestrial non-vegetated	AS
Natural terrestrial non-vegetated	BS
Artificial waterbodies	AW
Natural waterbodies	NW

environmental variables that are external to the LCCS taxonomy (e.g., soil moisture and crop type), examples of which are given in Fig. 13.6.

The availability of multi-temporal land-cover layers enables change matrices (e.g. T_1–$T_{baseline}$) to be generated between land covers obtained for any two time-separated periods. When only the LCCS Level 3 is considered, the temporal comparison between two land-cover maps results in 64 different change categories (Fig. 13.7a).

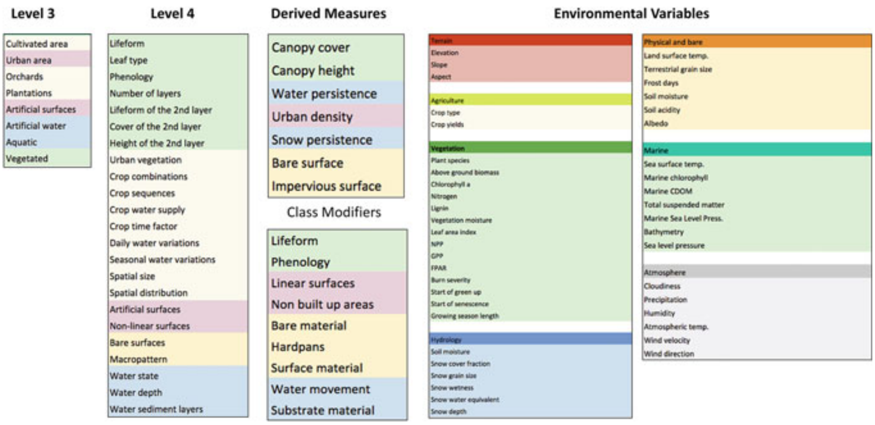

Fig. 13.6 Examples of environmental variables, class modifiers and derived measures required to implement the LCCS at level 3 and level 4 in Australia

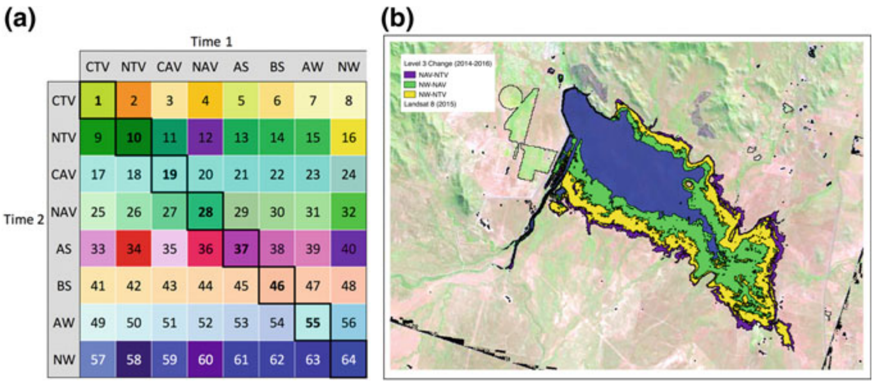

Fig. 13.7 **a** The 64 change categories generated through comparison of 2 LCCS Level 3 classifications (each with 8 classes) in the vicinity of Lake Ross (area of Townsville, Queensland) based on multi-temporal classification of Landsat images using LCCS level 3. The key changes are NAV-NTV: denoting changes from Natural Aquatic Vegetation (2014) to Natural Terrestrial Vegetation (2016); NW-NAV: Natural Waterbodies to Natural Aquatic Vegetation; and NW-NTV: Natural Waterbodies to Natural Terrestrial Vegetation. **b** The corresponding change map indicating a progressive loss of open water area, the retreat of aquatic (wet) vegetation and a transition to drier vegetation on the outer margins of the lake basin (Lucas et al. 2019a)

Diagonal cells represent areas where the land cover (e.g. natural/semi-natural terrestrial vegetation, natural water, artificial water, etc.) remains stable between the two time periods and unique codes can be assigned for the *From* → *To* changes in land cover. Figure 13.7b provides an example of a land-cover change matrix and map that result from applying FAO LCCS level 3 on an inland water ecosystem in the State of Queensland between two time periods.

One aspiration of DEA's land cover product is to better inform management and interventions in order to advance assessment and monitoring of progress towards the SDGs at national levels. In this regard, research is being undertaken to concurrently develop a change alert system (historically and when new data and data products become available) that can associate changes in states (i.e., environmental variables) with the causative mechanisms (i.e., human activities and climatic variability) and the impacts that such changes produce (e.g. defoliation, land clearing, and increases in built-up area). Such changes are based on evidence, and exploit a newly developed change taxonomy (Lucas et al. 2019b). Geoscience Australia is extending the idea to integrate, within DEA's land cover product, EODESM with the Drivers-Pressure-State-Impact-Response (DPSIR) framework (Lucas et al. 2019b; Metternicht et al. 2019). In doing so, links are—between economic and climate drivers and pressures of change and detailed information on states, state changes and environmental impacts (based on the change taxonomy). The drivers-pressure-state links can subsequently inform impacts on management and policy (from local to international l-levels). The ultimate ambition is to generate options for context-based policy and management responses related to the SDGs (Fig. 13.8). Through this approach, responsible

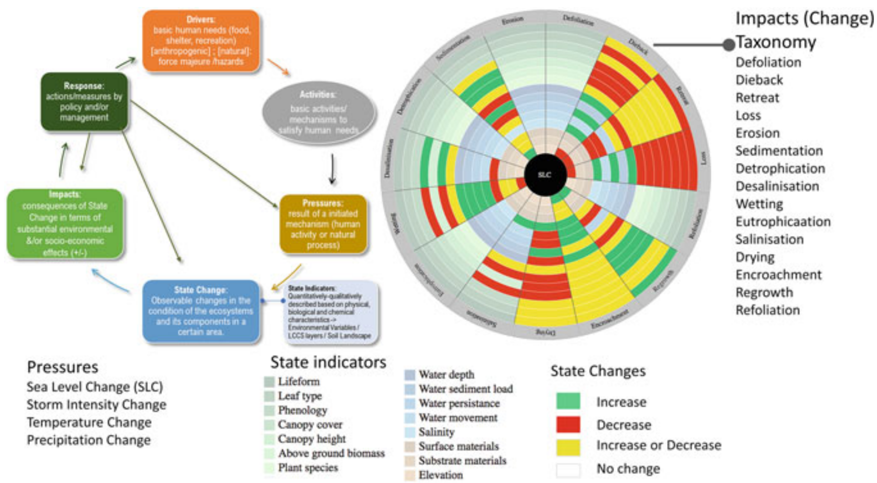

Fig. 13.8 Conceptual framework that links the DPSIR framework with the LCCS-derived land-cover maps within the DEA environment. Pressures (center of the wheel) are identified and state indicators derived from the LCCS comparison between T_0–T_1 provide an estimation of state change. Cumulative information on state change builds evidence on impacts (outer part of the wheel)

authorities can make informed and timely decisions on interventions (e.g. management decisions, new regulations).

As an illustration of the application of the integrated EODESM-DPSIR framework, Fig. 13.9a shows the impact of rising sea levels (between 1991 and 2011) on water and vegetation variables in Kakadu National Park, located in Australia's Northern Territory. An increase in water depth, salinity and hydroperiod and a corresponding rise in vegetation biomass, height and cover, along with an associated transition from shrubs to trees (i.e., lifeform state change) was observed during this period. Such changes might lead to an increase or a decrease in mangrove species. In 2015, a substantive drop in sea level in the Gulf of Carpentaria (Duke et al. 2017) was also noted in the Northern Territory (Lucas et al. 2018), which led to changes in water conditions and a substantive dieback of mangroves. A loss of canopy cover (%) and above-ground biomass (Mg ha^{-1}) were the EO-derived state-change indicators of short-term change; they were mapped through multi-temporal comparison (2014–2016) of vegetation indices (primarily a Normalized Difference Vegetation Index (NDVI) and a Plant Senescence Reflectance Index (PSRI)) derived from Rapid-Eye satellite imagery. Dieback-affected mangroves were not removed and their height (m) did not change (at least in the short term). A reduction in moisture content (%) of woody vegetation was the proxy applied to differentiate dieback from defoliation (Fig. 13.9b). Information on this proxy indicator can be discerned from, for example, time series of Advanced Land Observing Satellite (ALOS) Phased Arrayed L-band Synthetic Aperture Radar (SAR) data. Figure 13.9 shows further aerial images of sea-water encroachment along creeks and the associated colonization by mangroves (9e), as well as mangrove dieback along the eastern and western shores of the West Alligator River (9f).

The combination of the EODESM and DPSIR frameworks enables mapping of where and how much change has occurred (extent and magnitude), the root causes (sea-level change), and impacts (e.g., regrowth and dieback). Furthermore, likely impacts on policy (e.g., the United Nations Framework Convention on Climate Change or the Convention on Biological Diversity) and land management (e.g., associated with Kakadu National Park) can be indicated and future interventions suggested. In the case of SDG 6.6 ("*By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes*"), main policy actions to advance this target should address drivers of climate change (Metternicht et al. 2018; Asbridge et al. 2018), including also environmental monitoring through Digital Earth platforms (Lymburner et al. 2019).

Ongoing research is focusing on the use of DEA's land cover product to derive Australia-wide indicators for SDGs 6.6.1 (change in the extent of water-related ecosystems over time), 11.3.1 (ratio of land consumption rate to population growth rate), 15.1.1 (forest area as a proportion of total land area) and 15.3.1 (proportion of land that is degraded compared to total land area). For example, the 2018 Australia VNR mentions that the country is 'exploring data sources' for the implementation of Indicator 15.3.1.

The following are examples of how multi-temporal land cover maps produced within DEA using ARD satellite imagery (Landsat or Sentinel) and the combined

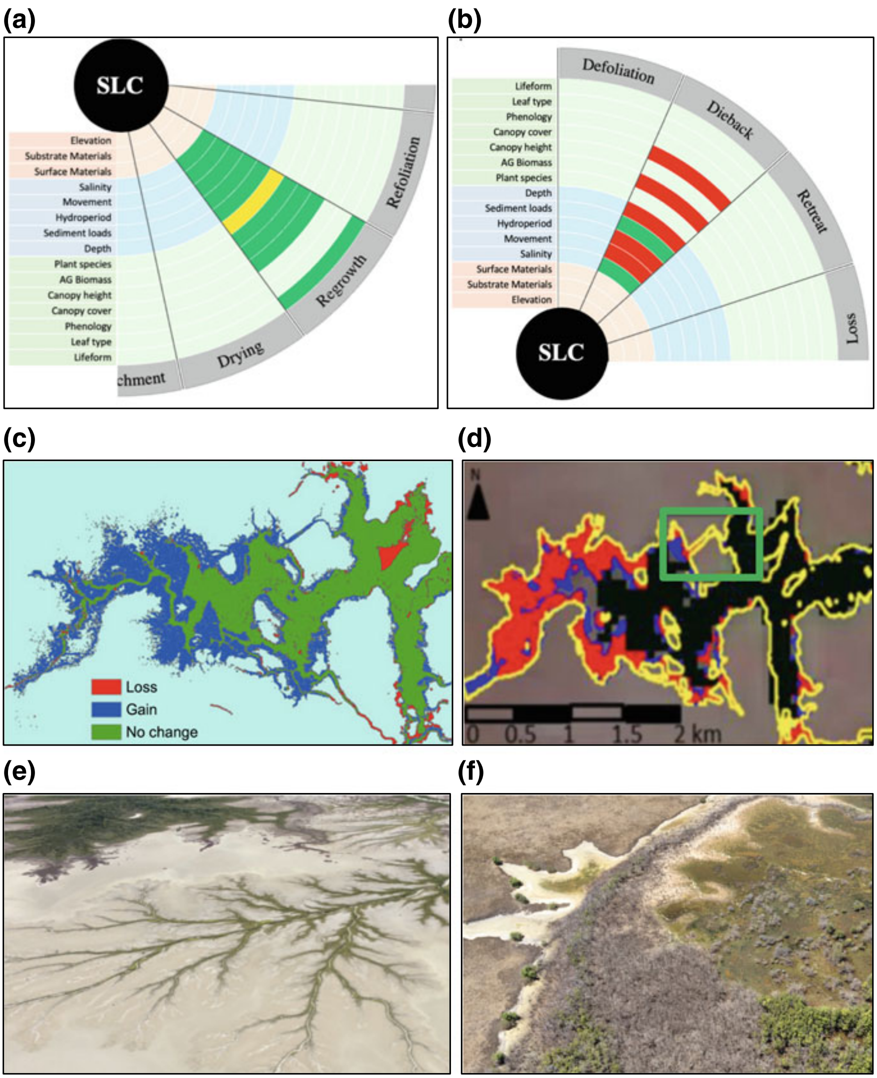

Fig. 13.9 Example of the application of the combined EODESM-DPSIR framework within DEA for Kakadu National Park, NT, Australia, where the impacts of sea-level change (SLC; center) result in **a** regrowth and colonization when rises occur and **b** dieback when drops in sea level follow. These impacts are illustrated by **c** high-resolution maps of change from time-series comparison of aerial photography from 1991 and LiDAR from 2011 (Asbridge et al. 2016), and **d** comparison of RapidEye data from 2014 and 2016. Aerial images of mangrove change taken in September 2016 show **e** landward colonization along small creeks and **f** dieback (see green box in **d**)

EODESMDPSIR framework could be used to derive metrics needed for baseline setting, target setting and/or monitoring and reporting of SDG Target 15.3, which aims '*to combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world by 2030*'.

13.4.2 DEA in Support of SDG Indicator 15.3.1

In the SDG Global Indicator Framework, indicator 15.3.1 "Proportion of land that is degraded over total land area" is based on the analysis of available data for three sub-indicators: land cover, land productivity and carbon stocks; this indicator takes a binary form (degraded/not degraded). Computing SDG Indicator 15.3.1 for the baseline (i.e., $T_{baseline}$) and subsequent monitoring years (T_1–T_n) requires adding up all those areas where any changes in the sub-indicators (i.e. land cover, land productivity and soil organic carbon) are considered negative (or stable if the baseline or previous monitoring year labeled the area 'degraded') by national authorities. In turn this involves:

i. assessing the land cover and changes in land cover (i.e., trends)
ii. analyzing the status of and trends in land productivity based on net primary production
iii. determining carbon stock values and changes, with an initial assessment of soil organic carbon as the proxy (Sims et al. 2017).

As a proxy for measuring progress towards SDG Target 15.3, indicator 15.3.1 presupposes that changes in land cover may point to land degradation if such change implies a loss of ecosystem services considered desirable in a local or national context. Hence, land cover information at the national level derived from a classification system such as the FAO LCCS can be used to assess and quantify land cover and trends in land-cover change (Step *i* from above) by disaggregating the landscape into 'degraded/negative/declining', 'stable/unchanging' or 'improving/positive'.

Based on the example presented in Fig. 13.10, the change matrix (containing 64 possible types of land change), obtained by comparing two satellite images from two different periods classified using LCCS Level 3, can be translated into descriptors relevant to SDG indicator 15.3.1. Changes indicative of land degradation can be decided by individual countries, according to their national circumstances. In Fig. 13.10, changes highlighted in orange (e.g., agricultural and urban expansion, wetland drainage and vegetation loss) are considered examples of land degradation. Diagonal cells in blue denote areas of no change (i.e., the land cover remained stable between periods 1 and 2).[3] Cells in green denote changes that the country would

[3]It is worth noting that land degradation can still occur within classes considered stable at LCCS Level 3. For example, a landscape may remain classified as terrestrial semi-natural vegetation at both T_1–T_2 even though a loss of canopy cover may have occurred. This is described at Level 4 of the LCCS (as illustrated in Fig. 13.9).

(a)

Time 2 (*To*) / **Time 1 (*From*)**

	CTV	NTV	CAV	NAV	AS	BS	AW	NW
CTV	Stable	Vegetation establishment	Change in agriculture	Vegetation establishment	Urban expansion	Vegetation loss	Inundation	Inundation
NTV	Agricultural expansion	Stable	Agricultural expansion	Inundation	Urban expansion	Vegetation loss	Inundation	Inundation
CAV	Agriculture drainage	Reforestation/ Abandonment	Stable	Reforestation/ Abandonment	Urban expansion	Vegetation loss	Inundation	Inundation
NAV	Wetland drainage	Wetland loss	Agricultural expansion	Stable	Urban expansion	Vegetation loss	Inundation	Inundation
AS	Withdrawal of settlements	Withdrawal of settlements	Withdrawal of settlements	Withdrawal of settlements	Stable	Withdrawal of settlements	Inundation	Inundation
BS	Agriculture expansion	Vegetation establishment	Agriculture expansion	Vegetation establishment	Urban expansion	Stable	Inundation	Inundation
AW	Agricultural expansion	Vegetation encroachment	Agricultural expansion	Vegetation encroachment	Urban expansion	Drought conditions	Stable	Removal of infrastructure
NW	Wetland drainage	Vegetation encroachment	Agricultural expansion	Vegetation encroachment	Urban expansion	Drought conditions	Infrastructure development	Stable

(b)

Count	ChangeType	Label	Description	Percentage
7281826	stable	NTV	stable	45.511412
1922451	degradation	NTV -> AS	urban expansion	12.015319
1661707	stable	NW	stable	10.385669
632635	degradation	NTV -> BS	vegetation loss	3.953969
551990	degradation	NAV -> NTV	wetland loss	3.449938
517389	stable	CAV	stable	3.233681
503453	improvement	BS -> NTV	vegetation establishment	3.146581
492064	stable	BS	stable	3.0754
374417	degradation	BS -> AS	urban expansion	2.340106
354845	stable	AS	stable	2.217781
315979	improvement	CAV -> NAV	vegetation establishment	1.974869

CTV Cultivated Terrestrial Vegetation
NTV Natural Terrestrial Vegetation
CAV Cultivated Aquatic Vegetation
NAV Natural Aquatic Vegetation
AS Artificial Surfaces
NS Natural Surfaces
AW Artificial Waterbodies
NW Natural Waterbodies

Fig. 13.10 Example of deriving the sub-indicator 'trend in land cover' through a change matrix that compares land-cover changes from time 1 to time 2. The land-cover layers are produced using the FAO LCCS level 3 and EO ARD available within the DEA. Expert knowledge input is needed to decide whether a change *From To* expresses an improvement (green cells), stability (blue cells), or degradation (orange cells)

consider to correspond to a decrease in degraded areas (i.e., an improvement) as a consequence of, for instance, sustainable land-management interventions that were made during the time period T_1–T_2. Figure 13.10b shows the output of this EO-based mapping process, summarizing the number of hectares of land that remained stable, were improved or have been degraded further between T_1 and T_2. This output can then be overlain and integrated with national information on land productivity status and trends, as well as soil organic carbon stocks, as suggested by the GIF metadata and good practice guidance for Indicator 15.3.1 (Sims et al. 2017).

Although it is still at the proof-of-concept stage, these applications show the potential of Digital Earth to assist countries in meeting several of the SDGs (particularly 6.6, 13, 14, and 15) where land cover and its change dynamics are relevant to reporting on the approved indicator (metric), tracking progress towards their attainment by 2030, helping to set targets according to national circumstances, and importantly, setting baselines. The baseline year for the SDG indicators is 2015 and for those related to land, its value (t_0) should be derived from time-series data for the period

2000–2015. The retrospective capacity of data provision by EO provides a unique comparative advantage to the achievement of this ambition.

13.4.3 Digital Earth in Support of SDG 17: Strengthen Means of Implementation

DEA is an example of big Earth data contributing to SDG 17 in aspects such as multi-stakeholder partnership, and production of data and systems for monitoring and accountability, and is also enhancing capacity-building support to developing and least-developed countries. The capabilities of the ODC to provide EO ARD and for scaling out across the world are significant contributions to Goal 17 in terms of strengthening means of implementation through technology transfer, capacity building and data, and monitoring and accountability.

The technology that lies beneath DEA, which was pioneered by Geoscience Australia, The Commonwealth Scientific and Industrial Research Organisation, and Australia's National Computational Infrastructure, underpins ODC initiatives being rolled out in developed (e.g. Switzerland) as well as developing countries (e.g. Vietnam) and regions (e.g. Digital Earth Africa: DEAfrica). DEAfrica is an example of Australia fulfilling Goal 17's aim of strengthening the means of implementation, as it builds technical and policy expertise as well as data analysis capability in-country with technical and operational guidance from DEA. A public–private investment partnership will provide continuing investment for DEAfrica, and it is envisaged that analysis, products and tools produced by DEAfrica will be accessible across the continent to inform decisions about land and water.

13.4.4 The Way Forward: Partnerships to Strengthen DEA in Support of the SDGs

The Australian Bureau of Statistics and other lead agencies (e.g. Department of Environment and Energy) that have contributed to the development of the Australian Reporting Platform (Fig. 13.11) recognize the importance of partnerships and collaboration with data providers for collecting datasets relevant to the SDG indicator framework. Big Earth data is needed to track the progress of Australia's performance on the goals and set targets, in addition to reporting to the United Nations High-Level Political Forum on the SDG Indicators Framework. Multi-source, multi-temporal data covering the socio-economic and environmental pillars of sustainable development can also assist in identifying interlinkages, overlaps and interactions between the SDGs, a key issue in the development of coherent policies and interventions, as discussed in Sect. 13.1.

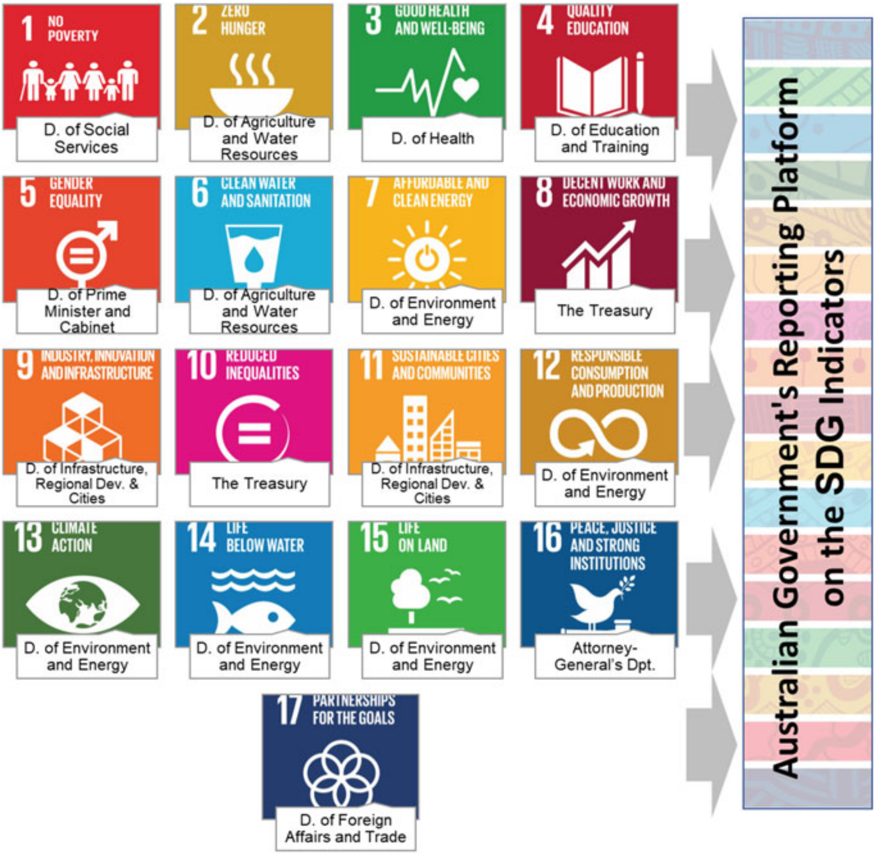

Fig. 13.11 The Australian Government's Reporting Platform for the SDGs adopts a participatory, whole-government approach

As progress is made on identifying datasets and on refining the SDG Indicators, particularly as they move from Tier III to Tier I or II, additional datasets will be uploaded to the platform, offering new data for indicator metrics and enabling the development of time-series of datasets. The government plans that the platform can assist in streamlining reporting for other nationally and internationally agreed goals (e.g. Aichi Targets, Sendai Framework, and implementation of the System of Environmental Economic Accounts (SEEA) framework). In keeping with the intention of the SDG indicator framework, the official GIF may be complemented by SDG indicators that are relevant at the regional and national levels (Australian Government 2018).

13.5 Big Earth Data for the SDG: Prospects

Measuring progress for the SDG targets through the Global Indicator Framework requires metrics that rely on biophysical, social, and economic data and information. This chapter has reviewed the current role of Digital Earth (EO as a sub-set of big Earth data) in the SDGs. It can be seen that progress has been made on identifying EO data and information for the SDG GIF (Sect. 13.3), and that participatory, cross-institutional approaches developed under a "Digital Earth" umbrella can deliver operational, standardized information that contributes to baseline and target setting, and to tracking progress towards the SDGs (4). Opportunities, and associated challenges, exist in relation to the realization of the full potential of DE for the SDG. This final section identifies and discusses these in terms of three main aspects: research and development (R&D) and technology; governance, institutional and normative aspects; and the science-policy interface.

13.5.1 R&D and Technology

Social sensing and other big data integrated within DE have the potential to meet current information and knowledge gaps for SDG indicators focused on socio-economic information (e.g. zero hunger, good health and well-being, and gender equality). Plag and Jules-Plag (2019) and Dong et al. (2019) conclude that new geospatial information for sustainability (e.g. on the built environment, land use and management), could be derived from the integration of traditional EO approaches to data gathering with citizen science, crowd-sourcing, social sensing, big data analytics and the Internet of Things. Hence, further research is needed to better establish how countries can profit from these new technologies for data gathering and analysis, embedded in a DE framework, and advance the development of indicators complementary to the core of the SDG GIF. This can support country-based interpretation and better, more coherent, narratives of national progress towards the 2030 Agenda for Sustainable Development (Metternicht et al. 2019).

Information on the *use and management* of land rather than land *cover* is needed for many SDGs (see Sect. 13.3 and Wunder et al. 2018); hence, it is relevant and pertinent to develop 'Essential Land Variables' or 'Essential Land Use Variables' to better support the information needs of the SDG targets and indicators. Digital Earth data, technology and analytics can underpin primary observations of the changes in state of land-related variables (Dong et al. 2019), with the potential to be linked to state-change indicators or to the pressures driving changes in state (see Sect. 13.4 and Lucas et al. 2019b), thus contributing to tracking progress on SDG implementation. Recent research (Plag and Jules-Plag 2019; Masó et al. 2019) has put forward ways of improving the current SDG indicator framework through considering Essential Variables. The Group on Earth Observation (GEO) and major international networks such as the Biodiversity Observation Network (GEO-BON) and the Global Ocean

Observing System (GOOS) have developed essential variables on climate (ECVs), oceans (EOVs), the water cycle (EWVs), and biodiversity (EBVs). However, standardized essential variables related to land (ELV) (or land use: ELUVs) are lacking. Global programs (e.g., Future Earth's GLP[4]) and EU-funded initiatives (e.g., the GEOEssential, ERA-PLANET[5] and ConnectinGEO projects) have started discussions on the design and development of essential land variables; the research of Reyes et al. (2017), Masó et al. (2019), Lehmann et al. (2019), Nativi et al. (2019), and Plag and Jules-Plag (2019) provide the conceptual principles and the information needs that these variables should fulfil in order to address current SDG policy and the knowledge needs of indicators. A constellation of Essential Variables on land cover/use, agriculture, biodiversity, water, and climate could better support implementation of the SDGs and the associated GIF, and also underpin systematic generation of sustainability-related knowledge from big Earth data. This would benefit Agenda 2030's global-change policy, as well as other major international agreements and conventions (e.g. the Sendai Framework for Disaster Risk Reduction, and the Paris Agreement on Climate Change).

13.5.2 Normativity, Governance and Institutional Arrangements

Google Earth Engine and Amazon Cloud-based Web Services are among cutting edge initiatives providing efficient solutions that lower the barriers to ARD products. These allow users to concentrate on data analysis and interpretation for better use of the growing volume of EO data (Giuliani et al. 2017), and expand the ecosystem of 'next users' beyond specialized scientific communities. While this is a key requirement for unlocking the informational power of big EO data and expanding the number of potential EO data users, it presents normative and governance challenges concerning big data veracity (Dong et al. 2019). Lowering access barriers for data analytics by users beyond the scientific community could potentially deliver low-quality information products. In this regard, the DE community needs to expand and build upon existing norms, standards and guidelines that have been advanced in the context of EO data storage and processing (see Sudmanns et al. 2019) to include data validation and quality assurance for information products. For example, Hernandez (2017) postulates that Digital Earth will need to consider how to store the proper metadata so that any user can easily understand how accurate data are, and how the quality of the data has been evaluated or validated. More to the point, he argues for adequate e-infrastructure and standards.

[4]An 'Essential Land Use Variables world café' session was held at the 4th Open Science Meeting of the GLP, Bern, Switzerland, April 2019. https://www.conftool.com/osm2019/index.php?page=browseSessions&cols=3&form_session=112&mode=table.

[5]ERA PLANET: The European network for observing our changing planet.

Normative challenges also remain regarding how best to determine the quality and veracity of big data from a statistical perspective (e.g., ethical questions regarding ownership of data and products). What is legally, ethically and culturally acceptable for accessing and using big data? What should the governance of digital repositories, particularly those hosting globalized or multi-national big data sets, look like? MacFeely (2019) rightly reflects that "*open cloud, centralised statistical production rather than replicating many times in countries is tempting, though it faces challenges of data and information sovereignty, as it places data owners and the data themselves beyond the reach of national level systems*".

Institutional adaptation for transformative data and information acquisition is needed as well. National Statistical Offices (NSOs) are tasked with assembling relevant data for national voluntary reports on the SDGs. The big Earth data community needs to understand how best to engage with this community to develop metrics derived from EO data that can be used for reporting. Soulard and Grenier (2018) summarize the challenges of using EO data for official statistics. Among the most salient are that datasets created from EO were not designed for use as official statistics. For integration of the EO datasets, and to better exploit the potential of big Earth data, Soulard and Grenier argue that NSOs need to develop methodologies to properly interpret existing datasets to provide estimates required by official statistics; evaluate the pertinence of global datasets that are often designed without regional considerations; keep up with the ever-increasing number of EO-generated datasets; adjust the national or regional data where local data of better quality highlight important shortcomings in the national or regional dataset; evaluate the complementarity of using EO data where other data often does not exist; and influence EO producers to integrate official statistical objectives into the EO processing workflow from the beginning. It is a two-way communication process.

13.5.3 Science-Policy Interface

Operationalization of big Earth Data proof-of-concepts is relevant to the scientific support for sustainable development policy strategies that are coordinated and coherent across goals. Reflecting on the status of operationalization of big data for SDGs from the perspective of NSOs, MacFeely (2019) argues that "*Advances, such as, the Internet of Things and biometrics will all surely present opportunities to compile new and useful statistics. The implications of this 'big (data) bang' for statistics in general, and the SDGs in particular, is not immediately clear, but one can envisage a whole host of new ways to measure and understand the human condition and the progress of development*". The UN Economic Commission for Europe (2016) reflecting on their experiences, noted 'High initial expectations about the opportunities of Big Data had to face the complexity of reality. The fact that data are produced in large amounts does not mean they are immediately and easily available for producing statistics'. Simply put, the interface between science and policy needs enhancement for context-based interpretation and communication as discussed below.

The implementation of 'transformational' policies and strategies for achieving the goals of the 2030 Agenda for Sustainable Development requires tracking the progress of set targets to ensure that responses to interventions (e.g., land restoration or sustainable cities) are as expected. In this regard, a major challenge of Digital Earth is the linking of scientific results concerning knowledge derived from EO to the policy decision space. On the one hand, multi-stake, whole-government, participatory processes, as implemented by the Government of Australia in setting its National Reporting Platform (see 4.1 and 4.4), contribute to bridging the gap between science and policy. On the other hand, DE frameworks more focused on the 'knowledge' element of the Data-Information-Knowledge-Wisdom (DIKW) paradigm are needed. SDG indicators should provide policy makers with the knowledge necessary for wise decisions, drawn from information gathered from observed data, whether through EO, social sensing, or other means. (Nativi et al. 2019). Most DE initiatives currently focus on 'Data' (i.e., ARD) as shown in the review by Sudmanns et al. (2019) of popular systems and portals for accessing or processing EO. This review makes clear that many portals facilitate data access—although in the end users struggle to produce information and 'frame' it according to context. This is an essential aspect of the policy and political decision-making processes related to the implementation of the SDGs, given that countries are to take into account their own national circumstances and priorities (UNGA 2015) in defining SDG targets and, hence, one-size-fits-all interventions do not exist.

13.6 Conclusion

The Sustainable Development Goals are highly ambitious and were adopted to stimulate action over the next 15 years in areas of critical importance for humanity and the planet (UNGA 2015). Digital Earth has untapped potential to improve the means of implementing the SDGs at both national and global scales. Through an extensive review of the recent literature and a case study of the operationalization of the SDG Indicator Framework in Australia, this chapter discussed information needs and promising operational initiatives underpinned by big Earth data and analytics, and, as importantly, multi-stakeholder partnerships. Digital Earth Australia is an example of the potential of Digital Earth to be an agent of 'partnerships for the goals', which can increase the availability of high-quality, timely and reliable data that is relevant in national contexts (SDG 17.18), and enhance regional and international cooperation on, and access to, science, technology and innovation (SDG17.6).

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Graciela Metternicht is a Professor in Environmental Geography at the University of New South Wales Sydney. Her research focuses on applications of geospatial technologies for environmental management and sustainability. Past appointments include Regional Coordinator of Early Warning and Assessment at UN Environment.

Norman Mueller is a Director of Product Development for Digital Earth Australia where he leads a team building time series tools and products for the monitoring and management of the environment from Earth observation data.

Richard Lucas holds a Sêr Cymru Research Chair at Aberystwyth University where his research focuses on the use of Earth observation data to better support monitoring, conservation, sustainable use and restoration of global environments.

Chapter 14
Digital Earth for Climate Change Research

Gensuo Jia, Li Zhang, Lanwei Zhu, Ronghan Xu, Dong Liang, Xiyan Xu and Tao Bao

Abstract Our planet is undergoing one of the most rapid climate changes in Earth's history. The current change is particularly significant because it is most likely a consequence of human activities since the 19th century. The Digital Earth platform, which includes Earth-orbiting satellites, ground-based observations, and other technologies for collecting, analyzing and visualizing data, has enabled scientists to see our climate and its impacts at regional and global scales. The Digital Earth platform offers valuable information on the atmosphere, biosphere, hydrosphere and cryosphere to understand Earth's past and present, and it supports Earth system models for climate prediction and projection. This chapter gives an overview of the advances in climate change studies based on Digital Earth and provides case studies that utilize Digital Earth in climate change research, such as in the observation of sensitive factors for climate change, global environmental change information and simulation systems, and synchronous satellite-aerial-ground observation experiments, which provide extremely large and abundant datasets. The mapping of climate extremes and impacts improves preparedness for climate change-related risks and provides robust evidence to support climate risk management and climate change adaptation for the public, decision makers, investors, and vulnerable communities. However, Digital Earth faces the challenges of multisource data coordination and integration, requiring international partnerships between governments and other organizations to advance open data policies and practices.

Keywords Digital Earth platform · Climate change · Sensitive variables · Information and model systems · Greenhouse gases

G. Jia (✉) · X. Xu · T. Bao
Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
e-mail: jiong@tea.ac.cn

L. Zhang · L. Zhu · D. Liang
Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China

R. Xu
National Satellite Meteorological Center, Beijing, China

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14.1 Introduction

Global climate change has long been recognized as the most critical issue of the 21st century. The 2016 Paris Agreement within the United Nations Framework Convention on Climate Change (UNFCCC) highlights the importance and urgency of climate action. Climate-related changes are becoming evident at various spatial and temporal scales, accompanied by a record increase in the frequency of extreme climate events and the emergence of complex environmental issues. As a result, vulnerability to climate change is expected to expand spatially, threatening larger human populations as warming continues. Understanding climate change and delivering climate information with high precision has therefore become increasingly important, especially to assist governments and decision makers in implementing appropriate mitigation and adaptation policies.

The Earth system is a complex collection of interlinked subsystems that require multidimensional, multiscale and multitemporal datasets. Understandably, challenges and uncertainties in studying climate change and its impacts are largely due to the massive amount of data that is required, and the complexity of analyses that can translate data into useful information. Earth observation for this purpose has become an invaluable resource. Earth observations, during most of the history of science, have predominantly been recorded at the ground level with limited spatial coverage. Methods such as those developed by World Weather Watch in 1963 combined a series of single surface pictures to provide global coverage but lacked network density and vertical resolution. Geophysical and biological phenomena have also been generally insufficiently sampled. However, the growing diversity and improvement of sensors and sensing platforms has greatly diversified data sources, benefiting global climate change research in the past few decades through technologies that can increasingly provide a more accurate and precise picture of biological, physical, and chemical phenomena (Table 14.1). Moreover, satellite platforms and the development of UAVs and other technologies have made multitemporal observations feasible, which have allowed for investigations into large-scale processes that were traditionally not possible. Synoptic Earth observations have changed the way we understand the planet, from the first weather satellite that revealed astonishing cloud features to their utility to verify and improve our understanding of the coupling between the El Niño-Southern Oscillation and ocean currents. They have been used to study temperatures at various altitudes, atmospheric processes, the effects of snow on water circulation, the effects of global and regional factors on sea level changes, and other phenomena. From 1960 to 2011, 514 Earth observation satellites were launched worldwide, and 200 more launches are planned by 2030 (Guo 2014). The huge amount of data collected over the years provides a rich resource of information for climate change research. However, this big data presents challenges in data collection, characterization and analysis. Therefore, there is urgent need for a Digital Earth platform that can integrate multisource spatial information into a single platform and allow for integrated investigation into Earth observation data to generate climate change information.

Table 14.1 Summary of the functions of satellites related to global change research

Satellite	Function
TIROS series, Nimbus 4 and 7, ERS-1, ERS-2, Envisat	Monitors global stratospheric ozone depletion (including Antarctica and the Arctic)
Nimbus 7, ERS-2, Envisat, Aqua, Aura, MetOp	Detects tropospheric ozone
Explorer 7, TIROS, Nimbus	Measures radiation balance
TIROS series, ATS, SMS, MetOp	Produces weather images
Meteorological satellites, including the TIROS series, GOES and POES (NOAA), MetOp (Eumetsat), ERS-1, ERS-2, Envisat	Weather forecasting
Radarsat, Landsat, Aura, Terra, Jason, ERS-1, ERS-2, Envisat	Investigates ice flows in Antarctica and Greenland
Topex/Poseidon, ERS-1, ERS-2, Envisat	Detects mid-scale sea surface topography and important variables in ocean mixtures
TIROS-N and NOAA series, ERS-1, ERS-2, Envisat	Observations of oceanic contributions to climate change
Landsat, SPOT series	Agricultural land monitoring
LAGEOS, GPS	Confirms high-precision terrestrial reference frames
GCOM	Observes Earth water and carbon dioxide
TANSAT	Monitors atmospheric carbon dioxide concentration
FY	Used in weather forecasting, climate prediction, natural disaster and environmental monitoring, and resource development

Sources NRC (2008), Guo et al. (2015)

14.2 Digital Earth and the Essential Climate Variables

Climate change is highly heterogeneous over the globe, with strong regionality. The UNFCCC provides 34 essential climate variables (ECVs) that require contributions from Earth observations from space (Table 14.2) (Guo et al. 2015). The spatial attributes of ECVs make it possible to effectively observe them through space technology (Guo et al. 2014a), and the Digital Earth platform based on space technology plays an essential role in better understanding the spatial and temporal changes in the climate.

Table 14.2 Essential climate variables (ECVs) that are feasible for global implementation and have a high impact on UNFCCC requirements

Domain		Essential climate variables
Atmospheric	Surface	Air temperature, wind speed and direction, water vapor, pressure, precipitation, surface radiation budget
	Upper-air	Temperature, wind speed and direction, water vapor, cloud properties, Earth radiation budget (including solar irradiance)
	Composition	Carbon dioxide, methane, and other long-lived greenhouse gases; ozone and aerosols, supported by their precursors
Oceanic	Surface	Sea surface temperature, sea surface salinity, sea level, sea state, sea ice, surface current, ocean color (for biological activity), carbon dioxide partial pressure, ocean acidity
	Subsurface	Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers, phytoplankton, marine biodiversity, and habitat properties
Terrestrial		River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (FAPAR, leaf area index (LAI), above-ground biomass, soil carbon, fire disturbance, soil moisture, terrestrial biodiversity, and habitat properties

Sources CEOS (2006), Guo et al. 2015

14.2.1 Earth Observation Data Parameters and Their Capabilities

Ground-based Earth observation systems such as rain gauge networks and radar have always been a major means of observing atmospheric structures and they are still being operated and maintained. However, satellite platforms have added valuable scientific data to monitor clouds, water vapor, precipitation, and wind at multiple spatial and temporal scales. Sensors such as the Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) developed by the U.S., the Medium Resolution Imaging Spectrometer (MERIS) from the European Space Agency (ESA), and the international A-Train satellite systems have provided a wealth of information on clouds, rain, and pollutants, leading to a greater understanding of cloud pollution influences (Guo et al. 2015).

The cryosphere, consisting of lakes, river ice, snow cover, glaciers, ice caps, and frozen ground (including permafrost), is one of the most important parts of the climate system. Thus, changes in the cryosphere as well as in soil moisture and salinity are very important for monitoring global climate change, managing regional water resources, and investigating water and land ecosystems and global sea levels. Data from polar-orbiting and geostationary satellites (carrying visible/near-infrared sensors), such as the Geostationary Operational Environmental Satellite System (GOES), Landsat, MODIS, MERIS, and AVHRR, have been used to monitor the melt flow from snow cover and glaciers. This information is also valuable for the management of water resources and disasters, and has been utilized for flood disaster prediction and reservoir operation. Data from the Sea Winds scatterometers onboard the QuikSCAT satellites can monitor seasonal changes in ice, track giant icebergs, and provide daily maps of ocean ice at a 6-km resolution.

Earth observation satellites also provide hundreds of data products (Table 14.3) to monitor water quality, water color (e.g., chlorophyll, suspended solids, and turbidity) and sea surface temperatures. For example, the AVHRR, AATSR, and MODIS sensors provide data on sea surface temperatures (CEOS 2006; Guo et al. 2015). In addition, many satellites can obtain data on elevation measurements, geopotential heights, and terrain. For example, P-band synthetic aperture radar (SAR) can penetrate cloud cover and the vegetation canopy and is useful in tropical and northern forest research at high altitudes. Improved SAR such as advanced synthetic aperture radar (ASAR) and phased array L-band SAR (PALSAR) are available for agriculture, forestry, land cover classification, hydrology, and cartography.

The main characteristics of climate change are the trends in temperature, precipitation, polar ice cover, and sea level. A new generation of satellite systems and advanced sensors such as Suomi NPP, GPM, OSTM/Jason-2, ICESat-2, and SWOT

Table 14.3 Remotely sensed oceanographic parameters, their observational category, and representative sensors

Parameter	Observational category	Satellite/Sensor
Bio-optical	Visible to near-infrared	ENVISAT/MERIS, AQUA/MODIS, OrbView-2/SeaWiFS
Bathymetry	Visible to near-infrared	Landsat, SPOT, IKONOS
Sea surface temperature	Thermal infrared microwave radiometers	POES/AVHRR, GOES/Imager DMSP/SSM/I, TRMM/TMI
Sea surface roughness, wind velocities, waves and tides	Microwave scatterometers and altimeters Synthetic aperture radar	ERS-1 &-2/AMI QuikSCAT, RADARSAT-1
Sea surface height and wind speeds	Altimeters	Topex/Poseidon, Jason-1
Sea ice	Visible to near-infrared microwave radiometers, scatterometers and altimeters Synthetic aperture radar	POES/AVHRR DMSP/SSM/I ERS-1 &-2/AMI RADARSAT-1
Surface currents, fronts, and circulation	Visible to near-infrared, thermal infrared microwave scatterometers and altimeters	POES/AVHRR, GOES/Imager Topex/Poseidon, Jason-1
Surface objects-ships, wakes, and flotsam	Synthetic aperture radar	RADARSAT-1, ENVISAT/ASAR

Source Brown et al. (2007), Guo et al. 2015 have further improved our capability for space-based observation of these key parameters related to climate change. In addition to the space-based data, in situ data from ground measurements and reanalysis data are used to provide information on key indicators of climate change. The Copernicus Climate Change Service (C3S) compiles all the information obtained by the Copernicus environmental satellites, air and ground stations, and sensors to provide comprehensive pictures of the past, present, and future climate of Earth.

14.2.2 Heterogeneous Changes in Temperature

Heatwaves and rising temperatures have gained prominence in the context of global warming. Digital Earth technology is relatively mature for monitoring global land and sea surface temperatures, although the algorithms and retrieval accuracy need to be further improved, and satellite LST measurements have uncertainties caused by data accuracy and inconsistencies between sensors. Nevertheless, satellite measurements have been very useful in monitoring surface temperatures and detecting extreme temperature events.

Thermal infrared surface temperatures from satellite platforms are frequently integrated into data assimilation systems and reanalysis data systems for climate parameters, including NCEP/NCAR and NCEP/DOE, ERA-40, and JRA-25, which effectively improves the accuracy and reliability of datasets. The most widely used global land surface temperature datasets are the monthly data measured by the AVHRR thermal infrared band (4, 5) since 1982, the 8-day composite data derived from the MODIS thermal infrared band since 2000, the daily global LST and SST data provided by ENVISAT from the ESA, and the LST measured by Aster at small scales. The geostationary satellite system operated by the United States, Europe, China, Japan, and others provide low- and middle-latitude LST data at one-minute intervals. In addition, SeaWiFS, FY-2/4 and FY-3 can acquire LST data. The Suomi NPP satellite launched in 2012 carries a 750-meter spatial resolution Visible Infrared Imaging Radiometer Suite (VIIRS) sensor, and its surface temperature data quality was an improvement (Guillevic et al. 2014).

The monitoring and impact assessment of heat waves based on multisource thermal infrared remote sensing data have made important progress in recent years. Since the heat wave in central Europe in 2003, most large-scale heat wave events have been successfully monitored, including the large-area heat wave in southern Asia in the summer of 2010, the continued high-temperature anomaly in eastern Asia during the spring of 2013, the extreme low-temperature event that lasted several weeks in central and eastern North America in the winter of 2014, and the persistent heat wave that swept over southern Asia and western Europe in the spring and summer of 2015. Progressive improvement of Digital Earth's thermal environment platform that integrates multisensor and multiresolution spatial data can provide automatic and more accurate extreme temperature information, and support government decision making and public information services.

14.2.3 Heterogeneous Changes in Precipitation

The accuracy of precipitation estimation has improved over the years with satellite-based sensors. Satellite systems allow for continual monitoring and observation of precipitation on a global scale, which was only possible at fixed intervals with limited spatial coverage using conventional ground-based observation systems. Infrared sensors onboard geostationary satellites, passive microwave sensors carried by the polar-orbiting satellites, and active radar onboard the TRMM satellite and its successors have collected a huge wealth of data on precipitation over the years. The establishment of Global Precipitation Measurement (GPM) realized a satellite constellation with coordinated, seamless observation of global precipitation, indicating a new era of "digital precipitation". GPM is an independent and complex project consisting of a core satellite and approximately eight other satellites. Its precipitation observation can reach a radius of 5 km, covering 90% of the global land and ocean surface at three-hour intervals, and can distinguish rainfall, snow, ice and other precipitation forms. It is much more advanced than the previous generation of TRMM.

Geostationary meteorological satellites such as FY-2, GOES, GMS, Meteosat, and MTSAT have seen improvements in multichannel scanning and real-time performance and have high spatial and temporal resolutions (from one-hour intervals to half-hour intensive observation, and 5-km and 1.25-km spatial resolution at nadir for the infrared and visible and near-infrared spectral channels, respectively). This makes them more effective in monitoring hazardous weather systems. Therefore, comprehensive application of multiple channels such as thermal infrared, visible light, near-infrared, and water vapor channels is an essential component of the Digital Earth platform for extreme precipitation monitoring.

14.2.4 Extreme Climate Events

Extreme climate events refer to serious deviation of the climate from its average state, including phenomena that are statistically less significant. Extreme climate events generally include high-temperature heat waves, extreme snow, strong tropical storms, floods, meteorological droughts, and natural fires. Space-based observation of extreme climate events consists of real-time warning and monitoring, rapid postdisaster assessment, and disaster risk reduction. This requires high spatial and temporal resolution satellite information and an efficient operational platform. This is both a challenge and an opportunity for Digital Earth. For instance, regarding disaster risk, the combination of multisource satellite data, land use data, and topographic data makes it possible to rapidly assess flood risk at the watershed and regional scales (Reager et al. 2014). Cold winter events have occurred frequently in Eurasia in the last 10 years, and extreme low temperatures have been record-breaking. Mori et al.

(2014) added Arctic sea ice data and SST to climate models and found that the reason for most cold winters is Arctic Oscillation (AO).

Digital Earth technology has shown great potential in disaster monitoring, emergency response, disaster assessment, and reconstruction. Disaster reduction is the most effective aspect of the Digital Earth platform, which can perform all-weather, all-day dynamic detection. Meteorological satellites, radar satellites, and high-resolution visible and near-infrared Earth observation satellites can be used to monitor rainfall, floods, and droughts in real time for emergency response. The Digital Earth platform can support rapid analysis of the statistics and distribution of flooded areas, flooded land use categories, and the number of people affected, especially when satellite data is combined with digital thematic maps such as administrative, land use, population, and socioeconomic maps.

14.3 Interactions Between Climate and Society Through Space and Time

14.3.1 Greenhouse Gas Exchange

The current global climate change is mainly attributed to rapidly increasing atmospheric concentrations of two greenhouse gases, carbon dioxide (CO_2) and methane (CH_4). Most of the body of research on greenhouse gases has focused on CO_2 rather than CH_4, which is a more potent greenhouse gas. The lack of high spatial and temporal resolution datasets on continuous flux is a major reason for the limited knowledge on CH_4 exchange (Holgerson and Raymond 2016). In the case of CO_2, the scientific community still lacks a detailed understanding. For example, according to existing ground measurements, 40–50% of the carbon dioxide produced by human activities remains in Earth's atmosphere, and the remaining 50–60% is considered to be absorbed by the ocean and ground vegetation. However, scientists do not know exactly where the carbon dioxide is stored, how this storage process occurs, and whether this process can limit the increase in carbon dioxide in the atmosphere. To date, spatiotemporal pattern studies of terrestrial carbon sources and carbon sinks based on space technology have been mainly achieved through satellite-based visible light and near-infrared band indexes. The 8-km inverted AVHRR continuous vegetation index data is the longest time series, since 1982, and the accuracy of the sixth generation of the MODIS (C6) vegetation index data has been greatly improved. In addition, Landsat, MERIS, VIIRS, SPOT Vegetation, and Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) data are available.

A key parameter for monitoring the temporal and spatial patterns of terrestrial carbon sources and carbon sinks is the fraction of absorbed photosynthetically active radiation (FAPAR), which largely determines the total gross primary production (GPP) or carbon assimilation capacity. To date, more than six different global FAPAR spatial databases have been released, inverted from MODIS, MERIS, SeaWiFS, MODIS-TIP, SPOT-VEG, and AVHRR time series data; however, the data are highly uncertain. A systematic evaluation of more than 800 ground sample datasets revealed that they differed greatly between continents and biomes, and all were insensitive to vegetation coverage and needed further improvement (Pickett-Heaps et al. 2014). Chinese scholars have made costrengthening observations among 25 field flux stations and driven vegetation productivity models with flux data, satellite-based vegetation indexes, surface albedo, and soil moisture indexes, which have significantly improved the estimation of FAPAR and GPP on a regional scale (Wang et al. 2010). A recent improvement was the use of chlorophyll fluorescence data from the GOME satellite to drive vegetation productivity models and monitor global crop photosynthesis (Guanter et al. 2014).

The Orbital Carbon Observing Satellite (OCO-2) is a satellite launched by the United States in 2014 to monitor the global space-time distribution of carbon dioxide. It is mainly used to observe the carbon dioxide level of the Earth's atmosphere and to understand the role of humans in global climate changes caused by greenhouse gas emissions. The satellite carries a three-channel spectrometer for accurate measurements. OCO-2 collects approximately 8 million accurate global carbon dioxide measurements every 16 days, with a measurement accuracy of one in a million. With instruments such as spectrometers carried on satellites, scientists can dynamically measure carbon dioxide from different sources in the atmosphere and monitor the adsorption of carbon dioxide by oceans and forests. The acquisition of such a dynamic global carbon dioxide map will help reduce errors and improve the accuracy of forecasts for global warming.

Prior to this, in 2009, JAXA (Japan) launched GOSAT, the first satellite dedicated to detecting the concentration of greenhouse gases such as atmospheric CO_2. The satellite was equipped with high-precision observation equipment that used greenhouse gases such as carbon dioxide and methane to absorb infrared rays of a specific wavelength, and estimated the concentration of greenhouse gases by observing the infrared rays reflected from the surface. The goal of GOSAT was to observe the distribution of global CO_2 and CH_4, with a measurement precision of 2–3 ppm for CO_2 and approximately 15 ppb for CH_4, to capture the spatial variation in the carbon flux each year. GOSAT was equipped with thermal infrared and near-infrared sensors to obtain carbon observations as well as cloud and aerosol images. As the infrared rays passes through the atmosphere, a gas that forms a greenhouse effect, such as carbon dioxide, causes a specific wavelength to be absorbed, and the concentration of the gas can be calculated from these data. TanSat, launched by China, has further improved our ability to detect atmospheric CO_2 and other greenhouse gases.

Many countries including China are actively planning to launch satellites for the special detection of atmospheric CO_2 and other greenhouse gases. Integrating spatial data from these different sources with station observation data on the Digital Earth platform will greatly enhance the accuracy of detection and the technical support for climate change research.

14.3.2 Connectivity and Teleconnection in the Earth System

The Earth system as a whole, its components, and the various regional subsystems are connected and closely related. For example, in ocean-air interactions, the transfer of energy between the two is a teleconnection. We are gradually recognizing the importance of teleconnections in the climate system. For example, variability in the El Niño-Southern Oscillation (ENSO) model across the equatorial Pacific is linked to widespread distribution of floods, droughts, and forest fires in often arid or semiarid areas such as East Africa, tropical and subtropical Australia, and North America within the mid-latitudes and the western coast of South America. Another good example comes from Mori et al. (2014), who showed that most cold winters are attributed to AO changes caused by Arctic sea ice.

Studying and understanding teleconnections is an important challenge and an undertaking that can greatly benefit from utilization of the Digital Earth platform's capabilities of macroscopic multiparameter data integration to enable discovery of hidden and underlying connections in the Earth system and reveal the mechanisms to improve predictions of climate and weather. Various aspects remain to be identified and can benefit from the Digital Earth platform. For example, regarding ENSO and the North Atlantic Oscillation (NAO), we know relatively little about the teleconnection between the stratosphere and the Earth's surface. A strong vortex is formed over the polar region in winter, and the vortex intensity changes. When the vortex is strong, a tightly stable cycle is concentrated in the stratosphere, with little connection to the troposphere and the Earth's surface. When the vortex is weak, the control is not very stable, and it can generate a large-scale dynamic process. Therefore, it can be transmitted to the surface of the Earth through the convective top layer. It causes unusually cold weather at high latitudes, for example, in Scandinavia. When the Arctic vortex weakens, cold air flows outwards and downwards. Another example is the study by Zhang et al. (2019), which showed that the mean winter visibility throughout most of eastern China is negatively correlated with the preceding Antarctic Oscillation (AAO), especially in northern China. It emphasizes the important roles of sea surface temperature warming or cooling tendencies in the northwestern southern Indian Ocean (NSIO) and provides possible pathways through which NSIO warming may influence the atmosphere of northern China.

14.4 Impacts and Response

14.4.1 Ecosystems

Currently, the spatial data used to analyze the response of large-scale ecosystems to climate change are mainly acquired from long-term time series data from medium- and coarse-resolution optical satellite sensors such as AVHRR, MODIS, SPOT, VIIRS, SeaWiFS, and MERIS, which have inconsistencies between the sensors and their time spans (Guay et al. 2014). Several released global data series are generally based on the records of a single sensor. There are few data series from multisource data fusion and integration. However, satellite data often contain uncertainties caused by biases in different sensors and retrieval algorithms as well as inconsistencies between continuing satellite missions with the same sensor. Undetected drifts in sensor sensitivity have been cited as the main reason for the apparent spectrum of change. If the procedures for merging data from different time series are not well-developed and calibrated, the uncertainties can potentially be high in combined datasets. An integrated vegetation index dataset based on system calibration and data fusion is an important requirement for the Digital Earth platform.

Due to the complexity of ecosystem dynamics in the context of climate change, traditional methods based on single-satellite data have great limitations. By integrating and comparing multiple satellite datasets and ground observation data, the Digital Earth platform can dynamically and effectively display and analyze the trends of climate-related parameters.

14.4.2 Water Cycle and Water Resources

The global water cycle involves transformation, flow, and redistribution, and the redistribution of global and regional energy and regulation of the climate. The Earth observation system can quantitatively monitor many key parameters of the global water cycle, including various forms of precipitation (such as rainfall, hailstones, ice rain, and snow), atmospheric water vapor, surface evaporation, vegetation canopy transpiration, surface water, snow, continental glaciers, sea ice, soil moisture, and surface runoff.

Using the Digital Earth platform, global hydrology cycle models can be developed to reveal the controlling factors of terrestrial water cycling and trends in water resource patterns. It is expected to lead to a revolutionary solution to a series of key issues in Earth's multiple spheres of interactions from the perspective of Earth system dynamics, including global ocean-atmospheric interaction, land-atmospheric interaction and the boundary layer process, ocean-land correlation, and coastal ecosystem evolution.

14.4.3 Coastline, Urban Areas, and Infrastructure

Smajgl et al. (2015) employed remote sensing land use data, digital elevation data, and high-resolution climate models to simulate the scenario of a regional sea level rise of 30 cm by 2050. The study predicted that urban floods and sea water backflow would be severe downstream of the Greater Mekong Subregion and that the land use structure would change significantly.

The urban heat island effect accompanies the expansion of human settlements and is closely related to regional climate change. As the most active region of economic growth and urbanization, the urban heat island phenomenon in Asia, especially in China, has become an important issue in regional climate change. The Digital Earth system provides comprehensive spatial information about urban areas (Hu et al. 2015), human activity intensity (Zhou et al. 2014), and thermal infrared land surface temperature. It provides a scientific platform for research on urban heat islands at different spatial and temporal scales. Regarding the potential contributions of infrastructure to a warming climate, researchers have examined the impacts of urban expansion on the trends in air temperature by investigating the changes in urban land use around meteorological stations and analyzing the relationship between the rate of urban expansion and air temperature magnitudes (He et al. 2013). Urban heat islands can influence land-atmospheric energy exchange, the turbulence regime of atmospheric flow, and the microclimate, and can accordingly modify the boundary layer processes over urban canopy and downstream areas. Research showed that estimation of key urban morphology parameters using high- and medium-resolution satellite data and intense field measurement along urban-rural transects can improve the performance of regional climate models in capturing critical climate effects over large and rapidly expanding urban clusters (Jia et al. 2015; Feng et al. 2014; Wang et al. 2012).

14.5 Multisource Digital Earth for Studying Climate Change Phenomena

Earth is a large, complex system, broadly grouped into three subsystems: the atmosphere, oceans, and land surface. Climate change involves understanding changes in one of these subsystems and understanding how these systems interact, their impacts on one another, and the consequences of changes in any one of them or their subsystems. This requires rich scientific datasets quantifying sensitive climate factors, which is not possible without integration of data from multiple sources. These multisource datasets have been collected over the years through synchronous satellite-aerial-ground observation experiments (Fig. 14.1).

Multisource datasets allow for comprehensive, continuous, and diverse information on the Earth's surface. Similarly, multisensor remote sensing datasets enable dynamic (and in some cases real-time or near real-time) monitoring of Earth's systems. It has played a fundamental role in supporting modern data-driven scientific innovation. Effective use of multiplatform Earth observation data with multiple sensors helps avoid and mitigate issues related to information extraction and inversions that arise from the use of a single sensor.

These datasets have enabled researchers to explore new theories by developing new methodologies and assimilation models that can incorporate multi-source/multisensor, heterogeneous spatial data to acquire precise information on

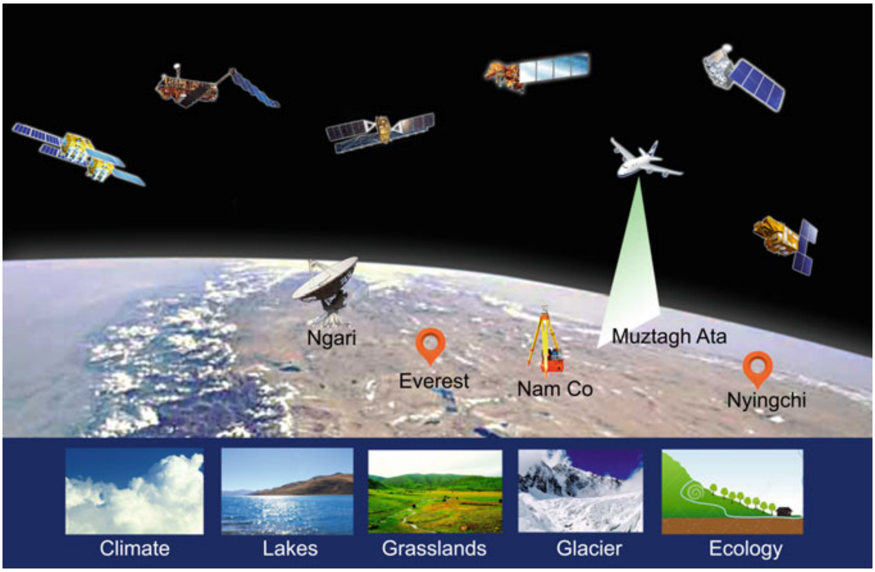

Fig. 14.1 Synchronous satellite-aerial-ground observation experiments on the Qinghai-Tibetan Plateau (revised from Guo et al. 2015)

sensitive climate factors and develop simulation platforms to understand regional climate change patterns. Multisensor Earth observations also provide long-term, stable spatial data for scientific research, compensating for uneven spatiotemporal observations, and play a fundamental supporting role in global change research.

The National Basic Research Program of China (973 Program) launched the project "Earth Observation for Sensitive Variables of Global Change: Mechanisms and Methodologies" on January 1, 2009. This was the first research project on Earth observation techniques for global change research in China. The project highlighted sensitive variables in terrestrial, oceanic and atmospheric systems based on big data from Earth observation from multiple platforms and multiband sensors, focusing on the development of new theories, technologies, and methods in these fields. The research scheme of the project is shown in Fig. 14.2. During the project, the new concept of moon-based Earth observation for global change monitoring was also widely discussed and considered as an efficient way to map the solid earth dynamics and radiation budget at the top of the atmosphere (Guo et al. 2014b, 2018).

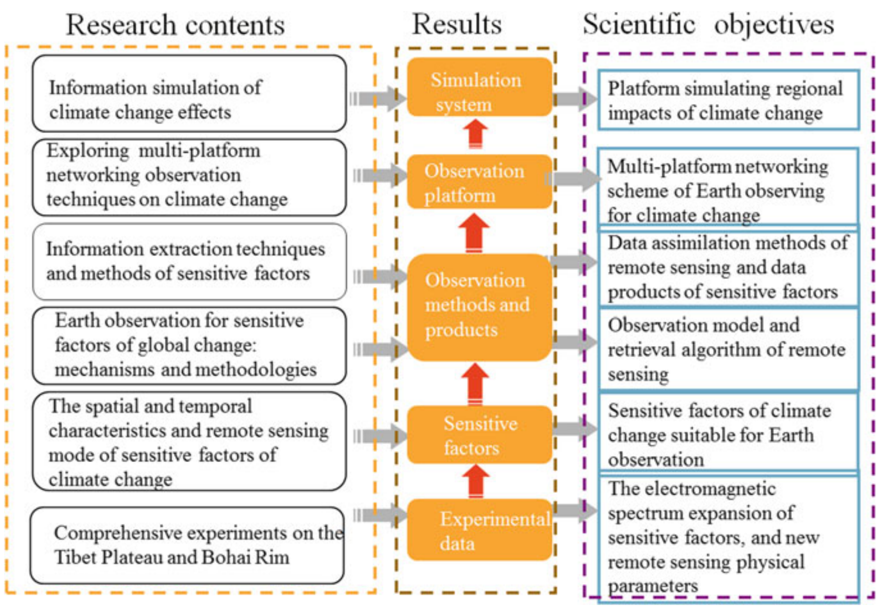

Fig. 14.2 Research scheme for the "Earth observation for sensitive variables of global change: mechanisms and methodologies" project (Guo et al. 2015)

14.5.1 Glaciers

Glaciers provide unique records and feedback that influence global climate change and are closely related to temperature, precipitation, and the material balance. The glaciers on the Tibetan Plateau have retreated considerably since the 1970s, and this rate of retreat has accelerated in recent years. In general, the retreat rate for glaciers covering less than 1 km^2 is faster than those of larger glaciers, but there are significant spatial differences. For example, glacial retreat was observed to be the fastest in the Himalayas and slower in the central plateau (Yao et al. 2003). It has been suggested that the retreat of the Himalayan glaciers is much more serious than expected (Ma et al. 2010). Consequently, with the rapid melting of glaciers, lakes supplied by the glacier melt water, such as Nam Co Lake (the highest lake on the central Tibetan Plateau), have expanded between 1976 and 2009 (Zhang et al. 2011; Guo et al. 2015).

A method for extracting glacier thickness has been developed based on interferometric synthetic aperture radar (InSAR) data and elevation data from the Geoscience Laser Altimeter System instrument aboard the Ice, Cloud, and land Elevation satellite (ICESat/GLAS14). As a result of calculations using the ICESat data along with the Shuttle Radar Topography Mission digital elevation model (SRTM DEM), a reduction of 0.63 m per year (water equivalent) was observed in the thickness of the Naimona'nyi glacier between 2000 and 2009 (Zong et al. 2013). This lies between the material balance of 0.56 m per year (water equivalent) and the glacier thickness reduction of 0.65 m per year (water equivalent) measured by GPS (Li et al. 2012). In general, glacial shrinkage decreases toward the interior plateau from the Himalayas, and the minimum degree of shrinkage occurs in the Pamir mountain range (Yao et al. 2012; Guo et al. 2015).

14.5.2 Lakes

Large fluctuations in lake surface area in a short time significantly influence water cycles and the local ecological environments. Studies have been conducted on lake areas, in addition to water level monitoring in different regions of the Tibetan Plateau using Landsat and ICESat data. Since 2003, a large spatial variation in lake area on the Tibetan Plateau has been observed, with a shrinkage of lakes in southern Tibet and an expansion trend for lakes in the Qiangtang region (Liao et al. 2013). In the Qaidam Basin, Qinghai Lake showed an expansion trend, and the annual rate of change in water volume in spring was greater than that in autumn. Gyaring Lake in the eastern Tibetan Plateau also showed an expansion trend that mirrored that of Qinghai Lake (Liao et al. 2013). Glacial melt is the dominant driver of the recent lake expansions on the Tibetan Plateau. By investigating detailed changes in the surface area and levels of lakes across the Tibetan Plateau from Landsat/ICESat data, Li et al. (2014) found a spatial pattern in the lake changes from 1970 to 2010 (especially after 2000). They observed a southwest-northeast transition from shrinking, to stable, to rapidly expanding lakes, which suggests a limited influence of glacial melt on lake dynamics. The plateau-wide pattern of lake area changes is related to precipitation variations and is consistent with the pattern of permafrost degradation induced by rising temperatures (Li et al. 2014; Guo et al. 2015).

14.5.3 Vegetation

The plant phenological period is closely related to climate change, and phenological changes influence the carbon balance of terrestrial ecosystems by affecting ecosystem productivity. The alpine vegetation on the Tibetan Plateau is extremely sensitive to global change. Zhang et al. (2013), Wang et al. (2015) used MODIS to analyze the response and driving factors of space observations of plant greenness and phenology (Fig. 14.3). Zhang et al. (2013) found that the normalized difference vegetation index (NDVI) showed a gradual increasing trend in the plateau during the growing seasons from 2000 to 2009. On the western Tibetan Plateau, the continuous decrease in precipitation resulted in a delay in the alpine grassland phenology; in the eastern part of the plateau, the precipitation continued to increase, resulting in an advance in the grassland phenology (Wang et al. 2015). In addition, Liu et al. (2014) found that the spring phenology of the grasslands on the Tibetan Plateau exhibited a stronger

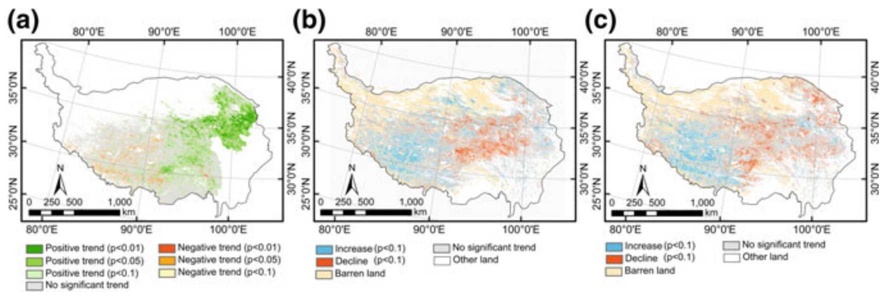

Fig. 14.3 Trends in **a** the growing season NDVI, **b** the start of the season, and **c** the end of the season on the Tibetan Plateau during 2000–2009 (Zhang et al. 2013; Wang et al. 2015; Guo et al. 2015)

response to changes in temperature at higher elevations than at lower elevations (Guo et al. 2015).

The remote sensing and monitoring of C_3 and C_4 grass species and their responses to climate change are mainly focused on the high-precision extraction of plant functional types and the transformation response of the grassland type to global climate change and human factors. In the U.S. Great Plains, vegetation with different functional types usually shows similar temporal trends in NDVI but different phenological characteristics (Wang et al. 2013). The onset of the growing season for C_3 grasses is earlier than that for C_4 grasses, and the growing season of C_3 grasses is longer. However, under mild weather conditions, C_3/C_4 short grasses have similar onsets of season dates and growing season lengths compared with C_3/C_4 tallgrasses (Wang et al. 2013). In northern China, a study by Guan et al. (2012) showed that temperate grassland was mainly occupied by C_3 species, yet C_4 species made an important contribution to the grassland biomass.

The fraction of photosynthetically active radiation (fPAR) is an important physiological parameter that reflects the growth of vegetation and is a key parameter for terrestrial ecosystem models and for reflecting global climate change (Fig. 14.4). Peng et al. (2012) found that the spatial variation in the global fPAR was affected

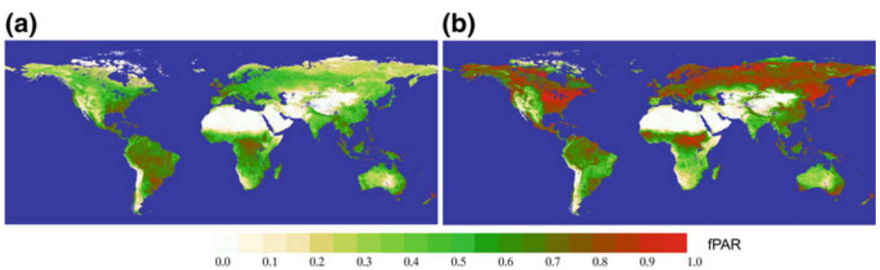

Fig. 14.4 Spatial patterns of global fPAR: **a** annual average fPAR in 2006, and **b** average fPAR in the latter half of August 2006. (Guo et al. 2015)

by the vegetation types as well as changes in the seasonal cycles. Temperature, precipitation and extreme drought have different effects on the fPAR. Climate change, deforestation, reforestation, and other human activities also significantly impact the fPAR in regions such as southeast Asia and the Three-North Shelter Forest area in China (Guo et al. 2015).

14.5.4 Radiation

(1) Impacts of aerosols on cloud cover and the regional radiation forcing effect

Based on satellite remote sensing data from aerosol-cloud-radiation and trace gases and meteorological observations, Xia (2010, 2012) analyzed long-term trends in the sunshine duration (SSD) and surface solar radiation and focused on the possible impacts of clouds on solar radiation in China over the last 50 years. The results indicated that the SSD and total cloud cover (TCC) showed a significant decreasing trend; however, with low-level cloud cover (LCC), a slight increasing trend was observed (Xia 2010). Short-term variability in the SSD is mainly determined by the amount of cloud cover, but the long-term change in the TCC cannot account for the decreasing trend in the SSD. Regarding the impacts of aerosols on clouds, Xia (2012) found that the data are inconsistent with the expectation that larger decreasing trends in cloud cover should be observed in regions with higher aerosol loading. Therefore, the aerosol effect on decreasing cloud cover in China does not appear to be supported by the results of their study (Guo et al. 2015).

(2) Spatiotemporal characteristics of land surface solar radiation in China

The land surface solar radiation in China and its temporal trends were calculated and the results demonstrate that previous studies overestimated the downward trend in land surface solar radiation in China (Tang et al. 2011). However, the aerosol abundance from human activities was still negligible on the Tibetan Plateau, and the decrease in solar radiation over the plateau was larger in magnitude than that for the rest of China after the 1970s. Further research revealed that the solar radiation on the Tibetan Plateau had continually decreased over the preceding 30 years due to the increasing water vapor and deep convective clouds. These increases were found to be connected to the warming climate and the enhanced effective convection energy of the Tibetan Plateau (Tang et al. 2011; Guo et al. 2015).

14.6 Digital Earth to Inform Climate Adaptation, Mitigation, and Sustainable Development

Effective strategies for climate change adaptation and mitigation require a comprehensive understanding of various underlying factors, including natural science, economics, society, and ethics. This makes climate change one of the most complex and challenging issues of modern times. Climate prediction and climate change projection are highly relevant to policy makers, investors, and vulnerable communities. The Digital Earth platform allows for investigations into many important processes that control the climate system, incorporates spatial dimensions at higher resolutions into the climate change context, and enables intuitive visual support for decisions and innovative actions. Strong visual and virtual demonstrations, supported by the Digital Earth platform, can help translate complex data into communicable information to support governments in decision and policy development and public information services.

Decades of Earth observation information is critical to improving predictions at different scales of climate projections. However, the existing remote sensing products have defects such as noise and time and space discontinuity (Brown et al. 2006; Jia et al. 2006). These defects severely constrain land surface processes and climate change simulations that are driven by spatial data parameters, and therefore reduce the reliability of climate change predictions and projections. It is necessary to synthesize multisensor remote sensing data to obtain high-quality and spatiotemporally continuous land surface observation data. The synthesis processes face the challenges of multisensor remote sensing data coordination and validation (Guo et al. 2015). These processes can greatly benefit from the Digital Earth data framework.

In addition to climate-sensitive environmental parameters, socioeconomic parameters characterize the demographic, socioeconomic, and technological driving forces underlying anthropogenic greenhouse gas emissions that have driven recent climate change and are key in the assessment of climate impacts, adaptation, and vulnerability. Conversely, the sensitivity, vulnerability, and adaptive capacity of socioeconomic systems also depend on their responses to climate change. The IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations recommend the use of socioeconomic scenarios, with and without climate change, to assess climate impacts and adaptive responses. This adds a layer of complexity to predicting future scenarios and is only possible in the integrative environment provided by the Digital Earth platform. The challenges in implementing socioeconomic scenarios in Digital Earth include compatible scales that match the socioeconomic and satellite data, and rational assumptions that represent the evolution of key socioeconomic drivers.

The Digital Earth platform can also support the implementation of the UN Sustainable Development Goals (SDGs) by providing a conducive platform for information and data sharing, access, and use, and as a multisource data fusion platform. In the near future, Earth science will extensively make use of large amounts of data to monitor and predict continuously changing climatic environments. The Digital Earth platform can handle the challenge of geographical big data and the new emerging threats from climate change more systematically and specifically (Elder et al. 2016; Guo et al. 2017). This greatly enhances preparedness, rapid response, and adaptation to extreme events (such as extreme weather events) and facilitates understanding of the climate and projection of climate change.

In addition to geographical big data, a new form of geo-referenced data from the internet and social media, when combined with newly available observational, reanalysis, or other data sources on the Digital Earth platform, can potentially expand the scope of climate change studies greatly and increase the spatial and temporal scales addressed. For example, by using data from social networking sites, smart phones, and online experiments, we can assess the vulnerability to weather events and the impacts of local and national policies and programs in real time (Hernandez 2017).

Digital Earth has great potential for increasing our understanding of global climate change and its impacts on various dimensions. It is a powerful platform for policy support in climate change adaptation and mitigation. New developments in emerging technologies such as "big Earth data", citizen science, the blockchain, and artificial intelligence further enhance the power of Digital Earth to support studies and actions on climate change.

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Gensuo Jia is a professor at CAS Institute of Atmospheric Physics and the Director of START Regional Center for East Asia. He serves as coordinating lead author of IPCC Special Report on Climate Change and Land (SRCCL). He has broad research interests in terrestrial ecology and atmospheric sciences, including remote sensing of land surface processes, ecosystem-climate interactions, climate extremes, and climate change impacts.

Li Zhang is a Professor in Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. She researches remote sensing applications for land-surface dynamics and coastal environment. She serves as the Steering Committee Member of the GEO Blue Planet. She has published over 110 scientific papers.

Lanwei Zhu is an associate professor, Institute of Remote Sensing and Digital earth, Chinese Academy of Sciences. She researches nature heritage change, coral reefs change and bleaching monitoring based on remote sensing.

Ronghan Xu is an associate professor at the National Satellite Meteorological Center, China Meteorological Administration (CMA). Her researches focus on climate change and extremes, land use/cover change, urban heat island, and thermal infrared remote sensing. She served as a lead author of global environmental outlook youth edition.

Dong Liang received B.Sc. and M.Sc. degrees in applied mathematics from the University of Hull, U.K. (2006), and Mälardalen University, Sweden (2009). He is pursuing a Ph.D. in cartography and GIS at the University of Chinese Academy of Sciences, with a focus on Big Earth Data and polar remote sensing.

Xiyan Xu is an associate professor at the Institute of Atmospheric Physics, Chinese Academy of Sciences (CAS). Her research fields cover land-atmosphere interactions, climate change, and climate effects of land use/cover change. She serves as a chapter scientist of IPCC Special Report on Climate Change and Land (SRCCL).

Tao Bao is an assistant professor at the Institute of Atmospheric Physics, Chinese Academy of Sciences (CAS). He researches changing soil and vegetation processes under climate change, land-atmosphere carbon flux, and interactive changes of climate and ecosystems in polar regions using field and satellite observations.

Chapter 15
Digital Earth for Disaster Mitigation

Milan Konecny, Temenoujka Bandrova, Petr Kubicek, Silvia Marinova, Radim Stampach, Zdenek Stachon and Tomas Reznik

Abstract This chapter describes the state-of-the-art of the potential of Digital Earth for progressively better solutions for disaster mitigation. The chapter illustrates the use of strong Digital Earth tools for data sharing and important potential for users, such as 2D or multi-D visualizations. Milestones of developments in early warning, disaster risk management and disaster risk reduction concepts are highlighted as a continuous movement between sustainable development and original concepts of disaster risk reduction. Improved solutions have been based on new research directions formulated in Sustainable Development Goals tasks and by expanding the possibilities of new effective solutions via newly organized data ecosystems generated by the United Nations Global Geospatial Information Management, the Group on Earth Observations and the Group on Earth Observations System of Systems, Copernicus and, more recently, the Digital Belt and Road initiative. The new trends in spatial big data are emphasized; the most important for disaster risk reduction are the basic theses of the U.N. Conference in Sendai. This chapter describes three aspects: innovative Digital Earth development, national and local disaster risk assessment and the benefits arising from the use of maps and dynamic data, and analyses of the contributions of cartography to disaster risk reduction.

Keywords Digital earth potentials · Big data · Risk assessment · Risk mapping technology · U.N. GGIM · DBAR

15.1 Introduction

In this chapter, we describe the state-of-the-art potential of Digital Earth (DE) for progressively better solutions for disaster mitigation.

M. Konecny (✉) · P. Kubicek · R. Stampach · Z. Stachon · T. Reznik
Laboratory on Geoinformatics and Cartography, Department of Geography, Masaryk University, Brno, Czech Republic
e-mail: konecny@geogr.muni.cz

T. Bandrova · S. Marinova
Laboratory on Cartography, University of Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria

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For over 20 years, DE has witnessed an ebb and flow in interest from the world's scientific community. Initially, it sought a place between activities focused strictly on maps, data and information (Global Map—GM, Global Spatial Data Infrastructure—GSDI, etc.). Later, it began to push through with a comprehensive concept and an emphasis on the need to share and integrate data and information, and impetus and knowledge from the scientific realm, the private sector, and the needs of people in different parts of the Earth. Today, novel solutions are expected from DE, which will also significantly help realize disaster risk reduction (DRR) and Disaster Mitigation projects. Al Gore (former vice president of the USA) described a concept and definition of Digital Earth in his speech in Los Angeles on January 1998, saying it is: "A multiresolution, three-dimensional representation of the planet, into which we can embed vast quantities of geo-referenced data" (Gore 1998). In 2008, Goodchild noted that "Digital Earth includes four aspects: visualization, ease of use, interoperability and mashups, modelling and simulation" (Goodchild 2008). Some of the best analyses of the potential of the DE concept in the European Union (EU) are the SWOT analyses by De Longueville et al. (2010a, b). Studies showed positive and attractive aspects based on the political and economic support of influential countries such as the USA, China and, more recently, Russia. They also found obstacles originating from overly complex DE approaches that did not fit the research concepts of the EU. Clarification of DE leadership was also an issue. These aspects are all important for finding more successful approaches to solve disaster mitigation and DRR problems that are natural, societal or economical, as well as complex ones including known and unidentified factors. In addition, knowledge and new technologies are developing. We now have access to new near- to real-time information resources such as Prevention Web, the knowledge platform for disaster risk reduction managed by the U.N. Office for Disaster Risk Reduction (U.N. DRR), and research analyzing some of the unsuccessful efforts in developed countries such as those during Hurricane Katrina and recommending adequate steps in the future.

Section 15.2 describes the terminology used in disaster mitigation and this chapter and as well as some of the supportive efforts of international scientific organizations. Section 15.3 describes the development of early warning (EW), disaster risk management (DRM) and disaster risk reduction (DRR) concepts. Section 15.4 describes Digital Earth for the future of disaster mitigation and DRR and innovative support of the implementation of the Sendai Framework and existing geospatial projects, including the U.N. Global Geospatial Information Management (U.N. GGIM), Copernicus, Global Earth Observation System of Systems (GEOSS) and Digital Belt and Road (DBAR). Section 15.5 introduces national and local disaster risk assessment and the benefits arising from the usage of maps and dynamic data. Section 15.6 analyzes and shows the development of selected disaster risk mapping approaches and technologies with examples of adaptation principles, context map composition and existing symbol systems. Studies have attempted to recognize how users and inhabitants understand information from databases, maps and specialized models. The final Sect. 15.7 discusses expected developments in the research and technology background in the near-future. It will be necessary to accelerate the creation of new concepts from new knowledge (like from the Hyogo Framework) and new environments created by the realization of ideas of the U.N. GGIM and Chinese DBAR. All these approaches were developed on the same background as part of new data and information media, demonstrating how the potential is open to all of society as well as specialists and decision makers. Some of the approaches, such as mobile tools and digital maps, are described in this chapter.

15.2 Terminology and Research Organization Efforts

A very important aspect of new approaches is the terminology. The United Nations International Strategy for Disaster Reduction (U.N. ISDR) created the first terminology from the fields of early warning, disaster risk management and disaster reduction, which has been updated according to development the field. In this chapter, selected terminology from the U.N. ISDR is used.

The definitions of disaster mitigation, emergency, disaster damage, disaster impact, disaster management, emergency management, disaster risk, acceptable risk, residual risk, disaster risk assessment, disaster risk management, disaster risk reduction, early warning system, multi-hazard early warning system, and vulnerability can be found in the U.N. ISDR (2009).

There are two globally operating organizations, the U.N. ISDR and Integrated Research on Disaster Risk (IRDR), which formulate global tasks in the disaster risk reduction (DRR) area. There are also activities in important world organizations and by members of the International Science Council (ICSU). The first working group and later the Commission Cartography for Early Warning and Disaster Risk Management were founded within the International Cartographic Association—ICA (in 2004 and 2007, respectively, arranged by Konecny). The activities of the International Society for Photogrammetry and Remote Sensing (ISPRS), which started the GI4DM organization, were also very fruitful as well as those of the International Federation of Surveyors (FIG), which was organized during Working Week 2016 in Christchurch, New Zealand, at the Recovery from Disaster conference.

15.3 Development of Early Warning (EW), Disaster Risk Management (DRM) and Disaster Risk Reduction (DRR) Concepts

In the past, DRM was solved together with problems of the environment, subsequently developed relatively separately, and a new DRR trend enhanced their close cooperation in contemporary sustainable development efforts. There are two lines of development in U.N. documents in approaches to crisis situations, both natural and anthropogenic. They are:

(1) Environmental, linked to finding the most appropriate environmental approaches to solve planet Earth's problems. They are mainly oriented around concepts of sustainable development (SD). As a first important document mentioning natural disasters in the Report on Approaches to Crisis Management Issues Related to Development, U.N. environmental policies were created at the United Nations Conference on the Human Environment in Stockholm on 5–16 June 1972 (http://www.biblebelievers.org.au/gc1972.htm). Later, this approach was documented at the United Nations Conference in Rio de Janeiro in 1992, in Johannesburg in 2002 and at many others.

(2) Crisis risk management (early warning, disaster management and disaster risk reduction). The second line of development includes the Yokohama and Hyogo World Conferences (1994 and 2005), the Global Platform for Disaster Risk Reduction in Geneva in 2010 and the key concept of the "U.N. International Strategy for Disaster Reduction" (ISDR—United Nations International Strategy for Disaster Reduction). Another concept was developed in disaster risk research, which addresses the problem of natural and human-induced environmental hazards in IRDR (Integrated Research on Disaster Risk) (Konecny et al. 2010).

Three United Nations Conferences focused on DRR have been held. First, the World Disaster Reduction Conference in Yokohama in 1994, which defined the Yokohama Strategy and Plan of Action for a Safer World: guidelines for natural disaster prevention, preparedness and mitigation. The Second World Conference on Disaster Reduction was held in Kobe, Japan from 18 to 22 January, 2005. The Hyogo Framework for Action (2005–2015) (HFA): Building the Resilience of Nations and Communities to Disasters was an outcome of the 2005 conference. The HFA set five specific priorities for action: (1) making disaster risk reduction a priority; (2) improving risk information and early warning; (3) building a culture of safety and resilience; (4) reducing the risks in key sectors; and (5) strengthening preparedness for response (WCDRR 2016). The third conference was the Third U.N. World Conference on Disaster Risk Reduction in Sendai, Japan in 2015 (United Nations General Assembly 2015). The goals and role of research in the realization of these topics are described in Sect. 15.4 of this chapter. The Sendai Framework materials highlighted the need to tackle disaster risk reduction and climate change adaption when setting the Sustainable Development Goals, particularly in light of the insufficient focus on risk reduction and resilience in the original Millennium Development Goals (WCDRR 2016).

15.4 Digital Earth for the Future of Disaster Mitigation and DRR: Innovative Support of the Implementation of the Sendai Framework

15.4.1 Sendai Disaster Reduction Conference Targets

In the Third U.N. World Conference (U.N. DRR) on March 14, 2015 in Sendai, Japan, the Sendai Framework for Disaster Risk Reduction 2015–2030 was adopted (United Nations General Assembly 2015). The U.N. DRR conference is a culmination of contemporary state-of-the-art approaches to solve the problems of risks and disasters on our planet. The conference materials mentioned the role of Information and Communication Technologies (ICT), geographical information system (GIS), remote sensing, mapping, sensors, and volunteered geographic information. The document does not mention explicitly Digital Earth, but the proposed solutions follow lines defined by Digital Earth pioneers and updated according to research frontiers in the world. The necessity of design for deep integration of data and information and the necessity of offering products to specialists, customers and all society in an understandable way were emphasized.

The Sendai Framework defined four new priorities of action:

- Priority 1: Understand disaster risk;
- Priority 2: Strengthen disaster risk governance to manage disaster risk;
- Priority 3: Invest in disaster risk reduction for resilience;
- Priority 4: Enhance disaster preparedness for effective response and "Build Back Better" in recovery, rehabilitation and reconstruction (United Nations General Assembly 2015).

The priorities are equally important to find better solutions, and the Digital Earth concept should be useful in addressing all of them. We discuss the priority 1 intentions here. Researchers know enough about individual disasters, but are weak in their knowledge when disasters are combined, as in the Fukushima nuclear power station collapse or the Wenchuan earthquake. It is very valuable that solutions are being accepted at global, national, regional and local levels. In priority 1: Understanding disaster risk, on national and local levels, there are requests to develop, periodically update and disseminate location-based disaster risk information such as risk maps to decision makers, the general public and communities at risk of exposure to a disaster in an appropriate format by using applicable geospatial information technology. In addition, local and national organizations promote real-time access to reliable data, make use of space and in situ information, including geographic information systems (GIS), and use information and communication technologies innovations to enhance measurement tools and the collection, analysis and dissemination of data.

The DRR framework defined in Sendai is inextricably linked with the main U.N. document defining the Sustainable Development Goals 2015–2030 (SDGs).

15.4.2 Global Development Policy Framework (GDPF)

With other U.N. documents such as the Sendai Framework for DRR 2015–2030, the SIDS Modalities of Action (SAMOA) Pathway, the Addis Ababa Action Agenda, the Paris Agreement on Climate Change and the HABITAT III Urban Agenda, the SDGs created a newly formulated Global Development Policy Framework (GDPF) (Fig. 15.1).

In addition to natural disasters, there are new issues connected with problems of cities or megacities from the geospatial information perspective in particular and for DE in general. These problems are defined in another activity of the GDPF—HABITAT III. Its key document "The New Urban Agenda" was adopted at the United Nations Conference on Housing and Sustainable Urban Development (Habitat III) in Quito, Ecuador (United Nations 2016) and represents a shared vision for a better and more sustainable future. If well-planned and well-managed, urbanization can be a powerful tool for sustainable development for both developing and developed countries. The conference reached a critical point in understanding that cities can be the source of solutions to, rather than the cause of, the challenges that our world is facing today.

The New Urban Agenda presents a paradigm shift based on the science of cities; it lays out standards and principles for the planning, construction, development, management, and improvement of urban areas. The agenda also incorporates a new recognition of the correlation between good urbanization and development. The New Urban Agenda realizes the 2030 Agenda for Sustainable Development, especially

Fig. 15.1 Global development policy framework. *Source* UN-GGIM: strengthening the global data ecosystem, by Scott, ©2018 United Nations. Reprinted with the permission of the United Nations

Goal 11 on Sustainable cities and communities. It also planned to adopt and implement DRR and management, reduce vulnerability, build resilience and responsiveness to natural and human-made hazards and foster the mitigation of and adaptation to climate change. DRR is aimed at preventing new risk, reducing existing disaster risk and managing residual risk, all of which contribute to strengthening resilience and therefore to the achievement of sustainable development. DRR is the policy objective of disaster risk management, and its goals and objectives are defined in disaster risk reduction strategies and plans.

To improve the quality of solutions in disaster mitigation and DRR, U.N. member states should facilitate the strengthening and normative capacity-building of global geospatial information management in support of the implementation of the 2030 Agenda. Efforts include promoting the use of geospatial information systems and services for modern mapping, methodological development, national and regional capacity-building, setting of standards, data collection, dissemination and sharing, and better integration of geospatial and statistical information systems of U.N. Member States.

15.4.3 U.N. GGIM

A newly established Global Data Ecosystem by the U.N. Global Geospatial Information Management (U.N. GGIM) will support realization of the SDGs, including all aspects linked with DRR, to respond to global data ecosystem needs. It helps to develop the global understanding of geospatial information and, in a second step, its coordination, coherence and implementation. The vision is to position geospatial information to address global challenges and missions to ensure that geospatial information and resources are coordinated maintained, accessible, and used effectively and efficiently by member states and society to address key global challenges in a timely manner.

In the U.N. GGIM, Scott defined the data needs for the 2030 Agenda as follows (Scott 2018): "The scope of the 2030 Agenda requires high-quality and disaggregated data that are timely, open, accessible, understandable and easy to use for a large range of users, including for decision making at all levels. There is a need for a reporting system on the SDGs that would have benefit from the subnational (local) to the national level; and allow for global reporting that builds directly on the data shared by countries. It is important to create an opportunity for countries to directly contribute to the global reporting. While the challenges are immense, the digital technology that is available today allows the necessary transformation. An aspiration is to strengthen countries' national geospatial and statistical information systems to facilitate and enable a 'data ecosystem' that leverages an accessible, integrative and interoperable local to global system-of-systems."

The U.N. GGIM is the newest initiative to qualitatively improve the potential to solve the problems of the world, including disaster mitigation. In addition, other important initiatives have the same aim in specific regions of the World—e.g., Copernicus for Europe and the Digital Belt and Road (DBAR) initiative in Asia.

15.4.4 Copernicus—A European Contribution to GEOSS

Copernicus (formerly Global Monitoring for Environment and Security—GMES) is a European project based on data received from Earth observation satellites and ground-based information. These data are coordinated, analyzed and prepared for end users. Through Copernicus, the state of our environment and its short-, medium- and long-term evolution are monitored to support policy decisions and investments. Copernicus plays key role in EU EW, DRM and DRR efforts. Copernicus mainly supports decision making by institutional and private actors. Decisions can concern new regulations to preserve our environment or urgent measures in the case of natural or man–made catastrophes (i.e., floods, forest fires, water pollution) on a global scale. The services are used by environmental agencies, local, regional and national authorities, and civil protection organizations. The new observation techniques and analysis of data will allow for these actors to better anticipate potential threats, to intervene in a timely manner and to increase the efficiency of the intervention. Figure 15.2 shows the structure and purposes of Copernicus.

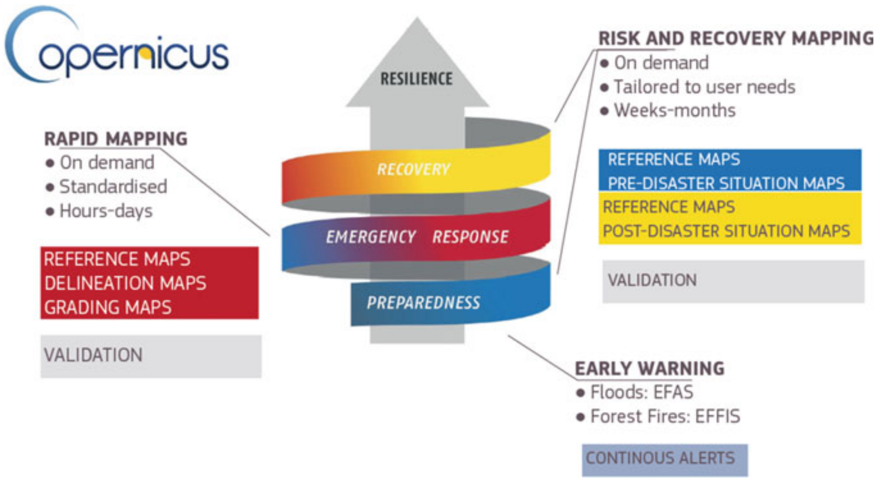

Fig. 15.2 Structure of Copernicus. Adapted from: EC (2019). Used with permission: Copernicus EU, European Commission

Copernicus (and its INSPIRE component) is the European contribution and participation in the worldwide monitoring and management of planet Earth organized by the Group on Earth Observation (GEO). The global community acts together for a synergy of all techniques of observation, detection and analysis. At the World Summit on Earth Observation in Washington in July 2003, the Group on Earth Observations (GEO) was established with the goal of addressing the information requirements for the environment on a global scale. In Brussels in February 2005, a 10-year implementation plan of an integrated global earth observation system of systems (GEOSS) was defined. A number of operational systems for supporting disaster response have made steady to strong progress. Collaborative supersites have been established for the scientific community to monitor and analyze volcanoes and earthquakes more rapidly and effectively; for example, supersites have improved the assessment of earthquakes in Haiti, China, Chile, and Indonesia. One example is SERVIR that provides mapping for disaster response and has assisted countries in Central America and the Caribbean in responding to hurricanes, earthquakes and other extreme events (GEOSS 2019).

15.4.5 Digital Belt and Road Program—Disaster Efforts

The Digital Belt and Road (DBAR) program and Digital Silk Road Alliance (DSRA) are relatively new activities initiated by the Silk Belt and Road (BAR) initiative. The DBAR is a pioneering international venture to share expertise, knowledge, technologies and data to demonstrate the significance of Earth observation science and technology and applications for large-scale sustainable development projects. The extensive geographical scope of the "BAR" initiative calls for smart uses and applications of big Earth data in the design, development and implementation of diverse projects related to infrastructure improvement, environmental protection, disaster risk reduction, water resource management, urban development, food security, coastal zone management, and the conservation and management of natural and cultural heritage sites. DBAR is committed to implementing projects and actions relevant to the 17 Sustainable Development Goals (SDGs) adopted by the United Nations in September 2015 (United Nations Brussels Team 2018). In the DBAR, natural hazards are an important issue. Belt and Road nations experience approximately 85% of the world's major earthquakes, tsunamis, typhoons, floods, droughts and heatwaves. For example, more than 86,000 people were killed or reported missing in a massive earthquake in Wenchuan, China in May 2008 and the 2004 Indian Ocean earthquake and tsunami killed hundreds of thousands of people. Seven of the top ten countries that saw major losses from disasters between 1995 and 2014 are in this region (Guo 2018, p. 26). The program monitors different types of ecosystems and their evolution, including grasslands, forests, glaciers, urban areas, farmland and coastal regions. Environmental and socioeconomic information will be shared through a platform for big Earth data, scheduled for roll-out between 2016 and 2026. This open-access gateway will allow for researchers, policy makers and the public to track changes, development and trends. The program will investigate indices and indicators to feed into the UN's 2030 Sustainable Development Goals (Guo 2018).

Working group 6 of the DBAR says that DBAR disaster aims to integrate Earth observations (EO) and social vulnerability data to promote implementation of the Sendai Framework in countries along the BAR region. The approach taken by this WG covers satellite information and communication technologies as well as implementation-oriented technologies that involve hardware solutions for risk reduction challenges. "If we do nothing, sensitive environments will be lost and exposure to risks will rise" (Guo 2018).

There are efforts to find solutions using newly defined ideas about big Earth Data. There are four main obstacles to a strategy for the Belt and Road region: poor access to data; a digital divide between developed and developing countries; a lack of awareness of the potential of Earth observations among some policy makers, local scientists and practitioners; and a lack of collaboration. These are long-standing problems—they also slowed emergency responses during and after the Indian Ocean tsunami in 2004, for example.

Important consequences of DBAR strategies necessitate research on new approaches and knowledge improvements. There should be proof of concept for the data. Guo is developing a new concept of big Scientific data and big Earth Data (Guo 2017, p. 4): "Big data is a revolutionary innovation that has allowed the development of many new methods in scientific research. This new way of thinking has encouraged the pursuit of new discoveries. Big data occupies the strategic high ground in the era of knowledge economies and also constitutes a new national and global strategic resource. "Big Earth data", derived from, but not limited to, Earth observation, has macro-level capabilities that enable rapid and accurate monitoring of the Earth, and is becoming a new frontier contributing to the advancement of Earth science and significant scientific discoveries. … Big data research is different from traditional logical research. It uses analytical induction applied to a vast amount of data to statistically search, compare, cluster, and classify. It involves correlation analysis and implies that there may be certain a regularity in the relation between the values of two or more variables; it also aims to uncover hidden correlated networks."

The substantive characteristics of big data computing comprise a paradigm shift from model-driven science to data-driven science, as well as the establishment of a data-intensive scientific approach.

As a branch of big data, scientific big data is a typical representative of data-intensive science. Scientific big data has a number of characteristics, including complexity, comprehensiveness, and global coverage, as well as a high degree of integration with information and communication technology. The approaches used in science are also being transformed—from single-discipline to multidisciplinary and interdisciplinary approaches, from natural science to the integration of natural and social sciences, and from work carried out by individuals or small research groups to projects coordinated by international scientific organizations.

In addition to helping scientists solve hard or previously unsolvable problems through real-time dynamic monitoring and analysis of various related data, the data itself can become an object and tool of research: scientists can conceive, design, and implement research based on the data (Hey et al. 2009 in Guo 2017).

Earth science research, including the atmosphere, land and ocean, has produced huge datasets derived from satellite observations, ground sensor networks, and other sources. This is collectively called big Earth data. Big Earth data has features in common with scientific big data and also has unique characteristics. Big Earth data is characterized as being massive, multisource, heterogeneous, multitemporal, multiscale, high-dimensional, highly complex, nonstationary, and unstructured. It provides support for data-intensive research in the Earth sciences. Modern Earth science requires globally established, quasi real-time, all-weather Earth data acquisition capabilities, and has developed an integrated space-air-ground observation system with high spatial, temporal, and spectral resolutions (Guo 2017).

To realize the above-mentioned efforts, the ISDE organization initiated the Digital Silk Road Alliance (DSRA), established in Sydney in April 2017 with the support of the China Association for Science and Technology (CAST), with the aim of building a network of scientists involved in the Digital Belt and Road initiative and using Digital Earth and geospatial information technologies to solve the scientific problems facing human beings, and to address problems related to the U.N. Sustainable Development Goals.

The DSRA wants to develop Digital Earth in the fields of cartography, remote sensing and geo-information sciences, which are essential for socioeconomic development. Further development of cooperation mechanisms and frameworks toward the development of Earth observation systems and Digital Earth is expected. It is important to use such approaches on global and regional levels in the realms of Earth observation and Digital Earth.

15.4.6 GGIM and DBAR Comparisons and Potential

Comparing the contemporary differences between the U.N. GGIM and the DBAR, the U.N. GGIM is a mature project connected with stable governmental and public infrastructures aiming to address the needs of the SDGs and Sendai DRR and contemporary needs of civil society and its organizations. DBAR has similar ambitions but primarily originated from the countries where spatial data infrastructure (SDI) and national data infrastructure (NSDI) were still not fully developed according to the Silk Belt and Road. The DBAR has a new approach to look for and elaborate big data, mainly based on satellite images. There are still missing concepts regarding delivery of data to interesting groups, the private sector and individual inhabitants (such as the U.N. GGIM using INSPIRE knowledge and experiences). Along the Belt and Road, countries have different political and economic systems and different data, information and knowledge policies. There has been great investment in the DBAR, which created hopes for fast improvement of the situation, but data and information are only part of the efforts, including DRR. In many countries, geoinformatics and cartography are unappreciated. Maps are created without knowledge of how they will be accepted by users (context and adaptive maps) and how the information should be delivered for professionals and public users. This is very important in EW, DRM and DRR.

It is difficult to say which areas will benefit more from Digital Earth. Because the problems are very complex, their solutions require powerful and adaptable tools. Digital Earth is based on integration of various streams and determination of adequate decisions. Informed decisions also rely on the wishes, opinions and reactions of societies, which can be collected via information from social media or volunteers in the field.

It is likely that the main tasks of the U.N. GGIM will be realized incrementally. DBAR activities elaborating important and new aspects of the big data reality will create new situations in data policies in the countries along the Silk Road and Belt. Convergence of both streams will be inevitable and will lead to realization of the dreams of the founders of SDI and NSDI as well as appreciation of modern visualization methods, mainly cartographical ones. Those methods will help experts and the contemporary public to understand problems and cooperate to create solutions for disaster mitigation problems.

15.5 Digital Earth for National and Local Disaster Risk Assessment

Digital Earth is suitable for reporting practices that have been already tested and implemented in one locality and can be successfully adapted in another. Sharing of practices is important in any field of human activity, including disaster risk management. As noted by Amaratunga et al. (2015), sharing of sound practices is intended to improve knowledge sharing for exchange of data and experiences between users on every level—global, national and local.

15.5.1 National Level

The goal of every state is to identify and minimalize risks in its territory. In the Czech Republic, a group of emergency management experts studied the emergency threats and vulnerabilities (Paulus et al. 2016) and identified and categorized the most typical emergency situations. From this analysis, 22 typological emergency situations were pinpointed. A detailed and typified plan for each emergency was defined, including the responsible public administrative organization and the administrative level on which the plans are used (central, regional, local). An indispensable part of each typified plan is the list of recommended spatial data and maps necessary for a successful reckoning of a particular emergency. Public administration bodies are responsible for the development of action plans on the regional and local levels and for identification of key stakeholders.

15.5.2 Local Level—Cities and Urban Areas

A report titled "State of Disaster Risk Reduction at the Local Level: A report on the Patterns of Disaster Risk Reduction Actions at Local Level" (Amaratunga et al. 2015) focuses on disaster risk reduction in urban areas: "Fast growing cities and urban areas of the world increase disaster risk due to economic growth and fast population expansion. … Sound practices that have been tested and implemented by different cities around the world aid knowledge sharing opportunities for future disaster risk reduction. … The intent is to provide local governments and other institutions learn from one another by effectively facilitating the sharing of sound practices and disseminating these established sound practices in risk reduction."

Ten essential goals and examples of well-functioning solutions for local governments to make their cities more disaster-resilient were defined and are listed below (U.N. ISDR 2012).

15.5.3 Existing Methodologies for Risk Assessment

Overviews of how to map and estimate risk have been presented by several scholars (Kappes et al. 2012; Klucka 2014; Forzieri et al. 2016). The European Commission published the Risk Assessment and Mapping Guidelines for Disaster Management (EC 2010), but it was not the first draft of such a pan-European manual. For example, the output of the European project Interreg IIIC Interregional Response to SIPROCI, to which seven countries contributed, is even wider and more thorough than the above mentioned EU final document but was never fully implemented at the European level (SIPROCI 2007). An example of a major non-EU agency that deals with risk discovery and estimation is the Federal Emergency Management Agency (FEMA) from the USA. FEMA announced the release of the State Mitigation Plan Review Guide in 2016 (FEMA 2016) that aids state, tribal, or local governments in developing hazard mitigation plans.

15.5.4 Using Maps for Risk Assessment

An important part of any methodology for identifying and estimating risks is the design of presentations to professionals and the general public. The ideal way to view the risk estimates clearly is a map. The significance and role of maps is described in the book Successful Response Starts with a Map (National Research Council 2007), prepared as a Hurricane Katrina analysis. The creation of maps for risk identification was also described by the above mentioned SIPROCI project (2007) and by other authors including Carpignano et al. (2009) and Winter (1993) described in Dymon (1994). Carpignano et al. (2009) described the development of a decision support system based on a multirisk approach that can overcome difficulties in the overall risk assessment for a territory. To define multirisk maps, a multirisk perspective and stakeholder's perceptions were integrated into a classical risk assessment frame. The specific purpose of this work is to describe the methodological framework built at this stage of the project and discuss the initial results.

Dymon (1994) describes a hazard management map taxonomy offered by Winter (1993) that regards hazard, risk and emergency as the three major categories:

- Hazard maps identify and display the location of hazard zones, areas where there are dangers to humans and their property.
- Risk maps (vulnerability) require calculation of the conditional probability that a given area will experience a particular hazard or a combination of hazards and portray the spatial distribution of those risk computations.
- Emergency maps comprise three additional types: planning, evacuation and crisis maps.

The SIPROCI report (2007) provides a comprehensive method for risk mapping. However, specific proposals were not included in the official final methodology (EC 2010). However, conclusions and recommendations were incorporated into the methodology, such as the by the Fire Rescue Service in the Czech Republic (Krömer et al. 2010), which recommends creating the following types of maps:

- Hazard map—a summary map of the different types of hazards, i.e., a digital map of the manifestations of individual types of emergencies.
- Vulnerability map—the indicator of accumulated vulnerability of the territory as a sum of partial elements of vulnerability.
- Preparedness map—readiness in the territory can be expressed as the availability of forces and means (components of the integrated rescue system) and the availability of means of protection of the population (e.g., coverage of the territory by end elements of the warning).
- Risk map—a summary of all the above map types.

In its official methodology, the EU Risk Assessment and Mapping Guidelines for Disaster Management (EC 2010) only include general recommendations for preparing these types of maps:

- Maps of the spatial distribution of major hazards show the spatial distribution of all relevant elements that need to be protected, such as population, infrastructures, and naturally protected areas.
- The spatial distribution of vulnerability in terms of the susceptibility to damage for all relevant subjects.
- These maps can then provide the basis for the preparation of risk maps in terms of showing the combination of the likelihood and impact of a certain event, as well as for creating of aggregated hazard maps.

However, specific mapping requirements for risk assessment only appear in EU directives for flood mapping such as the Floods Directive (EC 2007). Flood risk mapping is the area of disaster management in which mapping methodologies have advanced the most. The EU directive on the 'Assessment and management of flood risks' requires Member States to conduct an initial assessment for flood hazard maps and flood risk maps:

- The hazard maps should cover geographic areas that could be flooded according to different scenarios. Flood hazard maps show the extent of floods at high- (optional), medium- (at least a 100-year return period) and low-probability floods or extreme events.
- Risk maps should show the potential adverse consequences associated with floods under those scenarios.

15.5.5 The Benefits of Digital Earth for Risk Assessment—Using Dynamic Data

Creating maps with the standardized content and symbolism mentioned in the previous section is necessary for preparing the components of an integrated rescue system for crisis situations and for managing them. However, the basis of the Digital Earth concept is not the creation of printed and static maps, but the dynamic sharing of different types of data, including near-real time data sharing. The development of electronics, networks, databases, data sharing (included in Digital Earth) brings new possibilities for risk assessment.

As an example, for a risk assessment at a particular location and at a certain time, it is possible to take advantage of the current location of mobile phones, from which the present population can be estimated more accurately than using the standard census data. Extensive studies focused on different aspects of human presence estimation based on mobile phone data have been presented, particularly from Europe and Asia (Ahas et al. 2010; Batista e Silva et al. 2013; Cao et al. 2017; Järv et al. 2017; Kang et al. 2012). Kubíček et al. (2018) proposed analysis of human presence using data from mobile operators. The analysis is based on a dataset describing the estimated human presence (EHP) with two values—visitors and transiting persons—depending on the overall time spent within a specific mobile cell.

The advantage of using the EHP numbers over data from a census was analyzed during the Integrated Rescue System training held in 2017 in Brno, Czech Republic. The goal was to decide where to locate water tanks with supplies of drinking water for inhabitants in case the standard water supply network becomes contaminated.

This emergency situation is demonstrated in Fig. 15.3. "The location-allocation analysis on the leftmost side only takes into account census data and evenly distributed population throughout the administrative unit. Each water tank can supply approximately 2000 people. The second analysis adjusts the water tank locations according to the real locations of buildings and population in administrative units. The third and fourth analysis quantifies the EHP for working days and weekends. Using of EHP proposes a greater number of necessary water tanks in administrative units, and their optimal locations change according population fluctuations" (Kubíček et al. 2018).

Risk assessment is addressed at different levels (international, national and local), and each of these levels has its own goals and uses. It is very useful to share experiences and data between these levels. This allows for generalization of knowledge and results from the local level to the national and international levels. Such analyses can become an engine for developing better risk assessment methods and disaster mitigation. The Digital Earth concept linking databases and enabling data sharing provides a methodological and technological background for this goal.

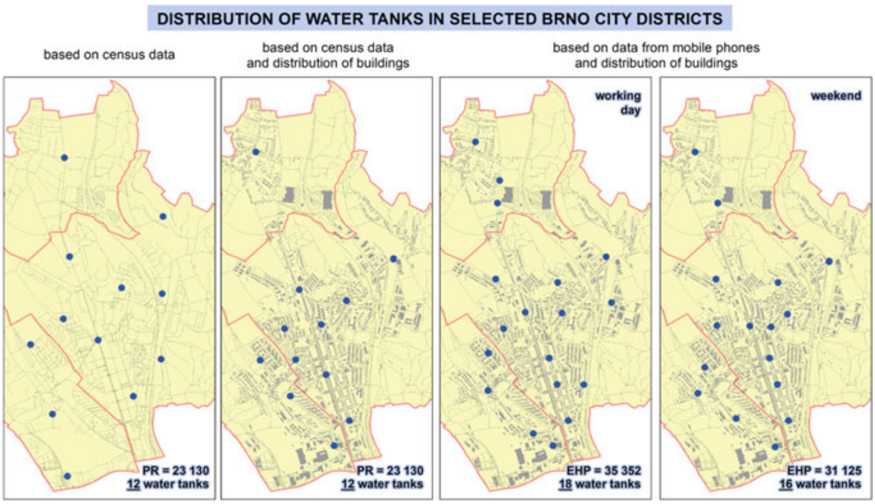

Fig. 15.3 The role of the spatiotemporal distribution of the population in the case of a water shortage. Reprinted from Kubíček et al. (2018) by permission of Taylor & Francis Ltd.

15.6 Digital Earth and Disaster Risk Mapping Technology

15.6.1 The Role of Cartography in Disaster Risk Mapping

In the frame of disaster risk mapping, geographic knowledge is crucial for making proper decisions. The importance of spatial information and its potential support for emergency actions were stressed and evaluated by several authors (Kevany 2008; Zlatanova and Li 2008; and Konecny 2006). Among the various ways to transmit, share, and visualize geographic knowledge, cartography is one of the most important. Cartography and geoinformatics have experienced a huge technological shift over the last 30 years. Digital Earth systems have become important foundations for data management related to geographic phenomena.

The application of dynamic cartographic visualization opens the possibilities of adaptive cartography. It allows for creating maps of current risks (e.g., current and predicted flooded area or direction of fire spread), the location of nearby emergency services, or escape routes for the population at risk.

The theory of using adaptive cartography for emergency management geographic support was described by Reichenbacher (2003) and Meng (2005). This method is based on the idea of geographic data visualization automation and adjustment according to the situation, purpose and user's background (Reichenbacher 2003).

The adaptation of maps can generally be defined by a number of "Ws"—what, when, where, who, and how—as documented in Fig. 15.4. It illustrates the types of contexts that can influence the conditions of disaster risk mapping.

		type of context	
What ?	What happend?	*SITUATION*	**EMERGENCY CONTEXT**
	What needs to be done?	*ACTIVITY*	
When?	When the event occured?	*TIME*	
	When the activity is realised?	*PHASE*	
Where?	Where the event occured?	*LOCATION*	
	(What area) is affected by the event? (What) is the extent of the activity?	*OPERATIONAL RANGE*	
Who?	Who is the user of the map?	*USER ABILITY*	
	Who is the data manager?	*DATA MANAGEMENT*	
How?	How the map is used?	*MAP FUNCTION*	
	(What) is the size of the display?	*TECHNOLOGY*	

Fig. 15.4 Possible contexts influencing map use and mapping. Adapted from Kozel et al. (2011)

15.6.2 Use Case Examples

The adaptive mapping principles described in the previous section were demonstrated in several scenarios, e.g., Talhofer et al. 2007, Mulickova et al. 2007. One of the scenarios, called "FLOOD", aims to improve flood management. A case study was practically verified in the winter of 2011/2012, when one of the field experiments was performed. Based on an analysis of the flood management system in the Czech Republic (Kubíček et al. 2011), five main ACTIVITIES were defined for the Flood Use case (SITUATION):

- PREDICTION AND PROGRESS—development and expected progress of the flood
- TECHNICAL SUPPORT—technical support in the inundated area—support of Flood Security Activities
- RESCUE—the evacuation of citizens
- ORGANIZATION—an organization of powers and means
- PUBLIC INFORMATION—information for the public on flood development, evacuation, etc.

Some of the ACTIVITIES defined above are universal (e.g., organization) and may be performed in different SITUATIONS whereas others (e.g., flood prediction) are situation-specific.

There were a few principal operational ranges defined in the presented use case: FLOODPLAIN for detailed information on the inundation, REGION/DISTRICT/MUNICIPALITY to comply with the hierarchical order of the flood management system, CATCHMENT to monitor the flood at natural borderlines, and SECTION for a detailed view of the municipality.

15.6.3 Use Case Adaptation Principles

The fact that an object is evaluated from the perspective of a defined context is fundamental to the map symbol adaptation process. The most important aspect of the geographic feature may not be the character of the object as defined by the data source, but what ROLE it plays in the decision-making process. The map symbol is an expression of such a ROLE. Because the data are typically collected for purposes other than emergency management, semantic relations must be defined, and new roles should be specified.

Based on context, the semantic relevance is assessed. Information on the geographic object is relevant if it is necessary for the decision-making process within the context. The relevancy assessment is important from the cartographic point of view since the large number of objects that are visualized on the map limit its legibility and thus the effectiveness of the cartographic visualization as a decision support tool.

When information is relevant, we can assess the degree of relevancy and use other cartography means to increase/decrease the importance of a spatial object or phenomena. The relevancy degree can be assessed for both the semantic and spatial aspects, as illustrated in Fig. 15.5.

The activity and the crisis event itself undergo temporal changes and thus the object properties change as well. For example, if the water level is rising and another house is endangered or a house is already evacuated. These facts should be considered during map symbol design.

15.6.4 Context Map Composition

The process of data model definition is illustrated in Fig. 15.6. The emergency context defines the basic data model (e.g. the information content of the map), and relevant

relevancy	*criterion*	*example*	*parametres - symbols*
SPATIAL	location to important object/phenomea	house vs. predicted flooded area	inside close to far from
SEMANTIC	importance for activity	fire stations according to category	high middle small

Fig. 15.5 Degrees of spatial and semantic relevance. Cartographic symbols prepared by L. Friedmannova. Adapted from: Brezinova et al. (2011)

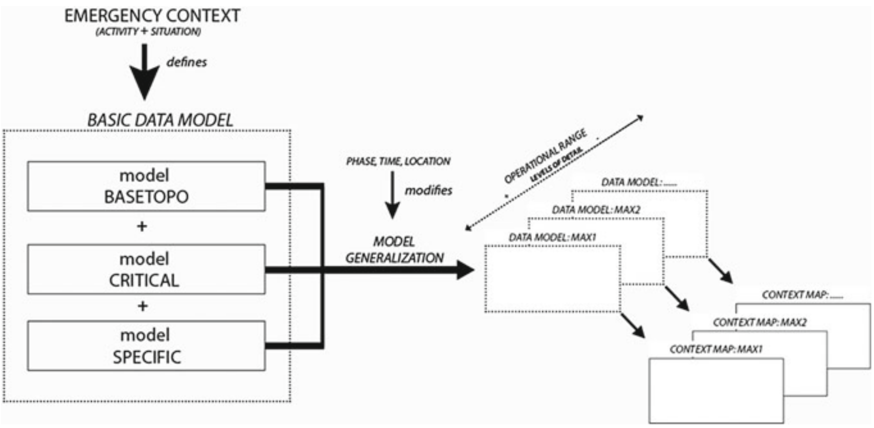

Fig. 15.6 Data model definition. Adapted from Mulickova (2011)

features of the models BASETOPO, CRITICAL, and CONTEXT SPECIFIC are selected. The basic model is then modified as the context is more precisely specified (i.e., according to the PHASE). The model is generalized and further specified for each level of detail within the operation range.

The examples of a context map for flood management in Fig. 15.7 document different context views of the spatial database. Context maps for three emergency contexts—PREDICTION (A), RESCUE (B, D) and ORGANIZATION (C) are shown. The level of detail corresponds with the operation range “section”. Maps share the same topographic background (i.e., BASETOPO) and, to a certain extent, flood-SPECIFIC features (i.e., the flood extent and buildings in it). The visualizations differ in activity-specific features—i.e., features specific to prediction (flood activity degree, number of affected persons), to the organization (places of intervention and its description) and to the rescue efforts (evacuation zones, routes). The features of the CRITICAL model are not included.

Maps A and B in Fig. 15.7 illustrate the phase of preparation—there is no flooding yet but there is a prediction of flooding. At that time, houses are endangered. In the response phase (Maps C and D), houses are already affected. The visualization changes are based on the progress of the disaster event.

Maps B and D support the same activity (i.e., rescue) but in different phases. The maps display visualization changes based on the progress of the activity. In the preparation phase, the zone of evacuation is marked and buildings for evacuation are selected. In the response phase, all the buildings are already evacuated.

A possible technical implementation is described in detail by Kozel (2009) and Kozel and Štampach (2010).

15.6.5 Existing Symbol Systems for Disaster Management

Cartography plays a key role in disaster management for a clear representation of the necessary objects and phenomena to decision makers. Upon the occurrence of disasters, crisis management actors need specialized maps to provide a clear idea of the emergency, localization, distribution and characteristics. One of the objectives of cartographers is to design effective representation of spatial information through graphic symbols (Akella 2009). The symbols should indicate information about depicted objects and phenomena without the use of a legend, especially in an emergency. They should also provide users qualitative and quantitative information for the presented object or phenomenon (Konecny and Bandrova 2006).

A number of agencies and organizations related to disaster protection have developed databases, geo-portals and cartographic products for crisis management and adopted their own standards for symbols.

One of the most popular symbol systems for crisis management is the set of 500 humanitarian symbols of the United Nations Office for the Coordination of Humanitarian Affairs (OCHA). The symbols are freely available at http://reliefweb.int/ and aim to help disaster responders present information about crisis situations

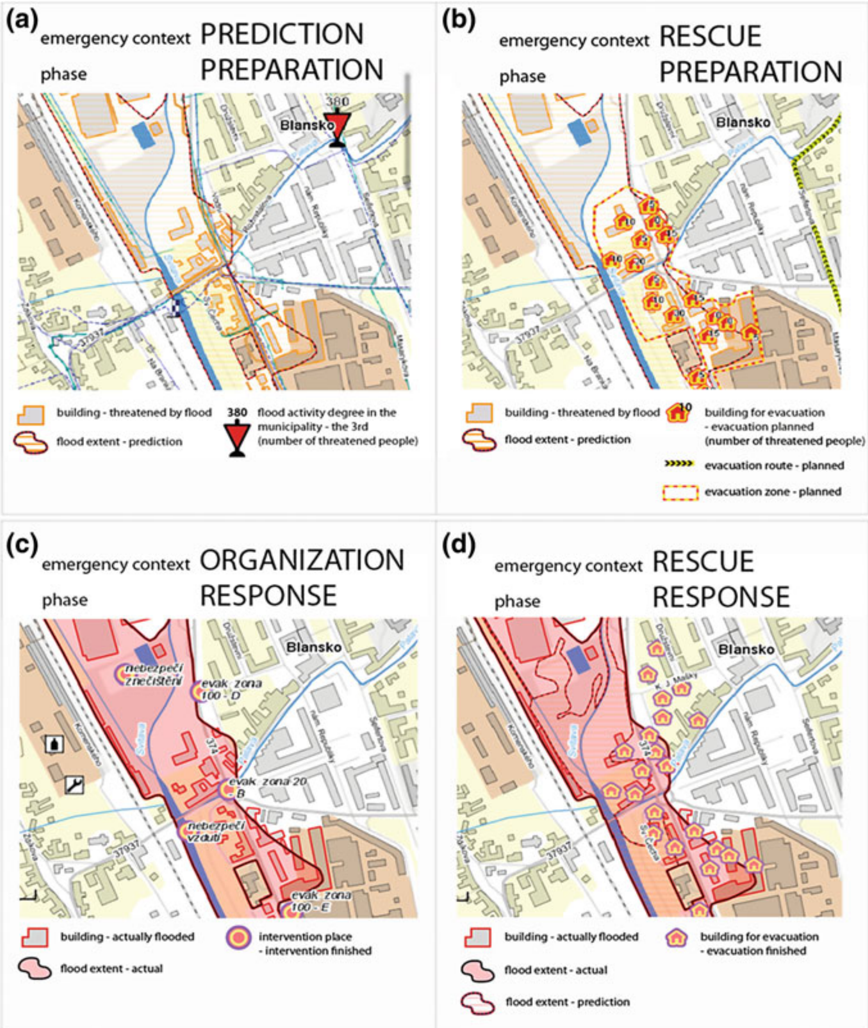

Fig. 15.7 Examples of context mapping for various phases of the emergency management cycle. *Source* Mulickova and Kubicek (2011)

quickly and simply (United Nations Office for the Coordination of Humanitarian Affairs 2012). The symbols can be used to produce humanitarian reports, maps, and websites. The OCHA humanitarian icons are divided into 17 categories. The set of symbols covers both disasters and activities, including the supply of water containers and equipment shelter, access to people in need and protection of civilians. The icons are associative and have a simple structure that allows for easy comprehension.

The Emergency Mapping Symbology (EMS) in Canada was developed under the auspices of GeoConnections, with participation from emergency management organizations across Canada. It was designed to be used by federal, provincial, regional and local organizations involved in the management of major events, disasters, and other incidents where emergency help and security are needed (GeoConnections 2010). The EMS contains a set of symbols and a four-level, hierarchical classification of the entities. The categories include incidents, infrastructures, operations, and aggregates. Symbols in the same category have similar colors. There is also a second version of the symbols adapted for black and white printing.

The Association of Volunteer Emergency Response Teams developed a project called Disaster Response Map Symbols (DRMS) as an effort to compile a standard set of symbols aimed to support the creation of efficient maps for disaster management. It comprises 285 symbols. The DRMS contains 5 families of symbols in a single font, including vehicles, infrastructure, mobile/temporary services and teams, events, ships and some special symbols (Association of Volunteer Emergency Response Teams 2009).

Another popular symbol system is the symbology developed by federal, state, and local agencies in the USA working together under the auspices of the Federal Geographic Data Committee (FGDC) Homeland Security Working Group. The symbol system includes symbols and their definitions for the categories of incidents, natural events, operations, and infrastructures. The structure of each category and a damage-operational status hierarchy were developed using color and frame shapes with line patterns (Homeland Security Working Group 2017). The symbols are designed to be presented in color or black and white formats.

The cartographic symbols should have clear and short definitions to be used in a map legend. One very important characteristic is that they are situated on a map and should indicate qualitative and quantitative information about the represented object, phenomena or process to users.

Considering the advantages and disadvantages of existing emergency symbol systems, a new symbol system for the needs of disaster management was developed at the Laboratory on Cartography of the University of Architecture, Civil Engineering and Geodesy in Sofia. The Symbol System for Disaster Management (SSDM) was developed to support thematic mapping for early warning and crisis management and operational activities of all participants in disaster management, as well as to help citizens understand specialized emergency maps. The SSDM was designed to be useful for the general public as well as for professionals.

15.6.6 *Opportunities for New Disaster Risk Mapping Technologies*

The technological shifts in cartography and geoinformatics were on the level of data analysis and visualization, bringing new data sources from different sensors and mapping strategies. One of the most notable examples of this is cell phone data.

Data derived from active cell phones or active SIM cards for some administrative units are becoming available for various uses (see an example from the Czech Republic, the O2 Liberty API, https://www.o2.cz/podnikatel/liberty-api/). Analysis of the number of SIM cards and existing demographic data has opened a novel set of possible applications for emergency management and disaster risk mapping. The availability of cell phone data enables the following:

- More accurate estimation of the actual number of inhabitants within the administrative unit and their temporal rhythms (example on Brno, Czech Republic in Kubíček et al. 2018). Comparing such an analysis with the existing census data and annual demographic reports (see Fig. 15.8), the administrative units can be further divided into several typological units (with the maximum during working days, weekends, etc.) In addition, the population estimations can be used to better plan the evacuation and other inhabitant-sensitive activities during emergencies.
- The cell phone data analysis often reveals regular trends as described above and some irregular peaks and peculiarities. These high concentrations of inhabitants are connected with cultural and sports events such as concerts and music festivals.

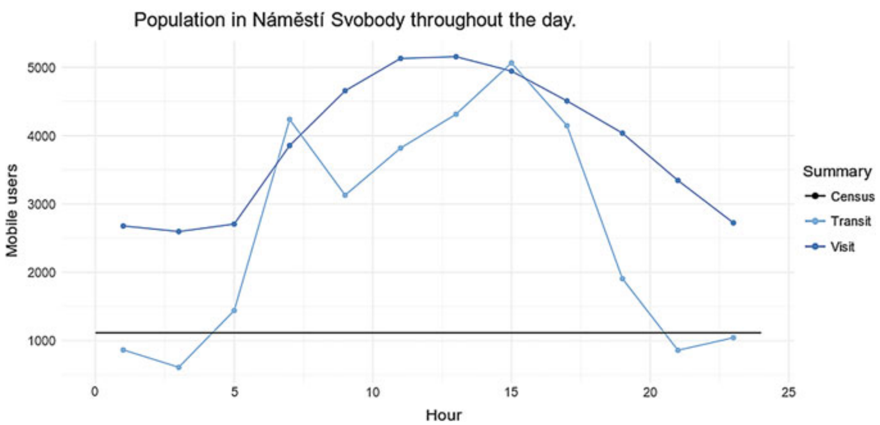

Fig. 15.8 Variability of the population in an administrative unit Náměstí Svobody, Brno, Czech Republic. Comparison of cell phone and census data. Reprinted from Kubíček et al. (2018) by permission of Taylor & Francis Ltd.

15.6.7 Future Directions—New Symbol System for Disaster Management (SSDM)

The examples, approaches and case studies described above provide various opportunities for future development and applications such as the development of virtual and augmented reality tools and devices. The Digital Earth concept can be also understood as a virtual reality system (Çöltekin et al. 2019).

The new cartographic Symbol System for Disaster Management (SSDM) was created in Bulgaria after proposing a classification structure of represented objects and phenomena, construction and design of symbols, implementation in real situations and use in map compiling for disaster preparedness.

15.6.7.1 Classification Structure

The SSDM consists of a 4-level hierarchical classification of objects and phenomena concerning disaster management and a set of 115 symbols. At the highest level, the objects are divided into 5 categories: disasters, infrastructure, protection services and safety infrastructure, affected people and infrastructure, and operational sites and activities. Each category is divided into classes, which are divided into subclasses that consist of objects and phenomena (Fig. 15.9).

15.6.7.2 Design of Symbols

The ability of symbols to transmit information and the way they are perceived by map users are critically important. The design process of the SSDM started with consideration of the rules of construction and use of symbol systems, examination of the relations between objects and phenomena, their classification and specifics.

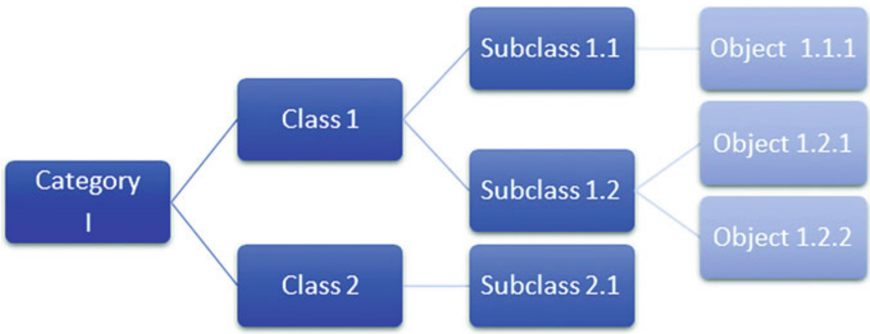

Fig. 15.9 Classification structure *Source* Marinova (2018)

The design was accompanied by optimal requirements to achieve readability, expressiveness and visibility, taking into account modern technologies and techniques in cartography. It is challenging to choose graphical variables so that all the symbols can be quickly and easily perceived and are associative and properly referred to their respective categories.

All categories of the SSDM are distinguishable by their shape and color. The symbols consist of white pictograms and shapes with various background colors. The choice of background colors, except to achieve clear distinctiveness, depends on the message that the symbols should express to the users. A psychological perception of the colors was taken into account. The different shapes for the categories aim to avoid potential problems resulting from low light or black and white printing.

Each category has an individual letter code for easy identification: A—disasters; B—infrastructure; C—protection services and safety infrastructure; D—affected people and infrastructure; and E—operational sites and activities. Each object and its respective symbol have an alphanumeric code formed by the category code and the serial number of the object in its category.

Figure 15.10 presents part of the symbol system, including the alphanumeric code, graphic symbol and a brief description.

The status of objects in "infrastructure" and "protection services and safety infrastructure" in a crisis situation is represented by a combination of symbols in category B (infrastructure) and category C (protection services and safety infrastructure), with symbols representing destroyed, affected and unaffected objects of category D shown in a reduced size (Fig. 15.11).

15.6.7.3 Maps for Disaster Protection

The new Symbol System for Disaster Management was applied in experimental development of training maps supporting actions in emergencies and in a series of maps for disaster protection at local and regional levels. The main tasks of local and regional disaster protection plans are the analysis and assessment of disaster risks, prevention and mitigation, early warning, and coordination of disaster management activities. Participants in these activities need specialized geographic information to support concrete actions.

The SSDM was applied in the production of base maps of the municipality of Troyan, Bulgaria, at a scale of 1:50000 (Fig. 15.12) and Troyan at a scale of 1:10000 (Fig. 15.13). The maps were compiled according to predefined elements of map content and aim to support activities described in the disaster protection plan of the municipality.

The main features of hydrography, settlements, infrastructure (including transport, telecommunication, energy, manufacturing and water infrastructure) as well as services and facilities related to disaster protection (such as hospitals, shelters, and helicopter pads) are represented by the SSDM. Based on the main disaster protection maps, a series of maps for disaster management in case of earthquakes, floods, fire, and industrial accidents were created. Additional information was provided for

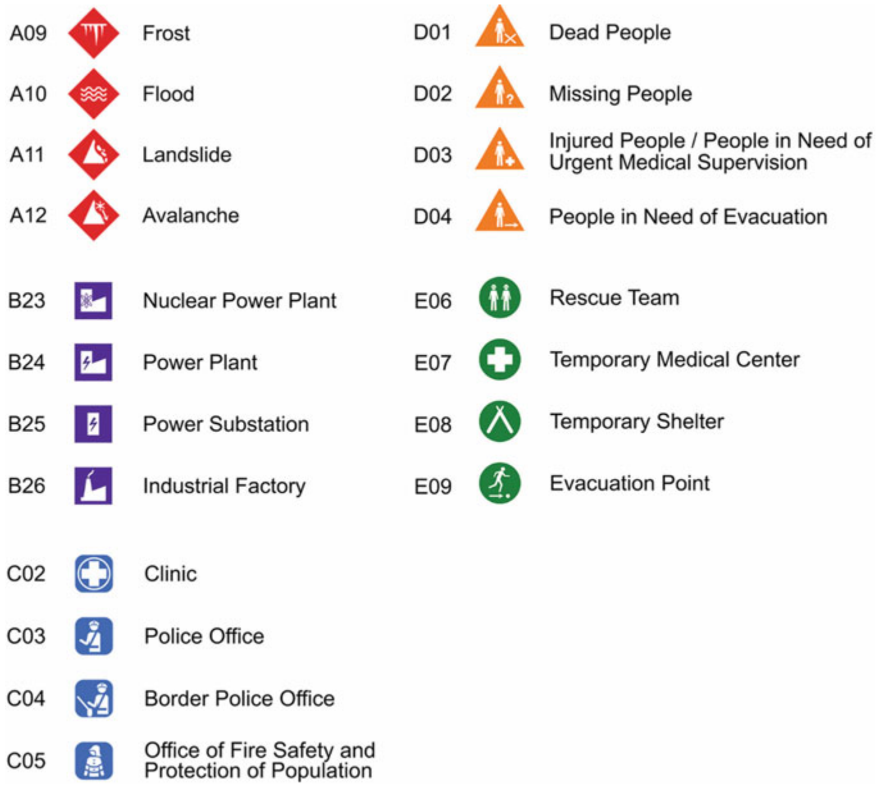

Fig. 15.10 Symbols of the symbol system for disaster management (SSDM) *Source* Marinova (2018)

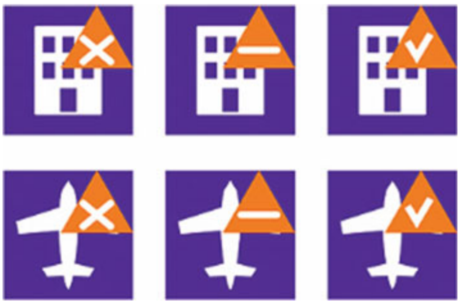

Fig. 15.11 Symbols to present affected infrastructure *Source* Marinova (2018)

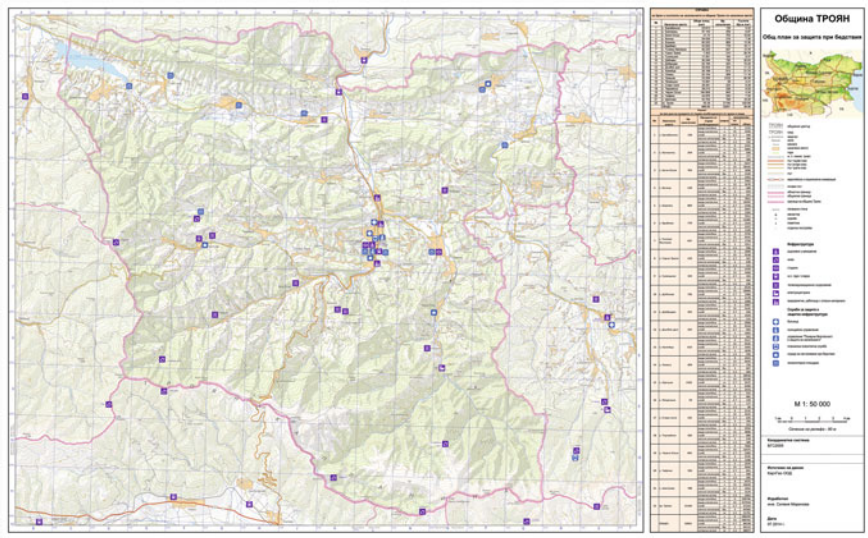

Fig. 15.12 Base map for disaster protection *Source* Marinova (2018)

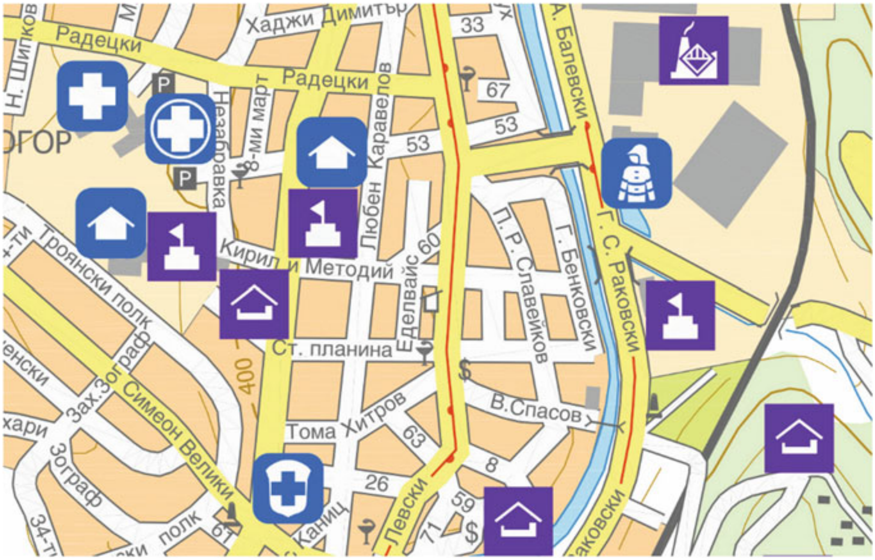

Fig. 15.13 Base map for disaster protection (partial). *Source* Marinova (2018)

Fig. 15.14 A map for evacuation planning Adapted from: Marinova (2018)

some features including the object name and description, number of beds in shelters, dangerous industrial objects, type of stored materials, and fire-fighting equipment. Infrastructure and services/facilities for protection are represented by the symbols in Category B and Category C (Fig. 15.13). These maps also support predisaster activities, including assessment and preparedness.

In a crisis situation base maps can be processed into rapid and reference maps presenting the type and location of disaster(s) by adding symbols from Category A and symbols for affected people and affected infrastructure in Category D (Fig. 15.14). The symbols for operational sites and activities (Category E) could be useful for damage assessment and recovery in the postdisaster stage.

The map content and displayed information of operational situations could help support the responsible authorities and individuals to make timely and effective decisions. Such maps could allow for identification of the affected areas in municipalities or regions, and provide significant contributions to population protection, mitigation and evacuation planning operations.

Cartography plays a key role in the main stages of disaster management. Efficient and cooperative preventive and protective activities of authorities require appropriate and easily understood geographic information. The use of a standard system of associative symbols can facilitate significantly cooperative disaster management strategies at local, regional and international levels.

15.7 Conclusion

Disaster mitigation and DRR are complicated processes, and solutions could be improved by using powerful tools such as Digital Earth. The concept of DE covers almost all activities occurring in ICT in the contemporary world. To be successful in employing the right solutions, we need to create improved concepts that consider the newest knowledge about disaster mitigation and DRR. To realize this, we need well-organized data and information such as in data ecosystems (as in the U.N. GGIM) that reflect the complexity of the problems to be solved, defined by the SDGs. Sharing data and information, visualization with the help of digital maps, cartographic models and their combinations hold important promise to support decision makers and society with true and understandable outputs to help to comprehend situations, to create instructions and standards on how to behave in various situations, and to be ready when risks transform into disasters. This chapter highlighted the newest projects, including the U.N. GGIM and DBAR. In the future, these approaches with commonalities and differences should be developed to support smart solutions for human society.

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Milan Konecny is a Professor at Masaryk University, Czech Republic. He was/is a Guest Professor of the Chinese University of Hong Kong, the Henan University, the Shenzhen University, the Vienna University, etc.; a President of International Cartographic Association; Acting President and the Vice President of International Society for Digital Earth and Academician and Vice-President of International Eurasian Academy of Science.

Temenoujka Bandrova is President of Bulgarian Cartographic Association and head of Laboratory on Cartography, University of Architecture, Civil Engineering and Geodesy, Sofia. She is a Vice-President of ICA and treasurer, bureau member of ISDE. She is an author of 40 school atlases and more than 100 wall maps.

Petr Kubicek is an Associated Professor at the Masaryk University. He specializes in digital cartography and geoinformation infrastructure. Kubicek cooperates with the International Cartographic Association commissions on Use, User and Usability Issues and Cognitive Issues in Geographic Information Visualization. He is a member of the national GeoInfo Strategy team.

Silvia Marinova is Secretary General of Bulgarian Cartographic Association and Chief Assist. Prof. at University of Architecture, Civil Engineering and Geodesy, Sofia. She also serves as a cartographer at KartGeo. Her science interests are focused on thematic mapping for disaster management, cross-border mapping and mountain cartography.

Radim Stampach Ph.D. is a lecturer and GIS specialist at the Masaryk University. He is interested in using VGI data and maps in crisis management and for humanitarian purposes.

Zdeněk Stachoň Ph.D. works as an assistant professor on the Department of Geography, Masaryk University. He focuses mainly on the principles of map design, cognitive aspects of cartographic visualization, and the geographic support of decision making. He is a member of the Czech Cartographic and Geographic societies, member of editorial board of M.A.P.S. edition.

Tomáš Řezník is an Associated Professor of Cartography, Geoinformatics and Remote Sensing at the Department of Geography and a vice-head at the Laboratory on Geoinformatics and Cartography (LGC) at Masaryk University. He worked as a post-doctorate scientific/technical project officer at the Joint Research Centre (JRC) of the European Commission, within Digital Earth and Reference Data unit (currently Digital Economy unit).

Chapter 16
Digital City: An Urban Perspective on Digital Earth

Davina Jackson and Richard Simpson

Abstract Digital Earth and many other satellite and semiconductor-enabled cartography advances imply the need for a globally useful schema for more scientific and eco-ethical management of cities. How should we plan an internationally cohesive and locally effective system for understanding and managing urban stocks and flows around our planet? The answer to this question depends on new systems for managing geodata to underpin increasingly automated systems for evidence-based decision making. The current concept of Digital Earth as a "self-aware nervous system" is being advanced by urban proto-projects that are supported or followed by globally applicable initiatives including Singapore's new Geospatial Masterplan, the International Standards Organization's City Standards, Denmark's Open Public Life Data Protocol, and the City-GML data model. These recent ventures are progressing a movement that extends far beyond the 1990s concepts of "smart cities" enabled by wireless telecommunications. In the Digital Earth science paradigm, cities must simulate their key situations and scenarios and analyze Earth observation data obtained via satellite-enabled devices that remotely detect and interpret all the light and radio waves of the electromagnetic spectrum.

Keywords Data cities · Geospatial · Digital urbanism · GEOSS · Digital earth · Earth observations · Smart cities · Urban modeling · Geodesign

16.1 Introduction: Satellites Meet Cities

The Digital Earth project (Gore 1992, 1999; Goodchild et al. 2012; Craglia et al. 2012; Jackson and Simpson 2012) is aligned with the intergovernmental program for a Global Earth Observation System of Systems (GEOSS was launched in 2005, the same year as the online commercial globe Google Earth; Group on Earth Observations (GEO) 2007, 2015; Jackson and Simpson 2012). These and many other satellite

D. Jackson (✉)
School of Architecture, University of Kent, Canterbury, UK
e-mail: dj5@kent.ac.uk

R. Simpson
Department of Infrastructure Engineering, University of Melbourne, Melbourne, Australia

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and semiconductor-enabled cartography advances imply the need to produce a globally useful schema for more scientific and eco-ethical management of cities (Ratti and Claudel 2016). This aspect of Gore's Digital Earth dream remains far from reality and was promoted earlier by Richard Buckminster Fuller, beginning with his 4D Air-Ocean World Town Plan concept diagram (Fuller 1928; Fig. 16.1), followed by various urban synergetics proposals and prototypes. These contributed to his influential late-career book *Operating Manual for Spaceship Earth* (Fuller 1969), which was published exactly fifty years before this *Manual of Digital Earth*.

How should we design an internationally cohesive and locally effective system for understanding and managing urban stocks and flows around our planet? This question requires comparisons and integrations of significant concepts published and prototyped by key scientists, technology innovators, architects and other leaders of the urban informatics revolution; especially since Fuller died in 1983.

His original World Town Plan sketch was invented when "computers" were mathematically minded people, more than a decade before German engineer Konrad Zuse invented the first electromechanical, stored-program computing machine; his Model Z3 was first demonstrated in 1941. Fuller expired shortly after *Time* magazine named "The Computer" instead of a human recipient for its annual "Man of the Year Award" cover feature (Brosan and Segal 1982).

Fig. 16.1 Fuller's air-ocean world town plan diagram, 1927–28 (Estate of R. Buckminster Fuller/John Ferry)

Although his vision of an electronic infrastructure to operate Spaceship Earth was inspired by radar and airplane autopilot systems, satellite navigation was not commercialized widely for terrestrial vehicles until the early 1990s. Accompanying the advent of GPS (global positioning system) devices linked to American NAVSTAR satellites were magazine and newspaper reports forecasting commercialization of the internet as a "new information superhighway" and revolutionary television and telephony advances (Negroponte 1993, 1995; Gates 1995). Leading professors of town planning and architecture expected computers to accelerate "smart cities" (Gibson et al. 1992) and the MIT Smart Cities Lab was founded by William J. Mitchell in 2003. Other urban prophecies included "fractal cities" (Batty and Longley 1994), the "city of bits" (Mitchell 1995) and "intelligent environments" (Droege 1997). At the time of writing this chapter, the world's main satellite navigation systems were GPS (US), BeiDou (China), Galileo (Europe) and GLONASS (Russia; Hunter and Hartcher 2019). We suggest that all of these 1990s terms emerged in response to global commercialization of wireless and mobile telecom infrastructure—and that this century's Digital Earth and GEOSS planetary systems simulations vision demands a new emphasis on the cruciality of satellite-enabled remote sensing data; thus, we now use the term Data Cities when considering the urban aspects of Digital Earth.

All of those end-of-century writers (and others before and since) highlighted that "wireless" (actually extensively cabled) telecom technology was unlocking a crucial new way to understand cities: not as static compositions of buildings and streets but as dynamic, unpredictable and increasingly networked flows of activity and connections. However, until recently (Jackson 2018) there was little emphasis on how satellites have become essential to what Batty called "a science of cities" (Batty 2005, 3; 2013) and Stephen Wolfram termed "a new kind of science" (Wolfram 2002) that would interpret fractal and cellular automata principles of evolutionary growth and behavior.

Satellites allow for today's environmental scientists and designers to use increasingly sophisticated machines and programs to monitor and simulate various processes that Jay Forrester termed "urban dynamics" (Forrester 1969). City monitoring and modeling are being accelerated by increasing numbers and constellations of Earth-observing (EO) satellites, including squads of tiny CubeSats carrying miniature remote sensing instruments. These include scanners and sensors to scrutinize atmospheric and ocean conditions for meteorological and marine agencies (producing data that are visualized dramatically for television weather reports). They also include many devices that use all the wavelengths of the electromagnetic spectrum to continually survey the world.

Earth observation methods such as SAR interferometry, GNSS reflectometry (GNSS-R), radar altimetry and lidar sensing are revealing many structures and activities that normally cannot be viewed by humans or have been long obscured. Some dramatic recent examples are digital heritage discoveries and detailed 3D mapping of various ancient cities that were lost for centuries under tropical jungle foliage or catastrophic floods. Specialists in digital archaeology can study early stone carvings under thick coats of dirt and moss, and explore fabled burial grounds, perhaps without touching a spade (Venkataramanan 2014).

For professionals developing and managing contemporary cities, satellite-enabled land surveying has become vital to understanding existing circumstances with unprecedented accuracy—allowing designers, decision makers and stakeholders to share the same eyewitness evidence in discussions of proposals and problems.

To understand how satellite technology and data are being applied to solve today's environmental planning and management challenges, Davina Jackson (coauthor of this chapter) devised a matrix diagram of five research themes and their flow-on priorities and projects in government, commerce and public sector contexts. Drafted from 2008 to 2011, it was published in a GEO-sponsored snapshot report on the scope of the GEOSS/Digital Earth project (Jackson and Simpson 2012, 5; Fig. 16.2). All five research themes are being pursued concurrently towards the ideal of a global model of complex environmental systems. They are natural systems modeling (NSM; projects simulating certain area-defined environmental behaviors), building information modeling (BIM; creating virtual models of structures and testing the viability and defects of each design before on-site construction), city information modeling (CIM; 3D mapping, satellite and aerial imagery, remote sensing and data analytics at scales from street corners to megalopolises), virtual nations and networks (VNN; data management and mapping the environmental conditions of countries,

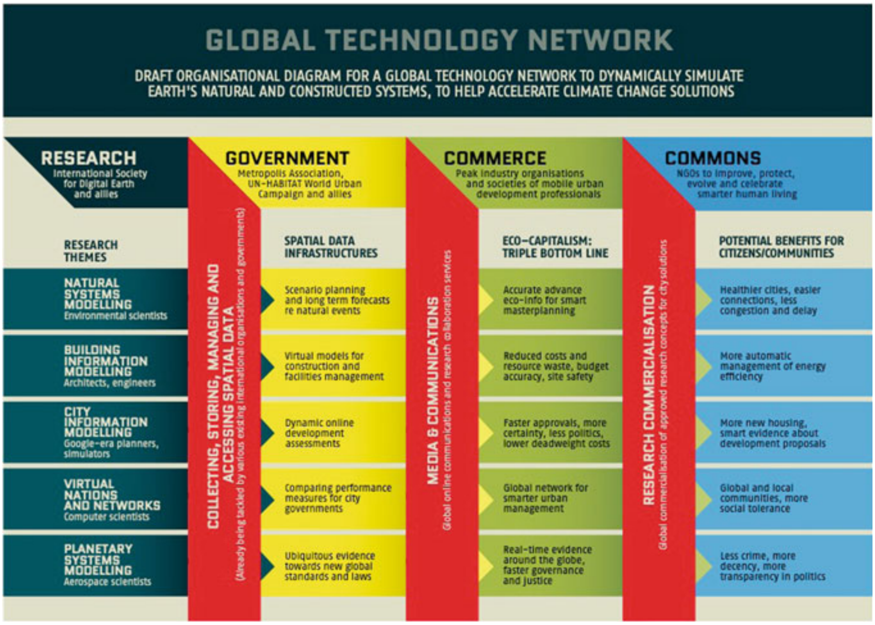

Fig. 16.2 Jackson's global modeling network concept diagram, 2008–2011 (Jackson and Simpson 2012)

multinational regions or continents—e.g., Virtual Singapore) and planetary systems modeling (PSM; integrated 3D data mapping of environmental conditions around the Earth).

All five scales of Earth observations and simulations must be integrated to achieve the concept of a global EO system of systems but the diagram identified them separately to reflect the reality that most researchers operate within specific professional disciplines and domains of study (Fuller 1980). The following sections explain current activities and recent projects that contribute to the integration of data and modeling that is transforming urban development.

16.2 Global and Dynamic Data Mapping of Cities: A New Cartography Paradigm

The Digital Earth vision and GEOSS program are both evolving through collaborations between several hundred international governments, space agencies, science, research and standards organizations, and United Nations entities (UN Global Marketplace n.d.). These groups are organizing different advances towards the system of systems that has begun to allow users to access, analyze, visualize and exploit the data collected by Earth observation instruments aboard or networked with satellites. In this section, we identify how this system is being progressed in ways that may help reform obsolete, insular and ecology-damaging practices by millions of influential actors in urban development and city governance roles.

Today's collaborations are underpinned by shared understandings of the imperative to scientifically tackle the deadly impacts of climate change, including extreme weather events (natural catastrophes), loss of biodiversity, rising sea levels, and extreme heat and drought (UNDP n.d.). Two key UN bodies are leading the task of broadly communicating information and strategies to deal with these wicked problems: the Intergovernmental Panel on Climate Change (IPCC), which releases five-yearly scientific reports recording the world's environmental threats and performance, and the UN Framework Convention on Climate Change (UNFCCC), which organizes annual conventions where relevant organizations discuss, and participating governments agree, how they will reduce ecology-damaging practices in their countries.

Another UN organization, the UN Development Programme (UNDP), globally promotes seventeen sustainable development goals (SDGs) that include climate action and sustainable cities and communities (UNDP n.d.) and other, mainly urban, agendas. Its urban targets for 2030 include upgrading slums, increasing the resilience of communities that are vulnerable to disasters, reducing the environmental impacts of cities, improving air quality and waste management and providing affordable, useful public transport and housing.

Certain places are evidently dangerous to occupy—flood plains, fire and earthquake zones, or countries prone to war. Vast land areas, especially deserts or polar regions, are shunned because they seem inhospitably dry or frozen. Should they be invigorated via hydro- and geo-engineering? This matter is being debated by ambitious scientists and engineers through their academic and professional organizations.

Many properties near water—clifftop mansions on New York's Long Island or entire island states such as Tokelau and Nauru—risk subsidence and submersion through the same forces (freak waves, storms and rising sea levels) that caused ancient monumental cities such as Thonis (Egypt) and Harrapan (India) to slide into the sea. Cyclones sometimes destroy popular resorts on South Pacific islands and towns along Asian coasts, and fires seasonally burn through leafy suburbs in southeast Australia and southern California. Residents of large hillside cities in Central America and South America—like La Paz in Bolivia—understand that their homes suddenly might slip down their slopes of clay. All these dangers appear to be escalating with the global warming that Swedish scientist Svante Arrhenius first predicted in 1896. He calculated that global temperatures would rise by 5 °C with the doubling of carbon dioxide burned into the atmosphere. This prediction seems consistent with today's UN forecasting of a 5 °C temperature increase globally by 2050 (UNDP n.d.).

In Geneva, the International Centre for Earth Simulations (ICES Foundation) archives scientific and press reports of environmental disasters on its website (Bishop 2018). Its articles from September 2017 to March 2018 included photographs of a hotel tower falling after a Taiwan earthquake, bridges collapsing in Colombia and Florida, homes buried under mudslides in southern California, a volcano erupting in Bali and Hurricane Irma battering Caribbean countries and Miami. ICES, led by Bob Bishop, a scientist expert in high-performance, real-time computer simulations, aims to establish an advanced computing facility in Switzerland for modeling complex environmental systems. His foundation offers a worldwide QLARM message service that promptly predicts and maps likely building damage and human casualties after earthquakes (Wyss n.d.). More than 1000 alerts have been issued since 2002 using geological data from the Swiss Seismological Service, settlement records from the *World Housing Encyclopedia* and population statistics. ICES also completed earthquake vulnerability studies of Haiti (for the Swiss Department of Foreign Affairs) and Kyrgyzstan (for Médecins Sans Frontièrs).

In recent lectures, Bishop analyzed the challenges and potential for building "an open, integrated, wholistic model of Planet Earth for decision support, disaster reduction and public good"—the same vision as the GEOSS, Gore's 1990s Digital Earth and Fuller's 1960s Spaceship Earth. He warned that quantities of data—mostly unstructured data—are growing far faster than global computing power—and that both are insufficient to crunch solutions for the world's many serious environmental and sociopolitical threats. He predicted that, as well as quantum computing systems, global simulations projects will ultimately be improved by neuromorphic computing to imitate information processing by human brains. Recent projects to develop neuromorphic chips include TrueNorth by IBM, SpiNNaker by Manchester University and BrainScaleS, initiated by Heidelberg University. The two academic ventures have transferred to Europe's Human Brain Project (HBP), which aims to substantively upgrade today's energy-guzzling computers built with von Neumann architectures (Modha n.d.). Bishop (a former chair of the HBP advisory panel) suggested that, while these computing capacity ambitions are being pursued, current projects can reduce energy consumption by installing processor-in-memory (PIM) technologies to use big data, preferably without moving it. While computer architectures would be global, the data should be applied to solve local urban and regional problems.

European scientists recently published the first sophisticated satellite mapping of the world's human settlements, depicting four decades of population statistics and machine-analyzed Landsat data, including some information on building heights, footprints and materials. Launched in 2012 as the Global Human Settlement Layer (GHSL dataset for GEOSS; Pesaresi et al. 2016), this project is included in the GEO Human Planet initiative that was announced at the 2016 United Nations Habitat III conference on settlements. As well as identifying several major new cities in Asia that were not UN-recorded, it applied astrospatial (developed for space exploration), geomatics (terrestrial monitoring) and telematics systems to the formerly paper-centric domains of land surveying, cartography, architecture and town planning. Outstanding 3D and 4D visualizations of the GHSL data, depicted as "population mountains", were produced by Alasdair Rae (Rae 2016, 2018) and Matt Daniels (Daniels 2018a, b).

The first example of global 3D video-mapping of urban population (including growth) statistics was Japan's PopulouSCAPE project, which included a 10-minute *Night Flight Over an Urbanizing World*, providing aerial views of cities as surging towers of population (visualizing UN Figures) and intercity transport and communications connections (Ito et al. 2005; Team PopulouSCAPE 2005). Another historically significant example of planet-scale modeling of cities was the *Pulse of the Planet* real-time video visualization of AT&T data recording telephone and internet traffic between New York and other cities. Produced by a Carlo Ratti-led team at MIT's SENSEable City Lab, it was shown in the *Design and Elastic Mind* exhibition at New York's Museum of Modern Art (MIT SENSEable City Lab 2008). These two projects were perhaps history's first world-scale depictions of the data cities movement (Jackson 2008; Jackson and Simpson 2012)—following some important mid-2000s video simulations of specific cities such as the *Virtual London* model (showing flood and shadow simulations) by University College London's Centre for Advanced Spatial Analysis (2002–2005) and the *Real-Time Rome* mobile phone data-mapping show at the Venice Biennale by MIT's SENSEable Cities Lab (2006).

One notable new world urban mapping project is the Global Urban Footprint (GUF), led by Thomas Esch's team at the Earth Observation Center of the German Space Agency (DLR, Fig. 16.3). Scatters of tiny black dots show settlement patterns with unprecedented detail and precision, using radar data from the TerraSAR-X and TanDEM-X pair of satellites operated by the DLR and Airbus Space and Defence. Although only depicted in 2D, the GUF shows the global distribution of human settlements with an unprecedented spatial resolution of 0.4 arcsec (~12 m), using 180,000 satellite scenes expressed in grayscale: black dots for urban areas, white for land and gray for water (DLR n.d.; Fig. 16.4). This instantly informative data visualization (seen on-screen via a swirling sphere) refreshes the adage that new technology

Fig. 16.3 Global Urban Footprint map by the German aerospace center (DLR/Thomas Esch)

Fig. 16.4 Sunlight control modeling for Auckland city (1988), with the operative envelopes visualized as “stained glass” windows (Cadabra)

paradigms (such as 3D time-series video-mapping) are not the only, or always the best, tool for communicating specific information in certain circumstances. As an obvious example, audio remains preferable to video when people are walking or driving cars.

16.3 Global Advances in Computer Design, Analysis and Construction

This section highlights five significant advances in data modeling solutions for major challenges in designing and managing built environments.

16.3.1 Environmental Performance Control Envelopes

New Zealand's Resource Management Act, passed in 1991, was ground-breaking legislation for the nation to conserve and sustainably manage its natural resources: land, air and water. It was underpinned by one of the world's first cases of using architectural computer modeling (then known as CAD, computer-aided drawing, now updated as BIM, building information modeling) to pretest the potential environmental impacts of new building proposals. Approval by a New Zealand court of law for uses of 3D computer models as evidence was first granted for the appeal of a planning decision that delayed construction of Auckland's Sky Tower. As the tallest freestanding structure in the Southern Hemisphere, Sky Tower was a radical departure from the city's conservative urban landscape and would not have been publicly acceptable without using computer simulation and 3D visualization to articulate the regulatory, design and environmental impacts (Fig. 16.4).

Before the Resource Management Act, basic prescriptive rules were used by NZ planning authorities to maintain unimpeded sunlight for specific open spaces. This approach was refined during the years after the 1987 stock market crash, when city property values slumped. In 1988, the Auckland City Council commissioned Cadabra, an applied computer graphics consultancy led by Richard Simpson (coauthor of this chapter) to develop one of the world's first performance-based 3D virtual city models to allow for patterns of sunlight to be more specifically and accurately simulated.

Cadabra's approach was to calculate an overarching operative control envelope (OCE) for the central city. This performance-based envelope was generated from an accurate 3D terrain model of the city, including twenty-seven designated public places (mostly parks) that were to maintain access to sunlight and views. The sunlight controls for these places were evaluated for every moment of the year to determine the overall impact that each would have on the city height limits. The result was a set of twenty-seven envelopes that intersected in complex and dramatic ways in 3D and 4D space above the virtual city skyline. The overarching operative envelope was determined by overlaying all the place-specific envelopes and defining the combined surface minimum to define the OCE.

This operative surface had the appearance of an exaggerated rugged terrain in the sky. It defined a "battle" between ground-based controls. In one place, one control might have a sweeping influence on the height of a potential new building, then would be overridden by another control. The hilly nature of the inner city, protection criteria, and eclectic formats of park boundaries all contributed to this complex expression through controls on the generated operative envelope. Visually, this model appeared like a paint-by-number on a wildly rumpled canvas.

The operative envelope was visualized as a contour plot of heights above a datum. The model enabled performance-based sculpting of the city's urban envelope and regeneration of the individual sunlight controls to ensure solar irradiation for any place for specific periods of the year and times of day. It was also rendered in 3D with proposed and existing 3D CAD models of buildings. If a building complied with the control, it would be visually obvious as it would not breach the envelope. The rendering treated each control as a differently colored "stained glass" window and thereby visualized the volumetric influences of controls in the airspace and throughout any day. Colored light for a specific control might flood the ground to clearly show the influence of any specific control through a day or year.

The final design of Auckland's OCE was published as a set of regulatory contour maps in the 1991 district scheme. This work defined the aesthetic balance and shape of Auckland's skyline and enabled a paradigm shift from obsolete prescriptive controls to more evidence-precise and context-responsive performance controls. The modeling removed legal ambiguities and provided more clarity and certainty for citizens to enjoy maximum sunlight and views when using public spaces.

16.3.2 Geodesign

In 2001, Pascal Mueller, then a postgraduate student at ETH-Zurich's Future Cities Lab, introduced CityEngine, a procedural modeling program to rapidly generate and modify basic forms of buildings in urban scenes. It offered designers flexibility to change the heights and floorplates of specific buildings on the fly, using process scripts rather than the prescriptions of parametric modeling. When commercially launched in 2008, it could generate a realistic 3D online (flythrough) depiction of Venice's Gothic-Byzantine building stock in a few minutes. Users could transform the heights and areas of one or various buildings, and simulate shadows cast at different times of day and year. Since 2011, CityEngine has been owned and updated by Esri, the world's largest commercial GIS mapping software supplier, to integrate with its formerly offline and 2D (pre-Google Earth) suite of ArcGIS mapping tools. Esri's transition to online 3D dynamic modeling and what-if design tools, and its SYMAP-derived topographical data mapping, catalyzed a new educational-promotional venture that the company's founder, Jack Dangermond, launched with the name Geodesign in 2010 (Steinitz 2012, 2013; De Monchaux 2016).

Until recently, the GIS packages needed by surveyors and land-planning professionals have been used separately from the building design (BIM and CAD) programs required by architects and building engineers. However, some surveying firms such as Britain's Severn Partnership are marketing "Scan2BIM" skills to provide point clouds of 3D laser-scanned, geotagged data about existing buildings and landscapes, giving precise bases for modeling structural alterations. Another example is the *ThermalMapper* project in Bremen, where Dorrit Borrmann and Andreas Nüchter from Jacobs University recorded a 360° aerial point cloud of the city square with temperature data from nine thermal images overlaid on eleven 40° laser-scanned poses of the historic buildings, plaza and streets. They used a Riegl VZ-400 3D laser scanner and an Optris PI infrared camera, with the pose files calculated using 3DTK based on odometry information (Borrmann and Nüchter n.d., Fig. 16.5).

In 2017, Autodesk and Esri announced a new collaboration to integrate their building design and environmental data modeling tools. Patrick Janssen, with the Singapore ETH Future Cities Lab, was skeptical that this partnership would resolve all

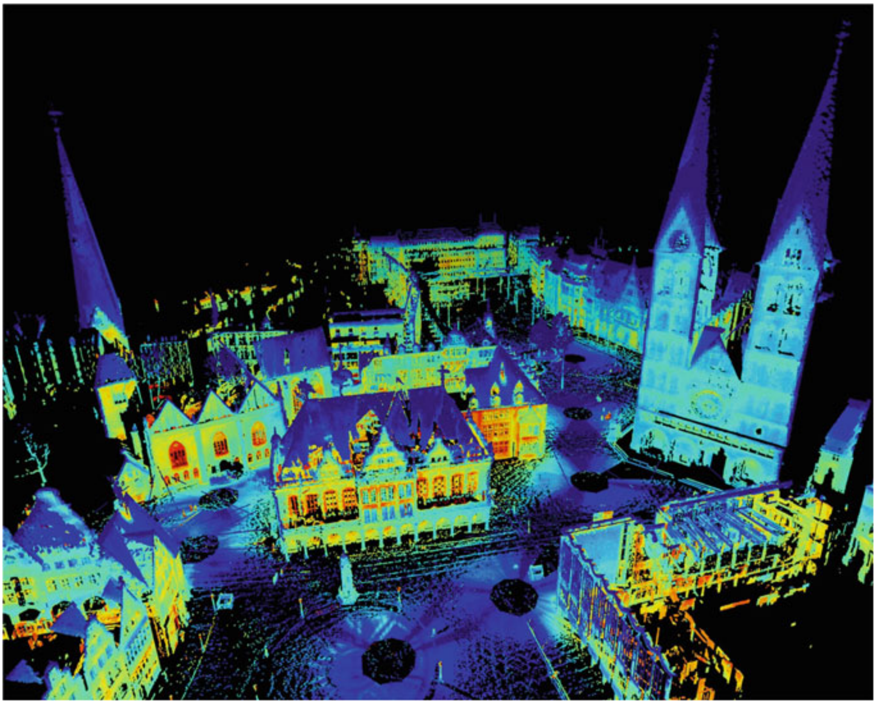

Fig. 16.5 *ThermoRathaus*, a point cloud of Bremen's city square, overlaid with temperature data from a thermal imaging camera (Borrmann and Nüchter, Jacobs University)

the aspirations of architects but recognized opportunities to resolve significant deficiencies in Esri's GIS and Autodesk's BIM and graphics packages. Janssen praised GIS software for providing data online and downloadable in tiles and criticized BIM programs for not providing online access to data and fine-grain imagery. He said advanced architects were eager for open semantics, "where you can compute your own stuff"; a capability now available to some extent in Houdini but likely to be more prevalent soon with new developers using Amazon Web Services or Web Assembly (Wasm). He said that most sophisticated modeling programs remain too complex in their structural routines—generating too many links and nodes in their data graphics. He was developing a new online geometrical design application, Vidamo, which he expected to be more efficient and more comprehensible for users without advanced programming skills (Jackson 2018, 37).

At the 2018 Geodesign Summit, Dangermond's presentation emphasized "the science of where" as being crucial for "understanding and managing our world" through "integrating people, processes, things and data about them" via three types of information infrastructure: records, insights and engagement. He also highlighted three major groups of trends that would evolve WebGIS during coming decades (and which are applicable to other types of software needed for urban planning and design). For professionals concerned with *data*, relevant advances include drones, lidar, scientific measurements, real-time video, crowdsourcing and much more detailed information on traffic, demographics, weather and locations. For experts developing *computer infrastructure*, he highlighted mobile communications, big data, machine learning, distributed computing, SaaS (software as a service), the IoT (Internet of Things), cloud storage and parallel computing, web services, microservices and networks. For *GIS innovation*, he focused on "expanding the power" via advanced analytics, open APIs, dynamic image processing, online content, apps, 3D modeling and smart mapping, data exploration, hubs, real-time visualization, Python programming and portals (Dangermond 2018).

As a corporation led by landscape architecture graduates from Harvard, Esri is focused on how to use computer tools to eco-sensitively integrate buildings and urban infrastructure with natural environments. Echoing three of the five research themes identified in Jackson's 2007 GEOSS-DE network diagram (Jackson and Simpson 2012, 5; Fig. 16.2), Dangermond identified four main types of modeling that should be increasingly integrated: landscape information models (LIMs; another term for natural systems modeling), building information models (BIMs), city information models (CIMs) and zoning information models (ZIMs; a CIM subset of particular value to government planners; Dangermond 2018).

16.3.3 Digital Engineering and Digital Twinning Standards

Also called virtual engineering, digital engineering is a shorthand reference to the consistent use of digital methods and tools throughout product development and production processes to improve planning quality and process controls over an asset's entire life cycle. Digital twinning involves modeling and simultaneously sustaining all the virtual systems associated with a physical entity. These terms emerged with computer modeling and autopiloting systems developed for aerospace, ship and car manufacturing and operations. Now these labels have transferred to BIM and geospatial environmental modeling—which evolved from different 2D paradigms (CAD drawing and GIS mapping) that depend on different methods of structuring data.

To establish interoperability, the buildingSMART International (bSI) group and the Open Geospatial Consortium (OGC) established a joint working group in 2017 to prepare a roadmap towards a global standards framework named the Integrated Digital Built Environment (IDBE). BSI administers Open BIM standards, including Industry Foundation Classes (IFCs), and the OGC administers OpenGIS, including geospatial data interoperability, and the Reference Model and GML standards. The IDBE is intended to underpin digital engineering and enable digital twinning of physical conditions with corresponding records held in digital repositories. The physical twin may be represented in the digital twin (virtual model) at any level of detail (LOD). However, there are new moves beyond formerly prescriptive notions of LOD to a more agile, performance-based, level of information needed (LOIN) approach, which specifies why data are required, what specific data are required, when they are required, and who is responsible for the transfers and uses.

16.3.4 Astrospatial Architecture

Architecture's ancient history switched tones around the turn of the third millennium. In May 2000, Aaron Betsky published *Architecture Must Burn*, a critique of late-twentieth century architectural culture and a "manifesto for architecture beyond building" (Betsky and Adigard 2000). This book preceded, by just eighteen months, the explosions that collapsed America's twin towers of modern capitalism, the World Trade Center, in September 2011. Five months later, Manhattan architects Diller Scofidio+Renfro revealed an unprecedented anti-icon: the Blur pavilion, a wide cloud of clean water vapor hovering low across Lake Neuchâtel during the 2002 Swiss National Expo. Solar-powered and with sensors dotted across its fog-obscured steelwork, this work symbolized two novel impulses: to evaporate architecture's antiquated focus on merely crafting static structures using weighty materials dug from the Earth and to steam-clean a world remaining stubbornly reliant on carbon-belching fossil fuels.

Blur catalyzed a post-internet design movement that was later named astrospatial architecture (Jackson 2016). Protagonists now intend to design extraordinary compositions of solids and voids and devise memorable interpretations and experiences via light and data. For example, in 2011 Joseph Paradiso's Responsive Environments group at MIT's Media Lab revealed perhaps the world's first video simulation of invisible atmospheric dynamics inside a building—using temperature, humidity, light, sound, human movement and other data, streaming from RFID and other sensors around floors of the real building. Visualized with the Unity game engine, the *DoppelLab* showed how space pulsates with unseen information (Paradiso 2011).

Architectural technology has evolved from computer-aided drawing (CAD) tools (beginning with light pens drawn on tiny screens in the late 1950s) to BIMs that are derived from aerospace engineering software and can script algorithms to operate fabrication machinery such as 3D printers and construction robots. Professors leading this international revolution tend to be involved in three overlapping design movements: Parametricism (Schumacher 2008), Smartgeometry (Smartgeometry n.d.; Peters and Peters 2013) and the more recent Advanced Architectural Geometry (AAG) group (Adriaenssens et al. 2016).

Building models created in programs such as Autodesk's BIM360 or Revit, or Trimble's Tekla BIMsight or Connect, can be exported for viewing with headsets using plug-ins such as Modelo, Prospect, Enscape, Umbra or AUGmentecture. Another capability was demonstrated by Greg LynnFORM at the 2016 Biennale of Architecture in Venice, where Lynn and his team used Microsoft HoloLens goggles and augmented reality (AR) software to compare multiple holographic scale models of the Tate Modern building in London with a physical scale model of a giant former car plant in Detroit (Fig. 16.6). HoloLens wearers could look inside the physical model and walk around full-scale virtual rooms defined by lines of ephemeral light. The team also highlighted and overlaid the history of the building being redesigned and showed different road and aerial vehicles flowing around the site (Jackson 2018, 19–20).

Beyond the design studio, VR, AR and nonimmersive 360° viewing systems are valuable tools for the property industry (Stanley 2017). They help clarify building proposals to stakeholders influencing council development approvals. They help in marketing buildings and apartments prior to completion or to inform remotely located investors. For example, spherical imagery captured by drones can clarify views from different floor levels of an unbuilt tower. The industry expects continuous

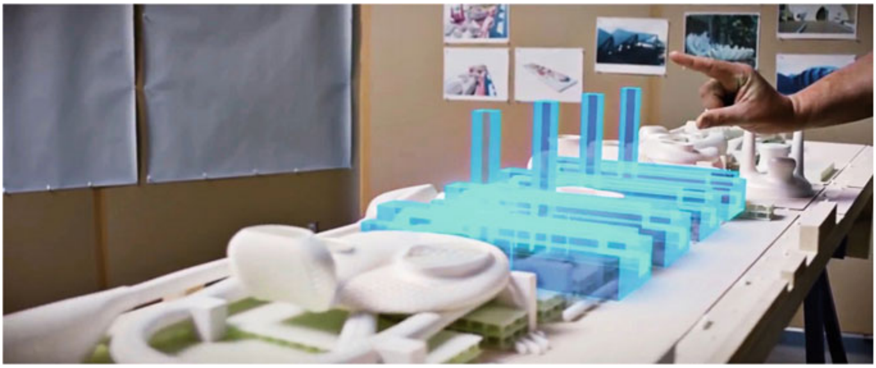

Fig. 16.6 Greg Lynn finger-snaps holographic (AR) building models of London's Tate Modern onto his physical model for car plant redevelopment in Detroit (Microsoft)

improvements to VR and AR experience kits and 360° cameras over the coming decade. Better graphics (pixel densities and spatial resolutions), audio, haptics (more touch-sensitive handset interfaces), and tracking speeds are still needed.

Another way to represent architecture and cities is with holographic images. These are data-coded recordings of light fields (waves of particles scattered off illuminated objects). Like sound recordings, holographic recordings can be reproduced later—but usually with considerable loss of fidelity, so the representations seem ethereal. Virtual building and city models can also be converted into 3D holographic imagery printed on film. When illuminated from above, these renditions seem to pop in three dimensions from their glossy sheets. If not precisely lit and viewed, holographic images appear spectral and chromatically fragmented.

Holographic glasses and headsets underpin augmented reality (AR)—a domain alternatively named "metasensory augmentation" by wearable computing visionary Steve Mann. At MIT in 1978, he prototyped the first AR spectacles, Digital Eye Glass, and later versions could be finger-tapped to convey holographic data. Those precedents inspired Google's Glass smart specs (sold generally from 2013 to 2015), Microsoft's HoloLens system (launched 2016) and the Vuzix Blade smart glasses (previewed in 2018, Statt 2018). The HoloLens has been surpassed technically by another of Mann's creations, Metavision's Meta 2 visor, released to Unity game developers in late 2017.

LiFi (light fidelity) is another emerging technology expected to energize built environments. Demonstrated by Harald Haas in a TED talk in 2011, a LiFi system uses the semiconductors of LED lamps (such as downlights) to transmit data (Haas 2015). In some early tests, LiFi networks transferred data at much faster speeds than is currently possible over WiFi networks conducting low-frequency radio waves and microwaves. This is because LiFi uses the higher frequencies and bandwidths that come from the visible light, infrared and near-ultraviolet waves that share the mid-range of the electromagnetic spectrum. Since Haas and his partner Mostafa Algani set up the pureLiFi company to commercialize his discoveries, several dozen startups and corporations have begun developing LiFi applications using next-generation LEDs with signal processing capabilities. In Dubai, Zero 1 used LED streetlights for networking data—exploiting pre-Haas research on urban transport-logistics telematics. In Dresden, the Fraunhofer IPMS research center has developed industrial automation solutions for several corporations. All major electronics manufacturers—General Electric, Panasonic, Samsung, Philips, Osram, Qualcomm and Cree—are racing to market with LiFi data-and-light product suites.

People in polar countries often feel depressed by the long nights of winter—needing treatment with mood-elevating colors and wavelengths of light. This affliction, called seasonal affective disorder (SAD), seems to emerge from changes to a body's circadian rhythm and serotonin and melatonin hormone levels. Some local governments in near-Arctic latitudes encourage their citizens to take therapy sessions and cheer their communities with winter light festivals (that also magnetise tourism). From 2012 to 2016, Oslo artists Christine Istad and Lisa Pacini responded to SAD in Norwegian towns (where there is no daylight during January) by trucking around a night sun—a 3 m-diameter circular panel crusted with hundreds of color-changing

LEDs (Anon 2013). A popular, three-dimensional, night sun is Rafael Lozano-Hemmer's *Solar Equation* aerostat (helium balloon), which is video-mapped with layers of computer-generated imagery and data derived from NASA's sun-monitoring instruments (Fig. 16.7). These are just two examples of creative urban (outdoor) applications advancing this century's revolution in 'electroluminescent' technology, based on semi-conductor controls of electric pulses (Neumann and Champa 2002; Jackson 2015).

16.3.5 Artificial Intelligence

Artificial intelligence was ignored by most built environment professionals until the internet caused widespread apprehensions during the 1990s, systemic disruption during the 2000s, and now, inevitably, new ways of understanding and doing things. Today, AI brings another wave of unfamiliar technologies and terms—including augmented intelligence, where machines are intended to improve human abilities to decide and perform. This seems less threatening than artificial intelligence, where machines are presumed to increasingly replace humans to a tipping point that Ray Kurzweil termed the Singularity (Kurzweil 2005).

Fig. 16.7 *Solar Equation,* a "night-sun" (helium balloon) designed by Rafael Lozano-Hemmer and mapped with NASA sun-monitoring data (Marcel Aucar)

All intelligence, artificial or natural, flows from competent processing of information. Most AI researchers have abandoned their early reliance on preprogrammed rules to solve problems. Instead, they are evolving machine learning, where computers use statistical learning algorithms to gradually teach themselves how to intelligently process big data. The more data that computers are given, the more capably they can perform complex tasks; partly through their supra-human powers of pattern recognition (*New Scientist* 2017).

Dacheng Tao at the University of Sydney has developed a classification system to help understand different concepts, methods and challenges that are being advanced in AI and robotics. His taxonomy highlights four basic functions performed by machines: perceiving, learning, reasoning and behaving. Devices fueled by data from sensors and cameras must perform one or more of these functions to help solve humanity's ultra-wicked problem of how to sensibly manage our planet.

Machine learning is a new field that is being divided into different specialties: unsupervised learning (training machines to identify untagged images), supervised learning (training using labeled or annotated information), reinforcement learning (training via rewards for correct actions) and deep learning (using complex neural networks). Neural networks are software circuits inspired by flows of information through human brains. They can deliver general artificial intelligence (solving various tasks) or narrow AI (expertise in one or two specific tasks).

One of the most promising potentials in AI is for robots to replace humans in performing extremely dangerous tasks: such as exploring nuclear power plants after an explosion, entering narrow cavities to replace damaged wiring or recording stress points in unstable structures. Czech writer Karel Čapek first coined the term robot in his 1921 play *R. U. R: Rossum's Universal Robots*, and today's humanoid versions such as Boston Dynamics' Atlas and Honda's Asimo are agile and realistic. Most of Boston's robots, being developed with the US Defense Advanced Research Projects Agency (DARPA), emulate fleet-footed animals and are intended to replace soldiers on topographically rugged battlefields. Swiveling, fixed-footed robots (mounted on a floor or ceiling) can print small masonry dome structures and assemble timber-framed houses (Jackson 2018, 42–48; Kohler et al. 2014).

Researchers developing computer vision systems are evolving improved ways for cameras, sensors and software to detect, recognize and track moving objects, including people, analyze environments by segmenting items of interest in changing scenes, estimate distances between cameras and objects in view, and enhance the clarity of images. Face-detection software can discern and frame almost every head in crowds of thousands. Any newly scanned face can be matched instantly with the same face from a digital archive. Data analysts can also clarify blurry, hazy, too-dark, wrongly colored and low-resolution images using smarter versions of the photoenhance tools found on standard laptops and smartphones. As these perception technologies improve, CCTV is becoming all-pervasive, with predictable reductions of both public crime and personal privacy.

Machine vision scientists depend on open-source datasets comprising images of objects that are classified and labeled to allow for comparisons with new images containing similar objects. The world's largest object dataset, ImageNet, contains more than 14 million crowd-labeled thumbnails, which can be downloaded to help identify different types of natural places, buildings, rooms, products such as fridges or dishwashers, furniture, fabrics, clothes, and apparel such as hats or sunglasses. Vision experts classify database images according to whether they depict "things" (box-frameable objects such as chairs, people or windows) or "stuff" (matter with no clear boundaries such as a patch of sky, an office corridor, a wall, a hillside or a street) (Stanford Vision Lab 2016).

Ironically, the image databases now being assembled to support AI analytics all depend on the "artificial artificial intelligence" (i.e., the non-electronic knowledge of humans working online) to label and cross-check the images uploaded by database compilers. One busy conduit is Amazon's Mechanical Turk (AMT) portal, which matches employers (such as public research groups) with freelancers to contribute to specific human intelligence tasks (HITs). One recent HIT, to assemble and correctly label 328,000 thumbnail images of "common objects in context" for the Microsoft COCO dataset, required 70,000 h of work by Microsoft-funded AMT participants (Lin et al. 2015).

Cameras and scanners capture images that can be analyzed, compared and manipulated, increasingly automatically and accurately. Some powerful processes are becoming common practices for owners and managers of major buildings and public places. For example, different faces, facial expressions, poses and walking gaits can be transferred or morphed between source videos featuring one or more people and "target" videos involving other people. Security cameras can detect licence plates and simultaneously track clusters of moving vehicles, even at night. All these observation systems are being integrated gradually with traffic lights, smartpoles and building heating, ventilation and cooling (HVAC) systems.

Data networks underpin the sensing and imaging infrastructure that is necessary to deliver key goals for the Global Earth Observation System of Systems. These include improving urban and disaster resilience; public health; energy, mineral and water resource management; infrastructure and transport systems; food security and agriculture, and healthy, biodiverse ecosystems. These domains overlap—integration of information and technology solutions is the main point of the GEOSS.

Caution pervaded a recent editorial for *Environment and Planning B*, in which Michael Batty warned readers not to expect too much sophisticated intelligence from "intelligent" machines. He said that machine learning through highly repetitive schemes of pattern recognition is "not much more than sophisticated averaging" but because machines could rapidly process vast quantities of data, they would continue to be useful for automated tasks such as monitoring and prediction of energy uses, delivery of location-based services, and transport. He suggested that machines would not be capable of replacing humans in planning long-term development of cities because they could not compute "the hard choices" of how a city functions economically and is organized in terms of social equity. He suggested both exploration of the limits of AI in understanding cities and "a concerted effort" by planners to invent new ways of automating urban functions (Batty 2018).

16.4 Some Recent Urban and Regional Case Studies with Global Potential

This section highlights seven projects and research groups that have advanced urban environmental simulations with methods that could be applied in many other cases and places.

16.4.1 MIT Media Lab Projects, United States

Carlo Ratti's SENSEable City Lab worked with government leaders in Cambridge, Massachusetts to prototype the *City Scanner* project to acquire weather and air quality data for different precincts using sensors fixed to garbage trucks. Christoph Reinhart's Sustainable Design Lab developed an urban modeling interface (*umi*) program that evaluates key environmental performances of neighborhoods and cities. First, the area being studied is architecturally modeled in Rhino 3D, and then the model is analyzed for walkability, daylighting and several types of energy consumption (Fig. 16.8).

Kent Larson's City Science group is continuing its *CityScope* project to model city precincts using color-coded Lego bricks, which are sensor-tagged and plotted on screens as data units. Users rapidly move the data bricks to reveal different ways

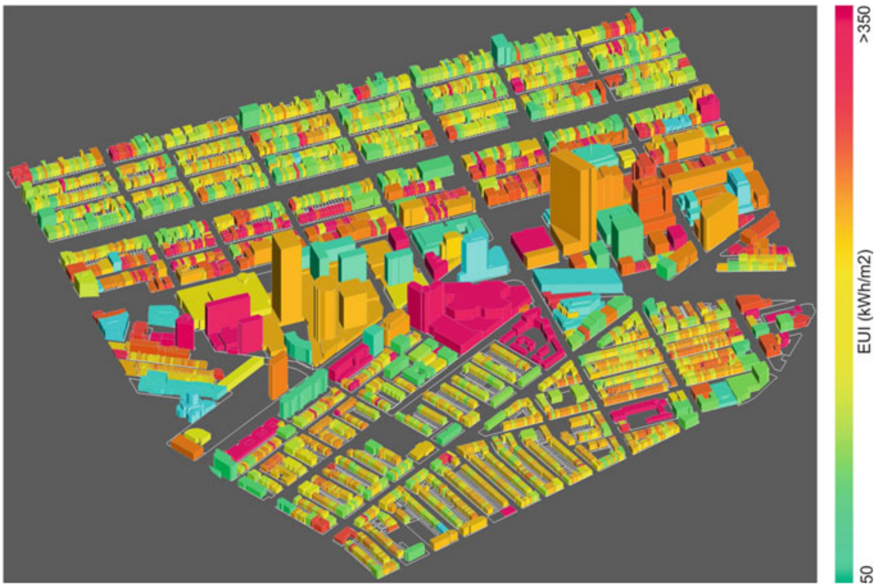

Fig. 16.8 Energy use analysis of a Rhino 3D city model in the urban modeling interface (umi) developed by MIT's sustainable design lab

to improve the density, proximity to services, and demographic diversity (vibrancy) of each area. City Science researchers have also prototyped ingenious "mobility on demand" (MOD) solutions. Their latest persuasive electric vehicle (PEV) can drive autonomously, even following its human passengers slowly if they decide to walk themselves; can be driven in bike lanes without the driver requiring a vehicle license; could be suitable for public sharing and can move both people and goods. In another project, Larson and Hasier Larrea showed how five hundred people could be housed in a medium-rise block of 25 sqm "action apartments" with the same footprint as forty-five conventional car spaces. Since graduation, Larrea has established a company, Ori, to make and sell these robotically mobile furniture suites.

16.4.2 Almere 2030, the Netherlands

In the Netherlands, one of a few countries noted for consistent innovations in urban spatial planning, architects MVRDV (Maas van Rijs de Vries) designed a 2030 vision plan to help the municipality of Almere plan polycentric growth on 250 sq km of polder land reclaimed in the 1960s (Fig. 16.9). The terrain is three meters lower than the water level of the adjacent IJseelmeer (lake) so Almere is constantly at risk of flooding, protected by a system of dykes and sluices. MVRDV's plan, gradually underway now, contradicted the popular Western strategy of transport-oriented development (TOD), where high-rise apartment buildings are clustered around suburban metro stations and new ribbons of low-to-medium-rise housing and commercial development are encouraged along main bus routes and rail lines.

Fig. 16.9 MVRDV masterplan for four "carpet cities" at Almere, the Netherlands

Instead, MVRDV proposed four "carpet cities". IJ-Land, designed with California architect William McDonough, will be a series of new island nature reserves in the lake, including 5–10,000 homes. Pampus will be a high-density, medium-rise village of 20,000 partly floating homes, with all streets leading to a lakefront boulevard. Almere Centre will extend the current city center with development of Almere Floriade, a compact and ultragreen neighborhood intended to be the horticultural campus for the World Expo in 2022. The public arboretum will contain 1,600 new homes, offices and facilities. In Oosterwold (Freeland), the first residents have begun to build their own neighborhood, with up to 15,000 new homes to be set in agricultural fields east of central Almere (MVRDV 1999, 2007, n.d.).

16.4.3 Jade Eco Park, Taiwan, China

French architect Philippe Rahm redesigned an obsolete airport in Taichung to provide a "meteorological" recreation landscape, Jade Eco Park, where vegetation and paths are interrupted by freestanding structures comprising white pipes, air ducts, sensors, filters and other electronic devices (Fig. 16.10). These were designed to mitigate Taichung's generally hot, humid climate and air pollution: they blow cool breezes, release mists or patches of rain, or clean local air to generate three types of artificial and contained atmospheric experiences: Coolia (four cool zones), Clearia (four areas of clean air) and Dria (three areas of dry air). Rahm's team first monitored and mapped the existing temperatures, humidity and air pollution conditions across the site and then used computational fluid dynamics to create an atmospherics map of the site. The

Fig. 16.10 Illustration of clean, cool and dry atmospheres generated across the Jade Eco Park in Taipei, designed by a team led by Philippe Rahm

new atmospheric zones overlap each other to allow for different sensory experiences to be selected at different times of day or during the year (Jackson 2018, 54; Rahm n.d.).

16.4.4 Nocturnal Barcelona, Spain

In Barcelona, the "datatecture" studio 300.000 km/s (speed of light) mapped the city's current and potential night-lighting of streets and public squares in a 2017 report for the city council's Municipal Institute of Urban Landscape and Quality of Life (Fig. 16.11). The project included analyses and visualizations of data on mobility, citizens' activities and business types in each location. The report also included comparison pairs of day and night photographs of city scenes, a satellite image of light pollution and the city's lighting regulations.

Fig. 16.11 Map of night lighting around central Barcelona by 300.000 km/s

16.4.5 Spatial Information Management Platform, Australia

Cities are complex, adaptive systems (CAS), where various dynamic systems evolve in interdependent ways. To "digitally twin" (computer-simulate) a city successfully in the Digital Earth context, this complexity needs to be represented accurately within the digital framework. Each component of the model must be able to evolve independently of the whole. Any viable CAS invariably evolved from a simple system that worked. Any complex system designed from scratch typically fails and cannot be repaired.

Modeling the behaviors of real-world complex systems with counterpart digital systems deepens our knowledge and improves our control of real-world scenarios. Recent projects undertaken by a Brisbane geospatial planning consultancy, Meta Moto, have adopted a CAS framework so that complementary systems of record, engagement, and insight can interact through a common semantic ecosystem supporting master data management and spatial data transformation functions. By adhering to open standards and exchange formats, the complementary systems can be made agnostic to one another. For example, graphics library transmission format (glTF) is a royalty-free specification for the efficient transmission and loading of 3D scenes and models by applications. This format defines the sizes of 3D assets and the runtime processing needed to unpack and use those assets. It defines an extensible, common publishing format for 3D content tools and services that streamlines authoring workflows and enables interoperable use of content across systems of engagement (such as web base viewers). Adopting this as a pipeline within a CAS framework ensures that the uses determine the engagement tools, and the semantic data model drives the user experience and presentation of the data in these tools. This approach removes the risks of vendor lock-in and ensures that the system has continuous opportunities to evolve. Meta Moto recently used glTF for data visualizations supporting Brisbane's Cross River Rail project and the next-generation spatial platform for South East Water in Melbourne (Fig. 16.12).

16.4.6 Greening Greater Bendigo, Australia

Bendigo, a regional city of 100,000 people in central Victoria, Australia, recently began to use EO imagery from Europe's Sentinel satellites to regularly monitor changes of vegetation around its towns and suburbs. A Melbourne landscape consultancy, Office of Other Spaces, analyzed sixteen multispectral Earth observation images (captured at 10 m resolution and stacked as a time-series 'data cube') to monitor seasonal and area-specific changes in vegetation throughout the city during the summer from December 2018 to February 2019. This pilot project allowed the city council to create new a vegetation cover benchmark (named the consolidated

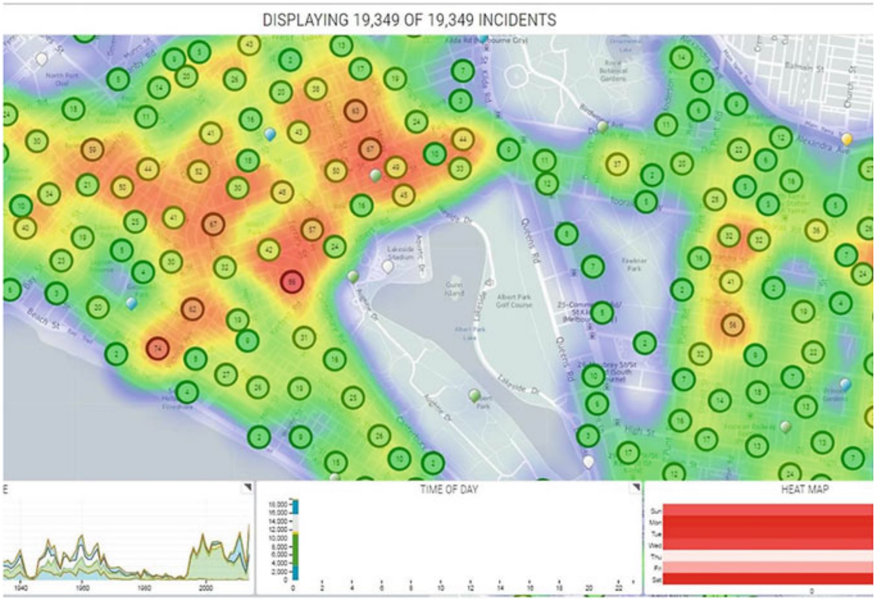

Fig. 16.12 Heat mapping of incidents over time is an example of a system of insight for South East Water, Victoria

mean value, CMV) to clarify the measure of its vegetation cover and determine any site-specific risks of new building developments destroying existing vegetation (Fig. 16.13).

16.4.7 Happy, Smelly and Chatty Maps, Britain

Computer scientists with the Cambridge node of the Nokia-Bell Labs network are advancing a Good City Life program that is intended to support happier citizens—not necessarily the prevailing corporate-governance agenda of 'smart' (time- and cost-efficient) cities (Aiello et al. 2016; Quercia et al. 2016). Led by Daniele Quercia, the Bell-Cambridge social dynamics team has been surveying, analyzing and mapping how people are enjoying—or could better enjoy—the sights, smells, sounds and other atmospheric experiences of public places that they navigate regularly (Fig. 16.14). With other computer scientists at Yahoo Labs in London, and with the Universities of Turin and Sheffield, they analyzed diverse social media tags and developed sophisticated algorithms which allow users of mobile devices to generate navigation routes on their GPS map apps (initially tested via OpenStreetMaps for specific zones of London and Barcelona). The paths they calculate are usually longer than the quickest journeys but can provide happier scenes, smells and sounds along the

Fig. 16.13 Time-stacked EO images of Bendigo, analyzed for urban vegetation changes by Melbourne's Office of Other Spaces

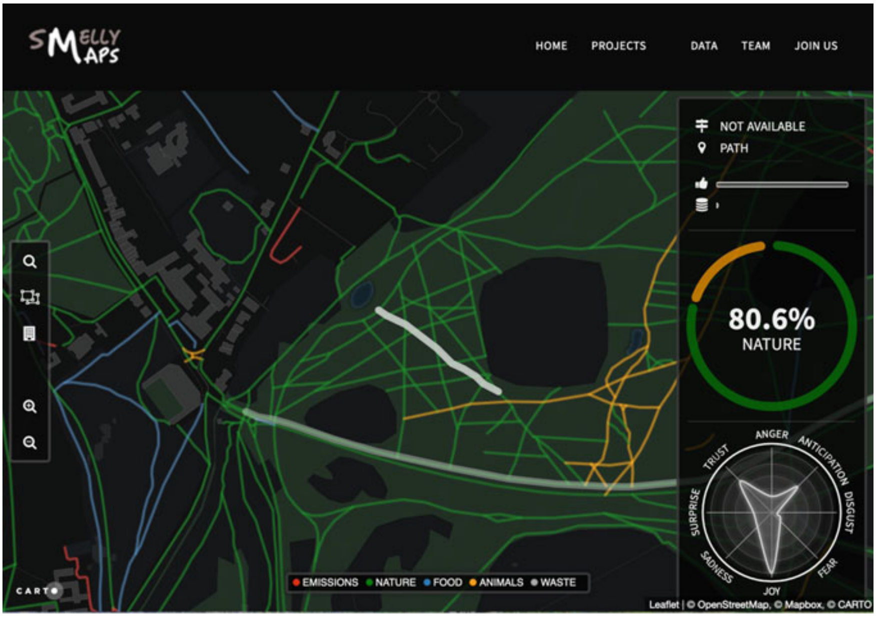

Fig. 16.14 Data-visual street map indicating five types of smells and likely emotions for people navigating an urban area, by Nokia-Bell Labs, Cambridge, UK

way. In recent papers, Quercia's team noted that urban planners and local government officials tend to focus on unpleasant odors and acoustics (signaling air or noise pollution) and mostly ignore desirable smells and sounds.

16.5 Urban Criteria, Process and Standards Taxonomies and Platforms

Many of the world's most intelligent and experienced urban professionals are not digital natives, sometimes refer to themselves as Luddites, and still use hand-inked diagrams, lists, tables and grammatical sentences to express their ideas. Some of these thought-leaders have devised schema for systems that could someday be programmed to analyze development proposals and building performance. This section reviews some taxonomies (matrices of criteria, goals, procedures and standards) that should be integrated into the future GEOSS-Digital Earth world-management system. These develop Fuller's concepts for what he initially named the 4D Air-Ocean World Town Plan then termed the World Game and Spaceship Earth. In one of his last books, Fuller said:

> This design revolution must employ a world-around, satellite-interlinked, data-banks-and-computer-accomplished conversion of present-day, exclusively geocentric, Spaceship Earth wealth accounting [… to a system where …] computers fed with all the relevant energy-efficiency facts will be able to demonstrate which uses will produce the greatest long-term benefit for all humanity (Fuller 1980, 199, 225).

Two critical factors lie at opposite ends of today's project to deliver Fuller's vision. One is the need to decide what data to collect to understand the world's conditions and how to organize it effectively (the main concern of UN-GGIM and other UN technical agencies, the Group on Earth Observations (building the GEOSS Common Infrastructure, GCI), CODATA, the Open Geospatial Consortium (OGC) and the (now disbanded) Global Spatial Data Infrastructure Association (GSDI; Crompvoets et al. 2008). The other challenge is for leaders of international land development organizations to clarify how to identify and deliver all data relevant to future modeling of eco-ethical developments. This agenda is being led by the World Bank (Global Platform for Sustainable Cities), the C40 Large Cities for Climate Change group, the Council on Tall Buildings and the Urban Habitat (CTBUH), the World Federation of Engineering Organizations (WFEO), the World Green Building Council (WGBC) and the OGC-buildingSMART alliance.

Guiding the collection and organization of satellite data are the essential climate variables (ECVs) for all three domains of our planet's environment: atmospheric, hydrographic and terrestrial. The ECV datasets are intended to underpin future eco-ethical practices in land development, and include river discharges, water use, groundwater and lake levels, snow cover, glaciers and ice caps, permafrost and seasonally frozen ground, albedo (surface reflectance), land cover (vegetation types), photosynthetically active radiation, leaf area, biomass, fire disturbance and soil moisture.

Geodata, urban planning and natural resource administration agencies will need to collaborate to obtain the ECV data relevant to their domains of governance and to integrate it with the cadastral and other topographical datasets that they administer. Also valuable are the lidar and radar scanning and 3D city modeling data that are obtained by commercial EO satellite operators (including DigitalGlobe, Airbus and Urthecast), aerial survey companies (such as AAM, Nearmap and Borbas), and locality-diverse providers of terrestrial environmental imaging and remote sensing services.

16.5.1 CityGML and 3D Cadastre

CityGML is an XML-based, 3D vector, open data model for storing and exchanging 3D city and landscape models that is based on the geography markup language (GML) produced by the Open Geospatial Consortium (OGC) and the International Standards Organization (ISO TC211). It defines the objects, properties, aggregations and relations contained in models, allowing for them to be readily compared and for correctly classified data to be reused. The platform allows for sophisticated analysis tasks and thematic inquiries relevant to most urban professions and management functions. CityGML is evolving continuously to improve 3D and 4D city modeling. Dynamic variations of the properties of a city object can be represented using the Dynamizer feature type. This enables specific objects in the 3D model to be linked with simulations or time series data. This can be used to trigger dynamic behaviors such as transformation of the geometry, thematic data, or the appearance of a specific object. This event-driven dynamic sentience of a city model is a foundation for advancing digital twinning of the physical world.

Current urban development approaches require more sophisticated conceptualizations of spatial data and new tools to holistically facilitate four key spatial planning tasks: urban management, impact assessment, site and road selection, and strategic planning. Sabri et al. (2015) developed a new framework to leverage current 3D geospatial and data model technologies in urban modeling and analysis. This framework, including recent insights by Biljecki et al. (2014), adopts a new conceptualization for CityGML that covers most 3D city modeling requirements. Sabri's team demonstrated how complex 3D urban scenarios enable city designers to have a greater understanding of existing and proposed urban forms and potential urban heat islands. The study showed how 3D analysis plays a critical role in examining the impacts of urban consolidation strategies and the densification of inner cities. Nevertheless, the 3D level of detail should be enhanced to support more accurate decision making.

In a recent study, Agius et al. (2018) explained how rule-based 3D city modeling enables planners to measure the physical impacts of building controls (e.g., heights, shadows, setbacks) and the functional impacts (e.g., mixes of land uses). This might be useful for land administration (including subdivisions) but, if strata title properties are to be visualized or the public and private ownership of future developments needs to be analyzed by stakeholders, today's tools must be improved.

The ability to measure the capacities and implications of underground infrastructure (Qiao et al. 2019) and the above-ground services needed for huge future developments can be added through combinations of 3D cadastre data and BIM methods. Adopting a 3D cadastre (Aien et al. 2013) will enable users to more accurately evaluate future changes in land and property values, which is a major concern for many stakeholders involved in inner city redevelopment (Shin 2009).

16.5.2 Graph Databases: Lossless Processes for Data Cities

Graph databases have nodes, edges and properties to represent and store data. They aid in analysis of many-many relationships and have applications in machine learning, fraud detection, social media, semantic harmonization and master data management. Graphs are a key enabler of next-generation spatial platforms for the integrated digital built environment (IDBE).

Recent Singapore research demonstrates potential for multidirectional lossless transformation of semantic and geometric data across the paradigms from design models to open standard formats. With traditional methods, there may be significant loss of data integrity and content at each step in the transformation from the proprietary design files (native BIM) into various OpenBIM standards (IFCs), and then into CityGML and a city model. This journey wrangles data between multiple paradigms. By adopting a triple graph-based framework for semantic and geometric conversions a "complete and near-lossless" mapping between the models can be achieved (Stouffs 2018). This framework can be applied to bulk and incremental updates between these models and may be applicable to lossless transformations between IFC versions (for example, IFC2x3 to IFC4x2) and pivoting from project information models (PIMs) to asset information models (AIMs) at handover.

Also significant for cities and major infrastructure projects and operations are graph application platforms for master data management (MDM). Property type graphs (with metadata at nodes and edges) will also become increasingly important for building asset registers and to enable sophisticated twinning of a sentient virtual model with its physical counterpart in the real world.

16.5.3 Open Public Life Data Protocol

Denmark's Gehl Institute, founded by Jan Gehl and now led by Shin-pei Tsay, has collaborated with city government agencies in Copenhagen, San Francisco and Seattle to produce a data protocol for assembling and comparing metrics about how people use and enjoy public environments. Launched as a beta version in late 2017, it includes a choice of eight components relevant to any public life survey: gender, age, mode of mobility, groups, posture, activities, objects (accompanying people) and "geotag" (which parts of a location are preferred). The protocol document explained how to structure the survey to record all the information in data tables, to be saved as CSV files that could be compared with the results of any similarly assembled survey. Although this project was focused on using digital tools to collect and process the survey information, it appears to be strongly influenced by Christopher Alexander's pattern language classifications (published before personal computers) to help design comfortable indoor and outdoor places at different scales and for different times and purposes (Gehl 2017; Alexander et al. 1977).

16.5.4 City Standards: ISO 37120

In 2014, the International Organization for Standardization (ISO) launched its first suite of indicators to measure and compare the performance of cities across seventeen general themes including the economy, energy, governance, health, telecommunications and innovation, transport, waste and water. Developed by the Global City Indicators Facility (GCIF) at the University of Toronto and promoted by the related World Council on City Data (WCCD), the ISO 37120 standard for sustainable cities and communities was updated in 2018. Two subset standards documents, *ISO 37122: Indicators for Smart Cities* and *ISO 37123: Indicators for Resilient Cities*, were also produced (ISO 2018).

16.5.5 Data Cubes

Launched in 2013 by the national EO team at Geoscience Australia, the Australian Geoscience Space-Time Data Cube is a system that stacks matching Landsat scenes in time sequences (currently up to fifteen years) to allow for faster analysis of changing conditions. The dataset for the whole of Australia amounts to almost four million scenes and 110 TB of compressed geoTIFF files, which are analyzed by the Raijin high-performance computing lab in Canberra. Technicians can access the dataset with a Python API that can generate specific mosaics and stacks of image files, which can be interpreted via users' own algorithms (Jackson 2013). The Data Cube system is the foundation of the Digital Earth Australia national satellite mapping project. It is supplied freely to research agencies in other countries under the name Open Data Cube (ODC), under the auspices of the Committee for Earth Observation Satellites (CEOS n.d.). One ODC was repurposed as the Africa Regional Data Cube, providing satellite surveys to an initial group of five African nations; it was later expanded to all 54 African countries as the Digital Earth Africa project (Digital Earth Africa n.d.)

In 2018, Peter Baumann at Jacobs University in Bremen received German research funding to lead a BigDataCube project to improve Rasdaman (raster data manager) software for data cubing satellite imagery from the European Space Agency's Sentinel constellation (source of the six terabytes per day of new satellite image files that are stored in Germany's CODE-DE archive). In addition to the commercial and free/light versions of Rasdaman, Baumann is developing data cube standards for the Open Geospatial Consortium (OGC), which works with the International Standards Organization (ISO; Anon 2018).

16.5.6 Compact Cities

In 2012, the Organization for Economic Cooperation and Development (OECD) released a list of fourteen characteristics of compact cities, which could be used as indicators to compare and improve operations. Compact and often high-rise cities such as Manhattan, Hong Kong and Paris are more efficient than sprawling low-rise cities with wide traffic thoroughfares, such as Los Angeles and Dubai. The criteria are high residential and employment densities, mixtures of land uses, a fine grain of land uses (small sizes of land parcels), strong social and economic interaction, contiguous development (rather than vacant land or street-level carparks), contained urban development within demarcated limits, good urban infrastructure (especially sewage and water mains), multimodal transport, high connectivity of streets (including footpaths and bicycle lanes), extensive coverage of impervious surfaces and a low ratio of open space (OECD 2012).

16.5.7 EcoDesign

Malaysian architect Ken Yeang pioneered ecological strategies for commercial towers and urban precincts. He clarified an "endemic" (climate and place-responsive) design system that is now standard practice in urban development. He rejected key modernist routines for tall buildings to look the same on all four sides, be built around a central lift core, have sealed windows and be mechanically air conditioned throughout. Instead, he designed buildings to respond to their different compass aspects and sun and wind conditions; positioned lift cores on the sides of buildings where they could best block excessive sun and wind and would allow for courtyards or atria to be landscaped in the center; introduced natural sunlight and ventilation via openable windows to the foyer, lift lobbies, fire stairs and toilets; and designed sky gardens and sunny courtyards on upper levels. By working closely with engineers on climate-response tests of his building models, he discovered that sky gardens could break the flows of winds down the surfaces of his towers to reduce gusts for pedestrians walking on nearby streets and plazas. On upper floor levels, some winds could be deflected into the buildings to ventilate spaces and cool the structures.

Yeang first applied green architecture principles to his tall buildings in tropical cities—beginning with Menara Mesiniaga, an office building in Kuala Lumpur (1992). His most substantial book, *EcoDesign* (Yeang 2006), was the first to clarify an eco-scientific system to design site-sensitive architectural projects anywhere in the world. His method requires understanding the natural context of each site by identifying its biome (regional community of diverse species sharing the same climate and terrestrial conditions). His system also included an "interactions matrix" that requires four sets of data to be gathered to assess four main ecological impacts of a building scheme: its relations to its environment, its internal relations, its inputs (of energy and matter) and its outputs. He urged architects to plan developments to avoid destroying healthy ecosystems or to rehabilitate damaged ecosystems. He also described three criteria for modeling any design: a description of the built system, a description of its environment and a mapping of interactions between the building and its environment (Yeang 2006, 59–73).

16.5.8 Positive Development

Counterproductive practices in the "sustainable urban development" movement have been targeted by Janis Birkeland, author of an evidence-based ecological building theory that she named "positive development" and "net-positive design" (Birkeland 2008). She proposed that every building should be expected to sequester the amount of carbon used in its operations and the amount of carbon emitted through resource extraction and consumption. Every building project destroys many tons of the Earth's natural resources and the link between mining and construction is the major global cause of excessive carbon emissions. The nature and extent of this problem are obscured by green building assessment practices that "measure the wrong things in the wrong ways"—and that measure negative impacts only up to zero without measuring positive impacts. Birkeland suggested that buildings that support substantial and permanent planting (green walls and roofs) will amortize carbon far earlier in their life cycles than if they are only operated with renewable energy sources. She expected machine-analyzed data to allow for much more comprehensive and accurate analyses of buildings before and after construction, but the issues being recorded and assessed must be changed and expanded.

16.5.9 Cities and the Digital Earth Nervous System

In a 2010 article for the *International Journal of Digital Earth*, European scientists explained Digital Earth as a "metaphor for the organisation and access to digital information through a multiscale, three-dimensional representation of the globe" (De Longueville et al. 2010). They extended that vision by forecasting a "self-aware nervous system" to provide decision makers with improved alerting mechanisms for crisis prediction and situational awareness. This goal may prove the most beneficial for governments and citizens in urban areas—and strategies are essential to clarify how the relevant officials and stakeholders can contribute to and usefully exploit such a sophisticated system of automated operations.

New international protocols are essential to give urban authorities rapid access and accurate, automatic analyses of the data sets relevant to their challenges. Several international corporations—including Mapbox, Orbital Insight and OmniSci—are managing and analyzing very large quantities of geodata for government customers which cannot afford or do not find it feasible to apply the necessary resources and infrastructure to maintain such sophisticated operations.

One geospatially advanced city (and nation) is Singapore, which ranked fourth in the 2018 countries geospatial readiness index—not far behind the United States, United Kingdom and Germany, and ahead of China (Geospatial Media and Communications 2018). Its extraordinarily integrated government created a national spatial data infrastructure (NSDI) system in 2009, is locally training urban geotech specialists through joint research programs with Switzerland's ETH Future Cities Lab and America's MIT SENSEable Cities Lab (with centers located at the National University of Singapore), has accelerated a Smart Nation policy since 2014, launched the Virtual Singapore project in 2016 and released the Singapore Geospatial Masterplan in 2018. Singapore aims to foster "geosmart government", "geoempowered people", and "a thriving geoindustry".

16.6 Summary

International scientists supporting the Digital Earth and GEOSS visions are applying satellite and semiconductor-enabled technology to accelerate delivery of Fuller's visions for a "4D Air-Ocean World Town Plan" and efficient management of resources on "Spaceship Earth". Many governments have been promoting "smart city" policies and programs since the 1990s, when wireless and mobile telecommunications began to be commercialized internationally. The authors of this paper suggest it is now important to not only emphasize systems that enable humans to communicate worldwide but also next-generation infrastructure for societies to be accurately informed about our planet's environmental conditions and challenges.

At the urban scale of today's planet-simulation project, there is a need to integrate area-specific modeling of natural environmental systems with current best practices in building information modeling and city information modeling. All three methods must be improved to incorporate real-time streaming of Earth observations data obtained via sensing and scanning the light and radio waves of the electromagnetic spectrum. This satellite and semiconductor-enabled movement has been labeled "the new science of cities", "geodesign", "senseable cities", "digital cities", and "data cities". As De Longueville et al. clarified in 2010, it seems crucial for the Digital Earth "nervous system" to become self-aware and be able to obtain and respond more automatically to unprecedented quantities of environmental information—far too much to be processed by humans. This chapter highlighted some urban advances, strategies, issues and case studies that are significant contributions to this millennium's Digital Earth/GEOSS imperative.

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Davina Jackson PhD is a Sydney-based writer on urban technology applications, an honorary academic with the University of Kent School of Architecture and a Fellow of the Royal Geographical Society. She co-edited the world's first snapshot report of academic contributions to the Global Earth Observation System of Systems/Digital Earth project and her latest book is Data Cities: How satellites are transforming architecture and design (Lund Humphries, 2018).

Richard Simpson is an Executive Director of Meta Moto, a consultancy firm specialized in advising governments on strategic spatial programs. He is a Senior Fellow at the Centre for Spatial Data Infrastructure and Land Administration (CSDILA) at the University of Melbourne, and at the Cities Research Institute, Griffith University; and expert advisor to the OGC-bSI joint working group for the Integrated Digital Built Environment. He has served on the ISDE Council since it was founded in 2006.

Chapter 17
Digital Heritage

Xinyuan Wang, Rosa Lasaponara, Lei Luo, Fulong Chen, Hong Wan, Ruixia Yang and Jing Zhen

Abstract Natural and cultural heritage, the common wealth of human beings, are keys to human understanding of the evolution of our planet and social development. The protection and conservation of natural and cultural heritage is the common responsibility of all mankind. Spatial information technology provides a new applied theory and tool for the protection and utilization of natural and cultural heritage. This chapter is divided into four parts. The first part elaborates the connotation of digital heritage, the differences and connections between digital heritage and physical heritage, the technology of digital heritage formation and the research objectives and content of digital heritage. Parts 2 and 3 discuss the contents and methods of digital natural heritage and cultural heritage, respectively, and some practical case studies. In the fourth part, the future development trends of digital heritage research in protection and utilization are described, as well as six research directions that deserve attention.

Keywords Digital heritage · Spatial information technology · Remote sensing · Archaeology · Heritage conservation · Case study

17.1 A Brief Introduction to Digital Heritage

Natural and cultural heritage, with unique value in the realms of science, culture, history and art, are like jewels emerging from a wide variety of ground object types that shine on the surface of the Earth. Heritage is defined as our legacy from the past, what

X. Wang (✉) · L. Luo · F. Chen · H. Wan · R. Yang · J. Zhen
Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China
e-mail: wangxy@radi.ac.cn

R. Lasaponara · L. Luo · F. Chen · H. Wan · R. Yang
International Centre on Space Technologies for Natural and Cultural Heritage, Beijing, China

R. Lasaponara
Institute of Methodologies for Environmental Analysis, CNR, Tito Scalo (PZ), Italy

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we live with today, and what we pass on to future generations. As common wealth of all mankind, its enduring value should be kept for future generations. Accordingly, the recognition and preservation of its outstanding universal value (OUV) has been a great concern for UNESCO, highlighting the emerging role of digital heritage, which is defined by UNESCO as the use of digital media in the service of preserving, protecting, studying and presenting these heritages.

The great value and significance of digital heritage was affirmed by two UNESCO documents released in 2003: the Guidelines for the Preservation of Digital Heritage (National Library of Australia 2003) and the Charter on the Preservation of the Digital Heritage (UNESCO 2009). The Charter describes digital heritage as "resources of human knowledge or expression, whether cultural, educational, scientific and administrative, or embracing technical, legal, medical and other kinds of information, are increasingly created digitally, or converted into digital form from existing analogue resources." When resources are "born digital", there is no other format but the digital original, including text, databases, still and animated images, audio tapes, photos, software, and web pages.

Many of these digital heritage materials will be passed down from generation to generation. Digital heritage may be classified by genres: information resources stored in specific carriers (such as optical disks, disks, and tapes), computer databases, or disseminated via the internet or digital media, and preprint materials or archives held in e-prints.

"Digital heritage", a concept that is distinguished from its physical counterpart, constitutes an integral part of the Digital Earth program. Digitalizing heritage enables the enduring value of physical heritage to be long-term preserved, easily accessible to, widely shared and disseminated to the public. Heritage in the digital form also facilitates in-depth research from various perspectives (Hu et al. 2003). Digital heritage plays an important role in permanently preserving the information derived from physical heritage. The implication of "digital heritage" used in this handbook is compatible with that described in the two UNESCO documents mentioned above. However, unless otherwise specified, the term of "digital heritage" here refers to "digital natural and cultural heritage", which means digital resources or products converted from existing natural and cultural heritage or analogue resources. It includes dynamic or static digital information created during the process of digitalization, which includes creation and documentation, preservation and protection, processing, dissemination and presentation. In this handbook, digital heritage refers to the categories of cultural relics and natural landscapes. Similar to general digital heritage, digital culture and natural heritage exist as information resources that are stored in specific carriers (such as optical disks, magnetic disks and tapes) or computer databases, or presented on display and disseminated via the internet.

The technologies involved in digital heritage cover a variety of aspects including creation, storage, monitoring, dissemination, presentation and protection.

The creation and documentation of digital heritage consist of technological processes such as digital perception, data collection and processing, information extraction and interpretation, and digitally documenting.

Joint efforts should be undertaken to preserve and protect digital heritage and to keep it accessible to the public and maintain its long-term availability to future generations. Efforts include developing technology and tools, designing management frameworks, initiating protection programs, taking management measures, and related law-making issues.

The dissemination and presentation of digital heritage involves several aspects including the technology and tools for digital creation, channels and measures for dissemination, management measures, and the support from regulations and laws. Digital heritage should be presented vividly to ensure that the public can understand, share and make good use of it.

Digital heritage focuses on the digital products derived from its cultural and natural heritage ontologies and related environment. The research covers the process of how digital heritage is created and presented, how to protect it and develop related products, and how to transform these products into new digital products in the form of knowledge. It is also necessary to have a profound understanding of the ontology-environment interaction, and therefore take effective protective measures in advance. Digital heritage research features noncontact and nondestructive ontologies.

Digital heritage shares some common characteristics of cultural heritage. The research is centered on the techniques and knowledge for (1) digitalization of the heritage ontology; (2) preservation of digital heritage; (3) the use of digital heritage (4) demonstration, sharing, and publicity of digital heritage; and (5) laws and regulations on digital heritage protection.

The creation of digital heritage, namely, the digitization of heritage ontologies, involves the use of satellite-based or airborne data as well as data obtained from ground and underground exploration or manual observation. It involves a set of techniques and methods for nondestructive detection, monitoring, and evaluation. In addition, heritage preservation and digitalization also need the support of legislation at the national level, which constitutes the cornerstone for implementing digital heritage programs. The use of digital heritage involves a wide range of technologies and knowledge in terms of digital generation, heritage protection, monitoring, and law-making issues on heritage protection.

The purpose of digital heritage preservation is to ensure that it remains accessible to the public and to prevent it from disappearing. Accordingly, digital representation of heritage ensures that the essential value of its ontology is widespread and enduring. To achieve this, specified approaches are suggested for the use, research and protection of two kinds of heritage, corresponding to its natural or cultural characteristics.

17.2 Digital Natural Heritage

17.2.1 Technology and Research Methods of Digital Natural Heritage

The Convention for the Protection of the World Cultural and Natural Heritage describes "natural heritage" as "natural features consisting of material and biological structures or groups of such structures of outstanding universal value from an aesthetic or scientific point of view; geological and natural geographical structures of outstanding universal value from a scientific or protective point of view, and clearly designated as threatened animal and plant habitats; natural attractions or clearly defined natural areas with outstanding universal value from a scientific, conservation or natural beauty point of view." Comprehensive use of digital technologies and methods for outstanding universal value (OUV) characterization of elements of natural heritage include the observation and its originality, integrity (AI) monitoring and evaluation as effective measures to achieve heritage protection and management.

To ensure the feasibility, effectiveness and long-term nature of digital technology for natural heritage monitoring, practical and simple monitoring and evaluation methods should be adopted, and the collection and management of monitoring data should be standardized. With the rapid development of 3S technology, multisource high-resolution (temporal, spatial, spectral) images form a large amount of remote sensing data. We have carried out different remote sensing spatial scale data fusion techniques. The spatial analysis function of GIS, high-precision satellite navigation and positioning functions, and different evaluation models of natural heritage site protection are used for Sustainable Heritage Protection and development monitoring, taking into account the monitoring objectives and conditions of different types of natural heritage sites. By combining qualitative and quantitative methods, field investigation and remote sensing investigation, the OUV and its original integrity can be effectively monitored and assessed, and natural heritage can be effectively protected and managed.

17.2.2 Case Study of Digital Natural Heritage

17.2.2.1 Information Extraction from Mountain Vertical Belt Based on an NDVI-DEM Method Model

Xinjiang Tianshan Mountain is an outstanding representative of the mountain ecosystem in temperate arid regions. It has a typical vertical natural belt spectrum in temperate arid regions. Within a horizontal distance of less than 30 km, Bogda's elevation rises from 1,380 to 5,445 m, and the vertical elevation difference is nearly 4,100 m. Six vertical natural belts from desert steppe to ice and snow belts have developed: temperate desert steppe belt, mountain steppe belt, alpine coniferous forest belt, alpine meadow belt, Alpine cushion vegetation belt and ice and Snow Belt. At the Bogda World Heritage Site, snow-capped mountains, glaciers, rivers, lakes, forests and meadows coexist with each other to present the superlative natural beauty of mountains in a desert area. The vertical natural belt distribution reflects the water and heat variations at different elevations, gradients and slopes. It is an outstanding example for the study of biological community succession in mountain ecosystems in an arid belt undergoing global climate change.

The impacts of climate change are the main driving factor of vertical belt change. According to the seasonal and periodic characteristics of the monitoring objects for the protection of the Bogda Heritage Site, Wang Xinyuan's research group (Ji et al. 2018) selected TM data from June 19, 1989, and OLI data from July 28, 2016 (Fig. 17.1), combined with auxiliary data such as ground object spectrometer information, field GPS acquisition and UAV data, and made use of scatter plot of DEM-NDVI-Land Cover Classification (Fig. 17.2) based on probability and statistics. Based on the study, the demarcation elevation of the vertical natural belts was

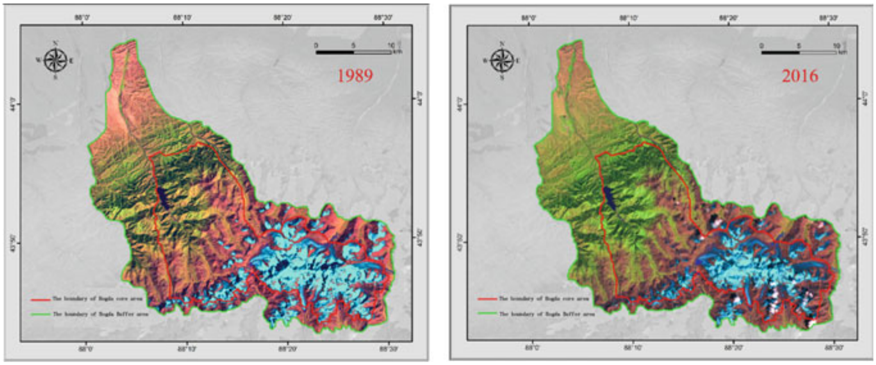

Fig. 17.1 Bogda images for (left) 1989 and 2016 (right)

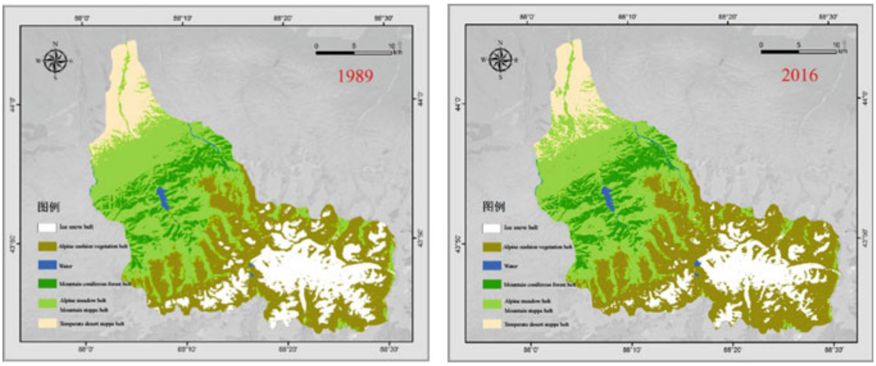

Fig. 17.2 Bogda classification results for 1989 (left) and 2016 (right)

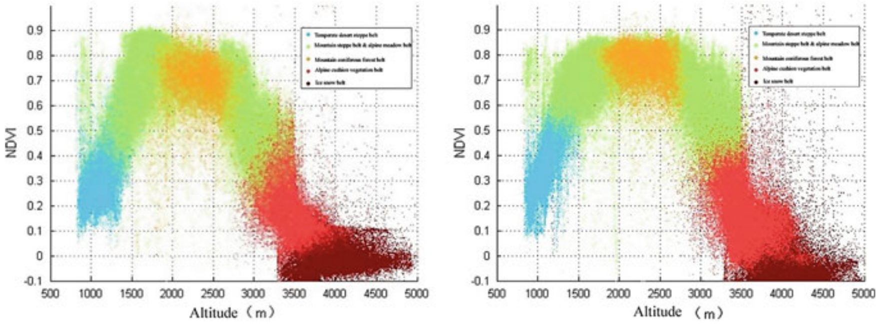

Fig. 17.3 Bogda scatter plot for 1989 (left) and for 2016 (right)

extracted to monitor the changes in the vertical belts in the Bogda Heritage Site in the past 30 years.

Remote sensing images are classified according to the zoning content of vertical zones. The images are classified by comprehensive supervised classification, decision tree hierarchical classification and visual interpretation.

Using the superpositioned DEM data, NDVI (Chang et al. 2015) and classification results of the Bogda Heritage Site, the "DEM-NDVI-classification information scatter plots" for 1989 and 2016 were created, as shown in Fig. 17.3. The two-year trend in the distribution of scatters shows an inverted U-shape of "uniform rise-remain stable-uniform decline".

With the elevation increase in the Bogda area, the heat and water and the environment of vegetation growth change, and the coverage types change regularly, corresponding to the six colors in the scatter plot. There was a clear demarcation between scatters in different vertical belts. The proportions of pixel classification attributes at different elevation ranges in the scatter map of the DEM-NDVI-Land Cover Classification was calculated by sliding statistics, and the vertical zoning results for the Bogda Heritage Site in 1989 and 2016 were obtained by setting thresholds. The extraction results are shown in Table 17.1.

Table 17.1 1989 and 2016 data with elevation results (spline data)

	Temperate desert steppe belt-mountain steppe belt (m)	Mountain steppe belt-alpine coniferous forest belt (m)	Alpine coniferous forest belt-alpine meadow belt (m)	Alpine meadow belt-alpine cushion vegetation belt (m)	Alpine cushion vegetation belt-ice and snow belt (m)
1989	1278	1784	2714	3277	3636
2016	1185	1759	2730	3288	3690
Difference	−93	−25	+16	+11	+54

Note + indicates boundary line elevation, −indicates boundary line elevation drop

The vertical belts of the Bogda Natural Heritage Site in the Tianshan Mountains in 1989 and 2016 were extracted, as shown in Table 17.1. The boundary between the temperate desert steppe belt and mountain steppe belt decreased 93 m, the boundary between the alpine meadow belt and alpine cushion vegetation belt moved up 11 m, and the lower limit of the ice and Snow Belt increased 54 m. This shows that the area of mountain grassland has greatly expanded, and the protection of natural heritage is critical; due to the impacts of global climate change, the glaciers have retreated. Therefore, considering the problem of OUV performance in heritage sites, it is necessary to carry out Sustainable Heritage monitoring using qualitative and quantitative methods, field investigation, social investigation and remote sensing investigation to protect and manage natural heritage.

Using field research and Google Earth high-resolution image data, six points were selected in each area where the land type obviously changed. Thirty-six verification points were selected to verify the mountain vertical band extraction results. As shown in Table 17.2, the elevation of the verification points fluctuated above and below the demarcation elevations, but the overall trend was consistent with the research results.

17.2.2.2 Recognition of Coral Reef Health Status Based on RS and GIS

Corals require harsh growth conditions, and subtle changes in sea temperature, salinity, sediment content and other environmental factors can lead to widespread bleaching or death of corals. Coral reefs are the most responsive ecosystem to climate change on a global scale. Therefore, it is very important to grasp the health status of coral reefs in time to study the effects of climate change and the utilization and protection of marine ecological resources (Holden and Ledrew 1998). Australia's Great Barrier Reef (GBR) is 2011 km long and 161 km at its widest point. The scenery is charming and the flow of water is complex. It is a sensitive area of global change, with more than 400 different types of coral reefs. The GBR, extending 2000 km along Queensland's coast, is a globally outstanding example of an ecosystem that has evolved over millennia. The area has been exposed and flooded by at least four glacial and interglacial cycles, and reefs have grown on the continental shelf over the past 15,000 years.

Kutser et al. (2003) used hyperspectral sensors to measure the reflectivity spectra of six different colors of coral communities in the Great Barrier Reef (approximately 5–6 m deep), and analyzed live corals, dead corals, and algae. The reflectivity of ground objects obviously differs between 550 and 680 nm; the spectral reflectivity of sand is the highest, the reflectivity curve is gentle, and the reflectivity curve is the easiest to distinguish from those of other materials. Coral and seaweed have low reflectivity. The waveform is determined by the light absorption characteristics of pigments in the body, which comprises wavelengths from 500 to 625 nm for the big difference in reflectivity waveforms between coral and seaweed.

Table 17.2 Vertical natural belt extraction verification results

	Temperate desert steppe belt-mountain steppe belt		Mountain steppe belt-alpine coniferous forest belt		Alpine coniferous forest belt-alpine meadow belt		Alpine meadow belt-alpine cushion vegetation belt		Alpine cushion vegetation belt-ice and snow belt	
	E(m)	D(m)	E(m)	D(m)	E(m)	D(m)	E(m)	D(m)	E(m)	D(m)
1	1174	+11	1774	−15	2713	+17	3309	−12	3681	+9
2	1186	−1	1761	−2	2745*	−15	3272	+21	3672	+18
3	1192	−7	1742*	+17	2726	+4	3232	+39	3697	−7
4	1105	+80	1740*	+19	2736	−6	3297	−4	3666	+24
5	1147	+38	1741	+18	2743	−13	3307	−19	3705	−15
6	1194	−9	1779	−20	2737	−7	3317	−29	3687	+3
R	1185 m		1759 m		2730 m		3293 m		3690 m	

Note E-elevation, D-difference value, R-extraction results, *represents in situ data
+ indicates the verification point elevation was greater than the extraction result
– indicates the verification point elevation was lower than the extraction result

In addition, Clark et al. (2000) found that recently dead corals can be distinguished from corals whose death time is longer than 6 months by derivative spectrum. In addition to spectral measurement and analysis of coral reefs, Landsat and SPOT series satellite data can be used to identify coral reefs with coarse accuracy (Benfield et al. 2007). Collin and Hench (2012) identified the healthy and unhealthy status of coral reefs from Worldview-2 high-resolution imagery using a support vector machine (SVM).

17.2.2.3 Habitat Suitability Assessment of Animal Habitat Based on Spatial Information Technology

A great deal of observed evidence shows that the combination of climate change and other pressure sources has led to the migration of species distribution, wildlife phenology, reproductive behavior, population composition and ecosystem function changes.

The giant panda is a rare wild animal unique to China. It is also the flagship species of biodiversity conservation in the world. The giant pandas are now confined to six mountain systems, from north to south: Qinling Mountain, Minshan Mountain, Qionglai Mountain, Big Facies Mountain, Small Facies Mountain and Liangshan Mountain. Based on spatial information technology, the Wang Xinyuan Research Group (Song et al. 2014; Zhen et al. 2018) carried out a habitat suitability assessment of giant panda habitat.

Based on remote sensing, geographic information system (GIS) and other spatial techniques, using the latest data from the fourth Giant Panda Survey and the maximum entropy model (MaxEnt), the assessment of the impacts of climate change on the habitat of giant panda (Ya'an) was carried out at this stage and is planned in 2050. In the course of carrying out the detailed assessment, the latest data on panda occurrences and human disturbance factors were based on the fourth Giant Panda Survey (2011–2014), with elevation, slope and aspect as physical environmental variables. The distribution map of the staple food bamboo and distance from water source were biological factors. Human disturbance factors included the interference factors, with a high encounter rate in five study areas of roads, mines, hydropower stations transmission lines and scenic spots. The bioclimatic data were derived from climate variables on the WorldClim website, 12 land cover thematic data from 2001 to 2015 that were uniformly processed by NDVI, and high-resolution remote sensing data such as GF-1, as shown in Fig. 17.4.

The research analyzed the suitable conditions of giant panda habitat and its changing trends and related rules under the background of the current stage of and future climate change in Ya'an, Sichuan Province in China. Through on-site visits to nature reserve management agencies and local residents' research, the evaluation results were verified through field studies. The evaluation results, such as those shown in Fig. 17.5, provide a deep understanding of the trends and extent of habitat change in

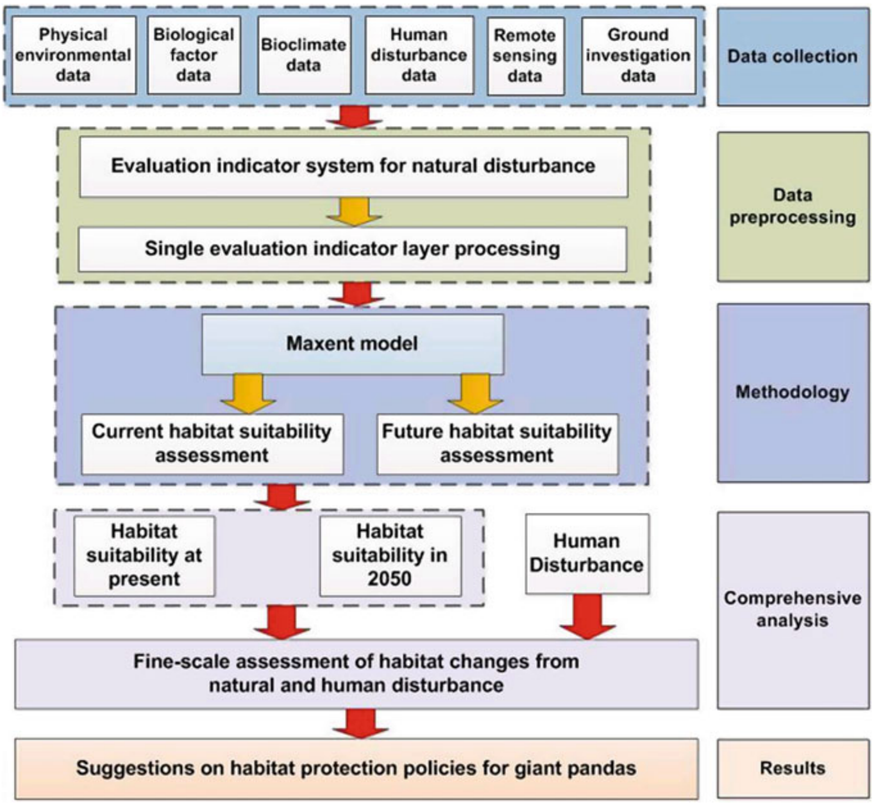

Fig. 17.4 Flow chart of fine-scale climate change evaluation and countermeasures

the context of climate change. They are of great significance for the effective protection of current and future giant panda habitat, ecological protection and coordinated development of the local economy.

17.3 Digital Cultural Heritage

Digital cultural heritage is the application of the theory, methodology and technology related to Digital Earth in the field of cultural heritage. Applying digital technology focused on spatial information technology to tangible cultural heritage is of great significance for the protection, inheritance and exploitation of cultural heritage.

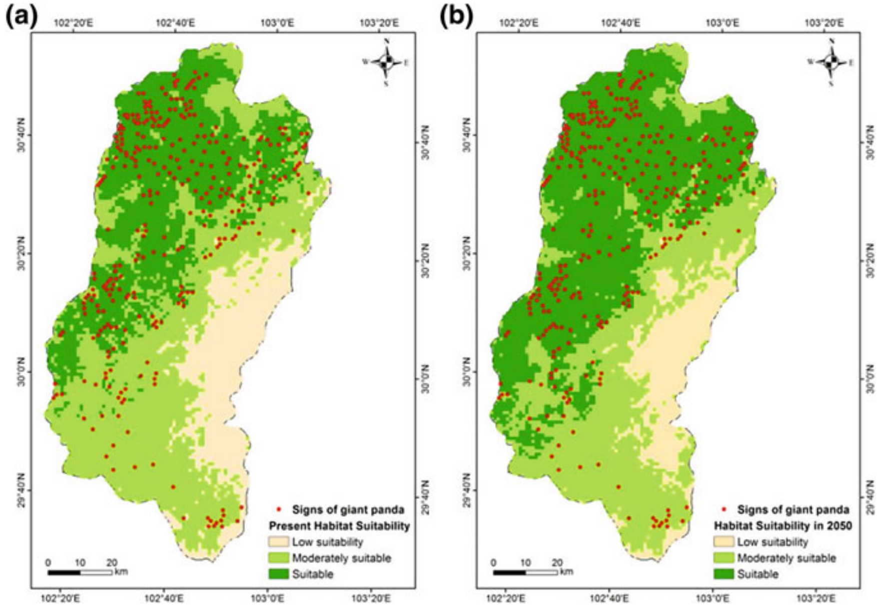

Fig. 17.5 Giant panda habitat suitability (**a**) at present; and (**b**) in A.D. 2050

17.3.1 Digital Cultural Heritage Research and Technical Methods

As the core technology supporting the deep development and wide application of Digital Earth, spatial technology provides new means as well as new tasks and connotations for digital cultural heritage research. Through digital technologies such as photogrammetry and remote sensing, digital cultural heritage can realize nondestructive archaeological detection, digital archiving, dynamic monitoring and evaluation of heritage, and support the preservation and sustainability of the heritage ontology and the environment on which it relies. The main technical methods for digital cultural heritage research include:

17.3.1.1 Space Archaeological Technology

Space archaeological technology integrates worldwide earth observation technology from space, air to ground and underground exploration technology to detect and discover archaeological objects (Luo et al. 2019). In the positioning and discovery of heritage, technical features of spatial earth observation technology including the high-resolution, multi-spectral and multi-resolution nature, objectivity and non-intrusiveness can be fully utilized to provide technical support for archaeological heritage investigation, exploration and research. The remains of ancient human activities (surface or subsurface) can lead to variances in the spatial structure between the remains and their surroundings. These are represented in the digital records of remotely sensed imagery as interpretation marks such as micro geomorphology, soil moisture, and vegetation growth distribution, which have become the theoretical basis of remote sensing archaeology. Space archaeology is the inheritance and development of remote sensing archaeology. It extends the working spectrum of remote sensing archaeology and has the advantages of multi-scale observation of a satellite with aerial and ground integration. The introduction of geophysical exploration and other technologies has enabled the development of spatial archaeological observations of the subsurface or even lower, providing a new approach for nondestructive detection of buried remains.

17.3.1.2 Digital Recording and Preservation of Cultural Heritage

Accurate digital recording is the premise of heritage protection and monitoring. Based on principles of photogrammetry and remote sensing, it collects and digitizes ground control points by acquiring satellite and aerial high-resolution remote sensing images, and uses photogrammetry software to produce high-precision maps of the heritage ontology. Through the three-dimensional (3D) data acquisition equipment of aerial, low-altitude aerial, car-based or ground platforms, 3D modeling software is used to construct 3D models and record the shapes and spatial attributes of the heritage ontology and the environment. A large heritage database system that can be queried and updated is then formed using geographic information system (GIS) and database technology to digitally manage various types of heritage information.

17.3.1.3 Heritage Ontological and Environmental Dynamic Monitoring

By obtaining data on the same heritage object at different times, through comparative analysis, changing information identification and model calculation, the status and potential risks of the heritage object can be evaluated. Earth observation technology based on Digital Earth has great potential for monitoring large cultural heritage remotely and dynamically and even in 3D form. The analysis and evaluation of the situation and risk of the heritage object are conducted by applying artificial or intelligent remote sensing recognition technology and monitoring and identification algorithms on remote sensing data at a certain interval (appropriate spatial resolution, spectral resolution and temporal resolution, etc.) or 3D digital models.

17.3.1.4 Heritage Demonstration on Virtual Reality Technology

Virtual reality (VR) is a new and integral technology in the sphere of computer science, which developed from the integration of disciplines involving computer graphics technology, multimedia technology, sensor technology, human-computer interaction technology, network technology, stereo display technology and simulation technology. With advantage of lifelike, immersive reconstructions, it can be applied in cultural heritage research, restoration and digital virtual tourism. The seamless integration of digitalization and virtual reality technology can be an effective means for digital protection.

17.3.2 Digital Cultural Heritage Application Cases

17.3.2.1 Space Archaeology

As a successor of remote sensing archaeology, Space archaeology is a new paradigm of space information technology employed in archaeology (Wang and Guo 2015). Through multiple technology integration and comprehensive analysis, it provides the essential information linked to the acquisition, interpretation and reconstruction of archaeological remains. Space archaeology research is in the emerging stages. At present, the work is mainly concentrated in deserts, Mayan jungles and the Nile Delta using remote sensing-based methods of archaeological faint information extraction, and has achieved a series of important scientific achievements and archaeological discoveries. American archaeologists discovered the notable ancient Egyptian city of Alexandria, which had slept in the sea for thousands of years; Greek archaeologists employed infrared photographs to discover the ancient city of Hekike, which was destroyed by an earthquake in 373 B.C. in Corinth. Guo (1997) used space shuttle imaging radar data to discover the great walls of the Sui and Ming Dynasties buried in the dry sand at the junction of Shanxi and Ningxia. Ninfo et al. (2009) visually interpreted and digitally reconstructed the urban structure and paleoenvironmental background of the ancient port of Altinum using high-resolution visible and near-infrared aerial photographs and digital elevation models. Evans et al. (2007) used GIS tools to map the most detailed archaeological information of the Angkor Wat site based on multisource remote sensing data such as optical and SAR information. Parcak et al. (2016) conducted a spatial archaeological study of the Nile Delta. They investigated thousands of ancient sites in the area and identified ancient city street ruins and unfinished pyramids based on high-resolution remote sensing data to reconstruct the ancient Egyptian empire.

The Silk Road is precious cultural heritage owned and shared by all mankind. To enhance the ability to rescue archaeological discoveries, space archaeology provides new technical methods for the detection, discovery and reconstruction of sites along the Silk Road at different scales. With the benefit of spatial information technology, a spatial forecast model of heritages based on GIS spatial analysis was built by Wang and Guo (2015) by considering the similarity of environmental and geomorphological landscapes of the ancient Silk Road between NW China (Luo et al. 2014a, b) and southern Tunisia using satellite imagery, historical documents, archaeological survey data and other multivariate data. Three ancient city sites related to old stages in Dunhuang, northwest China, were discovered on the high-resolution satellite remote sensing imagery. The field archaeological survey supported by GPS technologies and historical research material confirmed the specific locations of the ancient stages. Based on the Digital Earth platform and existing spatial archaeological results, the postal system between Guazhou and Shazhou (two prefectures) in the period of the post-Wuhou Tianshou second year (A.D. 691) was digitally reconstructed (Fig. 17.6). It laid a scientific database foundation to study the route of the ancient Silk Road and the changes in the ancient oasis in medieval China. The new

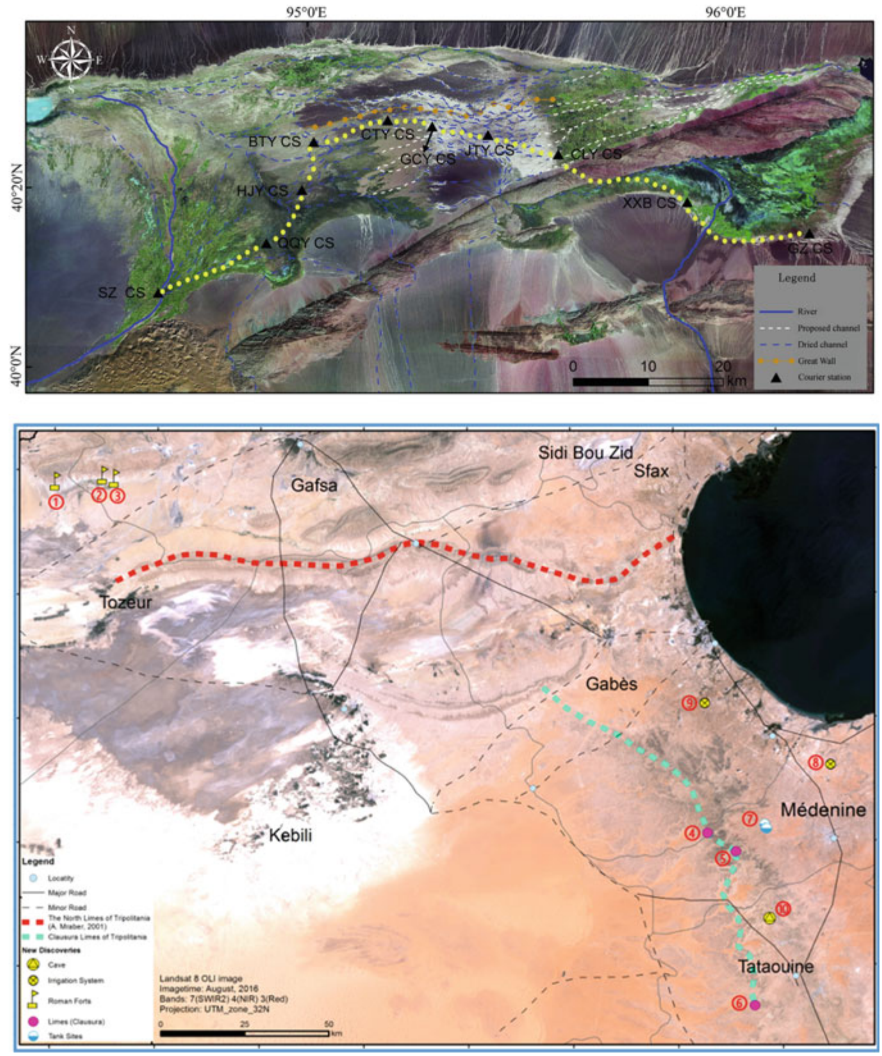

Fig. 17.6 Space archaeology of the silk road in China (upper) and Southern Tunisia (lower)

paradigm of spatial archaeology has been promoted and applied to Tunisia, where 10 ancient Roman remains have been discovered; the legacy evidence chain reflected the military defense system of the southern frontiers of the Roman Empire (Fig. 17.6).

The comparative space archaeological study of the defense system along the Silk Road between the Han Great Wall and the Roman Lima system provides detailed knowledge of the defense system, border defense strategy, human-land relationship and environmental changes in areas along the Silk Road as scientific references.

17.3.2.2 Cultural Heritage Monitoring and Protection

In the face of frequent natural disasters, global changes and increased human activities (such as urbanization, tourism development and local wars), the sustainable protection of cultural heritage has encountered challenges. As a common nonrenewable wealth of all mankind, safeguarding and protecting the world's heritage is the focus of the UN 2030 Sustainable Development Goal 'Sustainable Cities and Communities'. Considering the wide coverage, diverse types and different landscapes of cultural heritage, it is urgent to take advantage of near real-time, wide coverage and high precision of remote sensing big data under the digital earth framework for dynamic monitoring and intelligent protection of cultural heritage.

First, due to the rapid development of sensor technology and the Internet of Things in recent years, heritage protectors can now automatically monitor elements of micro environmental change information in near real-time, from the monument to the landscape (e.g., humidity, temperature, air pollution, power, precipitation, structure vibration and deformation), providing quantitative data for the identification of trigger mechanisms for heritage sites affected by diseases and for the consequent conservation measures.

Second, high-resolution remote sensing platforms with multiple bands and high revisit frequency and satellite-airborne (low-altitude) information processing technology make it possible to monitor the whole-day and all-weather dynamics of a heritage scene; the extraction and storage of topographic factors such as slope and water catchment can aid in detailed mapping for heritage protection; natural disasters such as landslides and human activities such as urbanization can be identified by remote sensing images, and the GIS platform space-time analysis function can be used to support early warning and assessment of heritage risks.

Third, the key advantage of Digital Earth platforms such as Google Earth, WorldWind and ArcGIS Explorer is the wide use of Keyhole Markup Language (KML) to ease the integration of multisource datasets from different providers and to simultaneously visualize and identify relationships for use in subsequent quantitative investigations. Cultural heritage applications require the integration of heterogeneous georeferenced 1D/2D/3D/4D data from local computers or data obtained 'on the fly' from distributed sources due to the demands of comprehensive archaeological understanding and knowledge discovery. In Google Earth, these data are usually in KML format. A case study was conducted on part of the Great Wall (Fig. 17.7a) in NW China (Luo et al. 2018) in the early 20th century by famous archaeologists and

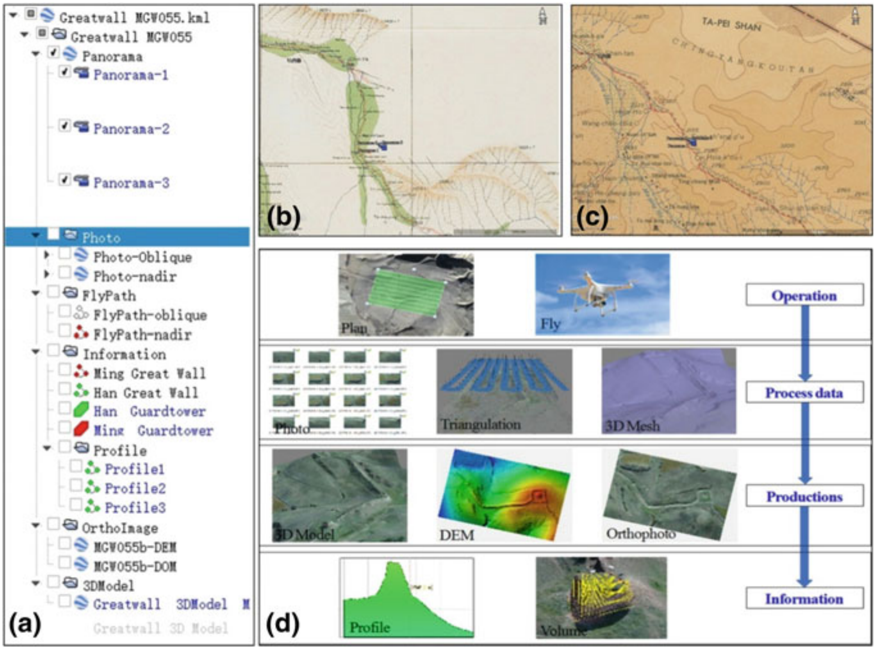

Fig. 17.7 The integration of geospatial data of the Great Wall in northwestern China. **a** The overall tree structure of the KML layers in GE; **b** the archaeological maps made by Stein; **c** the archaeological maps made by Hedin; **d** the operation flowchart for our UAV investigation. We deleted the photo layer in the supplementary file because the volume was too large

geographers, who made many great discoveries and uncovered its mysteries. The work of these expeditions served different roles and provided clues to researchers seeking to find unknown sites. The most famous explorers were Stein and Hedin, and their precious investigation reports and archaeological maps (Fig. 17.7b, c) play important roles in understanding the changes that have occurred in the Middle East and Central Asia in the past century, especially in terms of land use and land cover (LULC).

An unmanned aerial vehicle (UAV) investigation of the Great Wall was carried out (Fig. 17.7d). All of the original and processed data (courses, photos, triangulation and mesh), final products (orthophotos, DEM and 3D model) and derivative information (profiles and volumes) were saved in KML format. Members of the public and scientific peers can download and reproduce the data for integration with archaeological maps and their own data. For example, based on these high-resolution UAV-generated DEM and 3D model analyses, a Great Wall Integrity Index was defined and applied in quantitative evaluation of Ming earthen Great Wall erosion status. Stein and Hedin's archaeological maps were also used in this case; these can be downloaded from the Japanese National Institute of Informatics (http://dsr.nii.ac.jp). By browsing in GoogleEarth, it was evident that Hedin's archaeological map of our proposed pilot area was more detailed than Stein's (Fig. 17.7b). We were unable to find any marks showing the linear traces of the Great Wall in Stein's map but they are present in Hedin's map (Fig. 17.7c). In future research based on data visualization and integration in GE and the LULC specific situations established by GE VHR imagery, it will be possible to use UAV data and archaeological maps to deduce historical LULC changes in the past century along the Great Wall.

However, compared with spatial archaeological detection (which can be traced back to remote sensing archaeology), there is still a lack of research in the methodology and applied strategy of spatial technology employed for heritage monitoring and protection. The existing work on the monitoring of the heritage ontology and environment is often isolated and the monitoring elements and means are relatively simple, which affects the comprehensive understanding and systematic response to the sustainable protection of cultural heritage. Recently, Xiao et al. (2018), from the perspective of UN Sustainable Development Goals 11 and 8, proposed that geospatial information technology such as photogrammetry, remote sensing and spatial information would play an important role in defending and protecting cultural heritage and sustainable tourism. Chen et al. (2017) developed a two-scale radar interferometry method and model for deformation monitoring and health diagnosis of heritage sites affected by disease (Fig. 17.8) that considered the dynamic changes in heritage

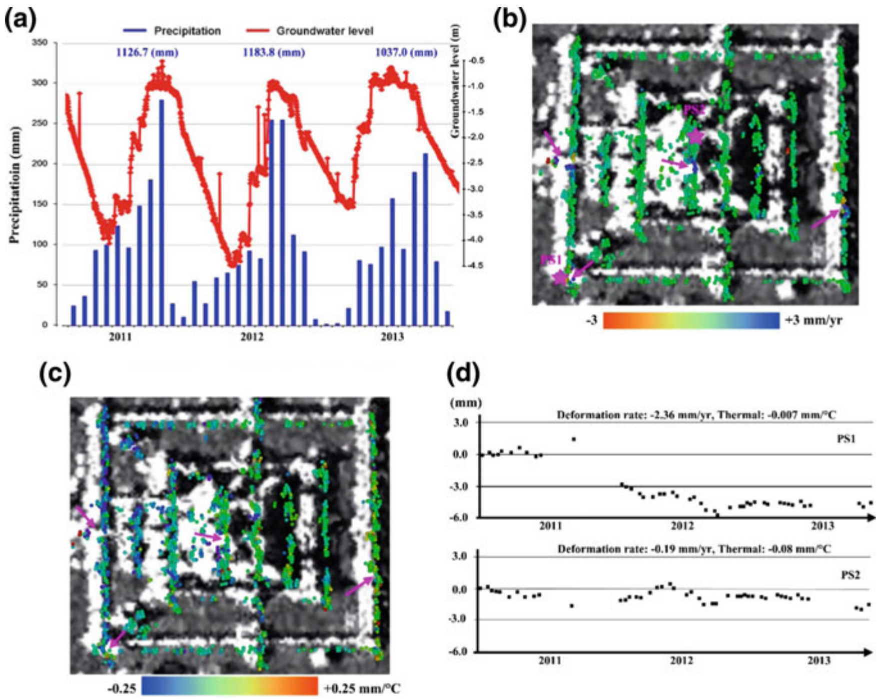

Fig. 17.8 Angkor's environmental remote sensing revealed the collapse of ancient temples and contributed to the sustainable protection of heritage sites. (following Chen et al. (2017))

ecosystems, monitored environmental factors (including urbanization, forest degradation, land use, groundwater level) to resolve the current controversy surrounding the potential structural collapse of monuments in Angkor. They constructed the dynamic model of the disease evolution of the Angkor temple complex and unveiled the mystery of the decline of the heritage site, bringing a new insight for the site sustainable conservation.

17.3.2.3 Virtual Reconstruction of Cultural Heritage

The protection and sustainable development of cultural heritage can be understood from a narrow point of view as the documentation, restoration and maintenance of the heritage site. From a broad perspective, it should be extended to the cognition, understanding and inheritance of the human civilization based on the protection of the heritage entity. Due to the rapid development of information technology in the internet and big data era, the visual demonstration of heritage information from multiple sources can be realized through virtual reconstruction scientifically, intuitively and vividly, which greatly promotes the dissemination and inheritance of ancient civilization.

The virtual reconstruction of digital heritage includes three main aspects. The first is to combine multisource data to model historical sites and the paleoenvironment and establish virtual ancient scenes; the second is to design lively and representative key historical and cultural events and scene elements (such as costumes or hairstyles that reflect the cultural elements of the time, street arrangements, etc.) considering the cultural background and geographical environment of specific historical periods; the last is to realize the digital display of virtual ancient scenes integrating virtual reality, holographic projection, augmented reality, digital animation and other technologies. By providing visual, auditory, tactile and other sensory simulations, it allows for users to immerse themselves in the cultural relic environment and its historical context (Mortara et al. 2014).

Some relevant experts and scholars have achieved fruitful results in this field, such as the virtual reconstruction of the cultural site of Pompeii by the University of Geneva and the digital restoration of Yuanmingyuanby Tsinghua University, but there are still some major challenges in the virtual reconstruction process for cultural heritage.

First, cultural heritage often contains various elements and complicated space characteristics. It is difficult for a single platform or sensor to meet the requirements of all types of data acquisition due to multi-platform, multisource, heterogeneous sensors. The need for collaborative stereoscopic observations is increasingly evident (Lin et al. 2014). The cultural heritage HuaixiuShanzhuang (HXSZ) in Suzhou, China, has a complex structure, which is a challenge for modeling. To acquire high-accuracy 3D models, Liang et al. (2018) collected point clouds via terrestrial laser scanning(TLS) and modeled texture via terrestrial digital photogrammetry(TDP) (Luo et al. 2014a, b). They fused the TLS and unmanned aerial vehicle digital photogrammetry (UAVDP) point clouds and integrated the TDP point clouds with the already-merged point clouds for 3D modeling and digital documentation. The multiple surveying methods, multisource and multi-scale data collection, procession and presentation and documentation overcome the limitations of a single technology and data source, providing a solution for high-accuracy preservation of cultural heritage sites that contain complex space characteristics.

Second, multi-sensor observations are prone to many structural problems such as data structure differences, uneven acquisition granularity, and weak spatial and temporal coupling. The development of collaborative observation, joint registration, and multisource data fusion modeling techniques can provide digital protection for cultural heritage. In addition, the integration of multi-source/multi-scale data and models requires efficient management platform. Hua et al. (2018) developed an internet-based 3D geographic information service system for Hakka culture preservation with data storage on the cloud and service functions such as scene loading and browsing, thematic cultural map display, online virtual experiences for tours, and tourist route navigation for users. The data sources were based on surveyed and collected materials and knowledge of Hakka culture through field work and the 3D model of Tulou reconstructed with TLS, UAV and digital camera data. It provides a virtual experience for a cultural tour in a 3D interactive way and a novel platform for Hakka culture presentation, cognition and heritage.

Third, to enhance the vivid experience and the comprehension of the public, Barsanti et al. built a virtual museum with 3D interactive scenarios of Egyptian funeral objects that was exhibited at the Archaeological Museum in Milan (Barsanti et al. 2015) (Fig. 17.9). In this scenario, users could grab, wave and rotate 3D models to observe them from different points of view with the movement of their virtual hands, which was implemented by wearable virtual reality devices named HMD. In addition, Eva et al. realized gesture-based natural interaction in a virtual reproduction of the Regolini-Galassi tomb, one of the richest and most famous tombs of the Orientalizing period (Pietroni et al. 2013). By exploiting the recognition of the skeleton and the grammar of common gestures, this application leaves users completely free to walk through the 3D scenes of the ancient cultural heritage site and dynamically choose 3D objects they are interested in with a gesture of their arms.

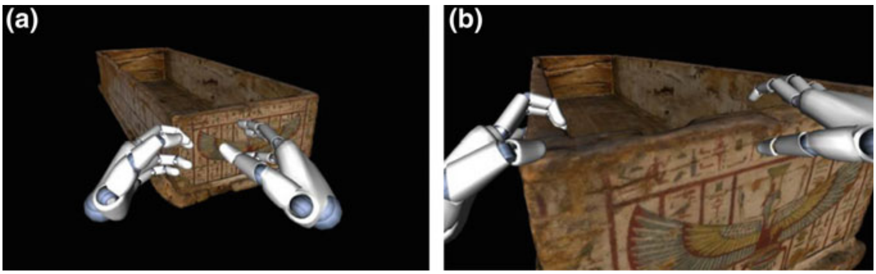

Fig. 17.9 Pictures of the implemented VR scenario: **a**, **b** grabbing and rotating of an object with the option to enlargeit (following Barsanti et al. (2015))

Furthermore, in most outdoor cases, users are inclined to compare the current site with the immemorial one that shared the same location with it, so that they can infer the changes that occurred over time. To address this issue and allow for the capability of combining the natural world and artificial world, augmented reality technology appears to be a suitable choice. Quattrini et al. (2016) reconstructed a Roman theatre in Italy using TLS point cloud data and validated the 3D models using a geometrical survey of evidence. Moreover, they showed how it is possible to realize on-site visualization of cultural heritage that no longer exists based on a mobile augmented reality (MAR) platform (Quattrini et al. 2016) (Fig. 17.10).

Notably, the whole life cycle of cultural heritage is a complex historical process that includes site selection, construction, completion, maintenance, and the current physical restoration, which comprises both natural processes and human activities. For example, the EU's Seventh R&D Framework Program officially launched research on the impacts of natural processes (climate change) on historical and cultural heritage (http://www.climateforculture.eu/index.php?inhalt=project.overview). To effectively recognize the temporal and spatial characteristics of cultural heritage, it is particularly important to develop and construct a dynamic knowledge environment. The dynamic knowledge environment requires integrated sensors for real-time observation, geographic process simulation and prediction, and agent behavior analysis methods and techniques to provide comprehensive analysis capabilities that can trace the past and more effectively predict the socialization process of cultural heritage.

Fig. 17.10 The development of MAR visualization for the reconstructed Roman Theatre in Fano, Italy, using Layar. (following Quattrini et al. (2016))

The effective solution of the above challenges rely on the development of related technologies such as the acquisition and digitization of cultural heritage related information, seamless integration of multisource/multi-scale data and models, non-rigid physical modeling and its free interaction and real-time response, space-time evolution modeling of ancient sites and ancient civilization activities, and behavioral model building. Narrowing the gap between high-tech virtual reality and cultural heritage remains a challenge. Academician Huadong Guo of the Chinese Academy of Sciences advocated constructing and developing spatial archaeology, an interdisciplinary field combining the strengths of spatial technology, cultural heritage, big data science, and computer technology, which practically applies new and sophisticated technology to heritage protection and sustainable development. At present, the pilot project "the Earth Big Data Science Project" of the Chinese Academy of Sciences, which oversees Academician Guo Huadong, has been set up to support related research on heritage protection along the Belt and Road. It will reproduce the past glory of the ancient civilization of the Belt and Road through the virtual reproduction of digital heritage.

17.4 The Development Trend of Digital Heritage

Cultural and natural heritage are the precious wealth of mankind, and the primary condition of heritage protection is to ensure the authenticity and integrity of heritage. Although digital technology applied to cultural and natural heritage, their preservation, protection, research and utilization provides an important support, digital heritage itself also faces issues such as data security, distribution, interoperability, cost, simplification and speed problems for application. It is also a challenge to open access and increase the ease of understanding. The preservation and protection of digital heritage involve technology and methods for preservation and protection, management systems, protection schemes, and management measures and laws regarding the protection of digital heritage. The future development of digital heritage preservation, protection, research and utilization has the following trends.

17.4.1 The Depiction of Heritage Objects via Remote Sensing Technology Is Becoming Increasingly Precise

Multi-platforms of satellite, airborne and ground remote sensing have increasingly higher spatial resolution. The development of multi-spectrum and hyper-spectrum technology has made object characterization more and more precise. Coupled with the progress of data processing technology and cognitive methods, the recognition of the geometry and attributes of natural and cultural heritage is closer to the actual items.

Especially in recent years, rapid development of laser radar technology as a new means of three-dimensional space data acquisition that can perform complex surface measurement quickly and accurately and obtain a record of the sites of cultural relics that is high-density, high-precision and three-dimensional, representing the information of cultural heritage sites truly, accurately and completely. In addition, hyper-spectrum data will become increasingly important in the fine classification of natural and cultural heritage. There will be great potential in the future for natural and cultural heritage information acquisition based on the fusion of hyperspectral information and LiDAR elevation information.

17.4.2 The Demand for Durable Digital Heritage Preservation Media Will Continue to Drive Innovation

How can advanced technology be used to monitor and protect valuable cultural and natural heritage, and what is the best medium for preserving such data? As early as the 1970s, people began to use photography, video and other technologies to record information about natural processes and cultural relics. However, these data are difficult to preserve for a long time due to the aging of videotapes, disk demagnetization, and image reproduction that produces distortion. In the late 20th century, with the emergence of virtual reality technology and the rapid development of networks, the heritage protection industry has a new opportunity—high-precision and high-fidelity digital heritage preservation technology. Modern high-quality digital image technology and advanced graphic image processing methods have brought the protection of natural and cultural heritage into a new era. Image-based rendering (IBR) and image-based modeling (IBM), three-dimensional scanning-based reconstruction and roaming, retrieval/restoration/color technology, multiple projection immersive virtual environment and other technologies have made digital natural and cultural heritage become a reality and have great potential in future applications of digital natural and cultural heritage.

17.4.3 Data Integration, Development, Publication and Dissemination for Heritage Protection Platform Software Urgently Need to Be Developed

To make full use of different sensors (obtained from aviation, space, and the ground), 3D models, airborne data, and ground laser scanning data, using a GIS environment and software to manage and integrate the available information (digital and the digital format) and synthesize, refine, comprehensively develop, and release multisource data (excavation reports, geophysical surveys, mapping, aviation and satellite photography) can provide effective solutions.

GIS environments or web-based GIS environment tools provide new and more efficient ways to conduct archaeological research, store and process data, and share multisource geospatial data collaboratively. To develop infrastructure, new methods and concepts are needed to handle the increasing big data and data integration requirements, the requirement of efficient archive processing and the simplification of GIS-based technology applications. These problems can be solved via building open source components based on the WebGIS platform. With the rapid development of archaeological WebGIS today, the combination and usage increase of related archaeological applications is occurring. Many platforms with various interfaces and functions have been created for professional and nonprofessional users.

WebGIS architecture provides flexible tools for multiple requirements, applications, and usage phases. The open source tools of WebGIS have played an important role for different application purposes in recent years, for example, a the release of mining results; b the design of archaeological clues to the land; and c the incorporation of archaeological data into the broader national geological portal for landscape conservation purposes.

A system platform and database for monitoring, evaluation, decision-making and exhibition of natural and cultural heritage are an expectation of researchers, users and the public around the world. The Digital Belt and Road (DBAR) Working Group (DBAR-Heritage) is developing such a platform.

17.4.4 Increasingly Convenient Digital Technologies Are Adapted to Non-professional and Wide Public Participation in Heritage Conservation

The growing availability of free data and open access software tools has strengthened the link between field surveys and computer analysis, providing new opportunities for the conservation, development and utilization of natural and cultural heritage sites. The key point is to create accessible tools for different people, including the domain expert groups (archaeologists, remote sensing experts, regulators, museums) and non-professional users, for tourism and education purposes concerning regional natural and cultural heritage of the people. In addition, the effective interoperability between different computer platforms, executing a program or data transmission between various functional units should allow for the user to have little or no need to understand the characteristics of these units. Related operations can also be hosted in the cloud by sending images to a remote powerful server and, after a short period of post-processing, the design model can be previewed. This makes digital archaeology work less exclusive than in the past, which makes it easier for government decision makers, schoolteachers and the public to use data and offers the possibility of wider participation.

17.4.5 Quantitative Research Based on the Value Assessment of Natural and Cultural Heritage via Digital Technology

Although the important role and significance of natural heritage in the ecological balance, scientific research, scientific popularization, natural aesthetics and tourism and leisure are difficult to estimate, some fields can be evaluated. In terms of ecological value, especially large natural heritage plays an extremely important role in the conservation of species and the ecological value of regional and global significance. The earth is an organic whole, and local destruction can affect the local or wider ecological environments. Although we may not see any examples of such local destruction causing an obvious overall imbalance, the changes in Antarctic glaciers and even mountain glaciers caused by current climate changes has been a "wake-up call" (e.g. Kaser et al. (2004)).

For both tangible cultural heritage and intangible cultural heritage, the value is diversified. The intangible cultural heritage of language, handicrafts, performance art and other forms of cultural expression make successive human knowledge to be realized from generation to generation. The result of the accumulation of knowledge greatly promoted human progress. Tangible and cultural heritage is the tangible evidence for humans to know themselves. The archaeological analysis and reconstruction of the physical remains (including artifacts, buildings, etc.) and their related living environments and cultural landscapes have led to the rediscovery of some lost ancient civilizations. The great value of cultural heritage must also be explored further.

Examples of the multiple values of nature and cultural heritage are numerous. Due to the large spaces, time spans and complex situations, quantitative research has not been well conducted. For quantitative research on the value of cultural heritage and natural heritage based on digital technology, the formation of a system and a standard are a possible and urgent innovation issue.

17.4.6 The Study of Effective Protection of Digital Heritage and Legal Protection Is Becoming Increasingly Urgent

At present, the main problems in the protection of digital heritage come from two aspects. One is the problem that researchers' understanding of the value of digital heritage is insufficient. The value of the digital information of heritage may not be recognized before it disappears or changes and it is too late to provide effective protection. Digital data may be well preserved, but the identification and description may be so poor that potential users cannot find them. As the independence of data and data processing applications cannot be confirmed, the use of data is reduced. The second aspect is the problem of incomplete preservation of digital heritage due to insufficient funds and responsibilities. No one is responsible for the information, or the person responsible may lack the knowledge, systems or policy frameworks needed to perform their duties. Information is vulnerable to disasters such as fires, equipment failures, floods, viruses or direct attacks that disable storage equipment or operating systems; measures such as password protection, encryption, and security devices will cause data to be unavailable when they are not applied.

Cyber space generated by the internet is a kind of living form that has not been experienced by humans. It will have an inestimable impact on contemporary and future human beings. Due to the openness and sharing of resource information in the network environment, anyone can obtain the desired information in any place by some means. Digital heritage is faced with the problem of destructiveness caused by openness and sharing. In addition, the problem of infringement occurs relatively easily. As a kind of digital heritage with the characteristics of cultural heritage, the owner of its property rights should be protected by the corresponding laws. Infringement in the network is different from general infringement. Due to the disguised characteristics of network information transmission channels, the copyright and communication rights of digital heritage easily lead to infringement caused by the transmission of digital heritage without the permission of property owners. Therefore, it is necessary to systematically form international legal documents and universal legal protection of digital heritage.

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Xinyuan Wang is a Professor in geography and remote sensing at the Institute of Remote Sensing and Digital Earth, CAS. He researches physical geography, space archaeology and digital heritage. He was Deputy Director of the HIST and the Deputy Director of the Key Lab. of Digital Earth, CAS, and was the board member of ICOMOS's SDGs Working Group.

Rosa Lasaponara is Research Director at National Council Research, where since 20 years she leads the ARGON research group and laboratory. She has over 25 years of experience in the field Earth Observation from satellite/airborne/ground based on active (radar, LiDAR) and passive (optical, multi-hyperspectral data) sensors. She is scientific coordinator of several research projects funded by the EU, ESA, ASI, etc.

Lei Luo is an Assistant Professor in remote sensing and GIS at the Institute of Remote Sensing and Digital Earth, CAS. He researches earth observation technologies and big earth data for natural and cultural heritage conservation and landscape archaeology. He was a member of HIST and published a series of papers related to space archaeology.

Fulong Chen is a Professor in radar remote sensing at the Institute of Remote Sensing and Digital Earth, CAS. He researches SAR interferometry for quantitative archaeology and heritage conservation. He was the Editorial board member of "Remote Sensing" and "Heritage", and elected as the Deputy Director of cultural heritage conservation Specialized Committee, China Society of Surveying and Mapping.

Hong Wan is a lecturer with College of Information Science and Engineering, Shandong Agricultural University. She is also working toward the Ph.D. degree in Cartography and GIS at the Aerospace Information Research Institute, Chinese Academy of Sciences from 2017.

Ruixia Yang is an Associate Professor in Digital Natural and Cultural Heritage at the Institute of Remote Sensing and Digital Earth, CAS. Her research field focuses on digital environmental archaeology and geographical information technique for conservation of natural and cultural heritage.

Jing Zhen is an Associate Professor at the Institute of Remote Sensing and Digital Earth, CAS. Her researches mainly focused on fine-scale observation and evaluation of the impact of climate change on world heritage sites. She was a member of HIST and published a series of papers related to Giant Panda habitats.

Chapter 18
Citizen Science in Support of Digital Earth

Maria Antonia Brovelli, Marisa Ponti, Sven Schade and Patricia Solís

Abstract Citizen science can be thought of as a tremendous catalyst for making Digital Earth a participation model of our world. This chapter presents a wide overview of the concept and practice of citizen science in terms of the technologies and social impact. Definitions of citizen science and various existing approaches to citizen involvement are described, from simple contributions to projects proposed by someone else to the design and planning of science as a bottom-up process. To illustrate these concepts, the relevant example of OpenStreetMap is described in detail, and other examples are mentioned and briefly discussed. Social innovation connected with citizen science is focused on to highlight different levels of direct citizen contributions to scientific research and indirect effects on academia, and studies driven by new questions that may support responsible research and innovation (RRI), governments and public administration in making better informed decisions. Despite its growth and success in relatively few years, citizen science has not fully overcome a number of persistent challenges related to quality, equity, inclusion, and governance. These themes and related complex facets are discussed in detail in the last section of the chapter.

Keywords Citizen science · Digital earth · OpenStreetMap · Social innovation · Public engagement

18.1 Introduction

The Digital Earth vision has evolved from a digital replica of the earth that enables knowledge sharing and simulation (Gore 1999) to a blending of our physical world with digital representations of past, present and possible future realities (Goodchild

M. A. Brovelli (✉)
Department DICA, Politecnico Di Milano, Milan, Italy
e-mail: maria.brovelli@polimi.it

M. Ponti · S. Schade
European Commission, Joint Research Centre, Ispra, Italy

P. Solís
Knowledge Exchange for Resilience, Arizona State University, Tempe, AZ, USA

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et al. 2012; Craglia et al. 2012; Ehlers et al. 2014). Digital Earth thereby provides innovative ways of interacting with our real and virtual environments. These interactions support different forms of decision-making and enable new approaches of data and knowledge cocreation and facilitate dialogue between conflicting communities (Ehlers et al. 2014). This chapter is dedicated to the possibilities for active contribution that Digital Earth offers citizens, with a special focus on the relationships between Digital Earth and public participation in scientific research (also known as citizen science).

First, central definitions for citizen science, crowdsourcing and volunteered geographic information (VGI) are elaborated. A detailed analysis of a crowdsourcing and VGI application (OpenStreetMap—OSM) provides concrete practical insights on the roles of communities and institutions, technical considerations, and data quality. Following this example, the view is widened to other approaches and categories of citizen science and their relationship to Digital Earth. Additional considerations are taken into account and briefly expanded to wider concepts such as social innovation and public engagement. The chapter concludes with a summary and lists central challenges for future research.

This chapter addresses citizen science broadly, but additional information about citizen science in the European context is presented in Chap. 20. Citizen science addresses the direct and self-conscious participation of people (citizens) in scientific research—which makes it considerably different from passive contributions to research that are carried out by third parties, for example, in the case of social media analysis (see Chap. 12).

18.2 Definitions

To fully understand the value and potential impact of citizen science, it is necessary to consider at least three relevant phenomena of the last twenty years. The first is Wikipedia, the free wiki encyclopedia, which was created in 2001 (Kock et al. 2016). Just over a decade later, in 2013, it had become such a successful enterprise that an asteroid was named after it (Workman 2013). Wikipedia currently boasts approximately 79 Million registered users and is probably the most widely known and used encyclopedia. By definition, an encyclopedia is a narrative model of the world that includes all human knowledge, and had always been written by scholars. As a result of new technology and the collaboration of volunteers (who are not necessarily scholars), Wikipedia has become the largest encyclopedia, written in a few short years.

A second example is the Global Biodiversity Information Facility (GBIF), an operational system that is very relevant for the environmental challenges addressed by Digital Earth. The GBIF was founded in 2001 upon the recommendation of the Biodiversity Informatics Subgroup of the Megascience Forum and subsequent endorsement by the Organisation for Economic Co-operation and Development (OECD) science ministers (GBIF 2011). Today, the GBIF has evolved into a renowned data infrastructure and single access point for biodiversity data (Robertson et al. 2014), much of which originates from volunteer citizen scientists (Chandler et al. 2017). According to its website, the GBIF provides access to almost 45 thousand data sets, including more than 1.3 billion species observation records. This tremendous source of knowledge has led to the publication of more than three-and-a-half thousand peer-reviewed scientific publications.

A third notable example is OpenStreetMap project, which is a free map of the world. Before considering the history and success of this initiative, it must be noted that mapping was a prerogative of governments (mainly for military purposes and land taxation) and that, in some countries both then and now, military forces hold the legislated national monopoly on mapping services. The knowledge of the territory and the science of "where" are a way to monitor and control territory. In this context, OSM represents a complete change of paradigm: everybody contributes to mapping the world; the map is free to everybody for every purpose. Created in 2004, OSM has seen success equivalent to that of Wikipedia and approximately 5 million volunteers have contributed to this project. OSM is the largest existing geospatial database. These examples illustrate the social and technological environment in which the concept and substance of citizen science are situated.

Although public participation in scientific achievements has a long history, recent decades have seen greater attention and an impressive increase in the number of people involved. The term citizen science was used in scientific papers in the mid-1990s (Kerson 1989; Irwin 1995; Bonney 1996). The term was first reported in Wikipedia in 2005 and entered the Oxford English Dictionary in (2014). It describes the scientific work done by laypeople often with the collaboration or under the supervision of scientists. (OED 2014).

However, citizen science is a very diverse practice that encompasses various forms, depths and aims of collaboration between scientists and public researchers in a broad range of scientific disciplines. There are different classifications of citizen science projects based on the degrees of influence and contributions of the public.

Shirk et al. (2012) classified projects into different models based on the degree of participation:

(1) *contributory projects,* which are mostly data collection;
(2) *collaborative projects,* involving data collection and project design refinement, data analysis, and disseminating results;
(3) *cocreated projects,* designed together by scientists and the public, and the public participates in most or all of the steps in a scientific project or process; and
(4) *collegial projects,* developed by noncredentialed individuals conducting research independently with varying degrees of expected recognition by scientists.

Haklay et al. (2018a, b) distinguish projects in three different classes:

(5) *long-running citizen science*, which are traditional projects similar to those run in the past (Kobori et al. 2016; Bonney et al. 2009);
(6) *citizen cyberscience,* strictly connected with the usage of technologies (Grey 2009), which can be subclassified as follows:

(6.1) *volunteer computing,* where citizens offer the unused computing resources of their computers;
(6.2) *volunteer thinking,* where citizens offer their cognitive abilities for performing tasks that are difficult for machines; and
(6.3) *passive sensing,* where citizens use sensors integrated into mobile computing devices to carry out automatic sensing tasks.

(7) community science, involving a greater commitment of citizens in designing and planning project activities in a more egalitarian (if not bottom-up) approach between scientists and citizen scientists (Jepson and Ladle 2015; Figueiredo Nascimento et al. 2014; Breen et al. 2015). This can be divided into the following:

(7.1) participatory sensing, where citizens use the sensors integrated into mobile computing devices to carry out sensing tasks;
(7.2) Do-it-yourself (DIY) science, in which participants create their own scientific tools and methodology to carry out studies; and
(7.3) civic science, the science built on the needs and expectations of the community (Haklay et al. 2018a, b).

In addition to citizen science, the term crowdsourcing (or geo crowdsourcing or crowdsourcing geographic information) is used. The general term (with no geographic declination) was coined in 2005 to describe the outsourcing and spreading, generally through an open call, of a job previously made by a worker to the crowd, i.e. a large group of people (Safire 2009). When related to the location, it refers to a new source of geographic information that has become available in the form of user-generated content accessible over the Internet.

Citizen science considers the process as a whole, and attention is paid to the community of contributors. Geo-crowdsourcing also considers the contributed data and their condition of usage. In some cases, the contributors (e.g., when they are using Twitter, Instagram, Facebook or Google traffic) are unaware that they are contributing to a project: they simply want to communicate with friends and relatives (in the former cases) or to find directions and traffic conditions (in the latter case). Thus, they are treated more like moving sensors than human beings. The person is an appendix of the sensor and not vice versa. The user-generated data can be provided as open to everybody or (more often) used by the service provider for analytics for diverse purposes. For instance, in the case of Google, one advantage could be to build a powerful database for self-driving cars.

Considering the (re)use potential of citizen science contributions, issues related to fitness for the purpose and data quality should be discussed. Those who are new to the field of citizen science often doubt the quality of the results produced. However, it has been shown on numerous occasions that citizen science can deliver high-quality information (Kelling et al. 2015; Bell et al. 2015; Senaratne et al. 2017), and provide new knowledge that could not be gathered with any other approach (see, for example, Walther and Kampen 2017). Literature on data management, quality assurance, and

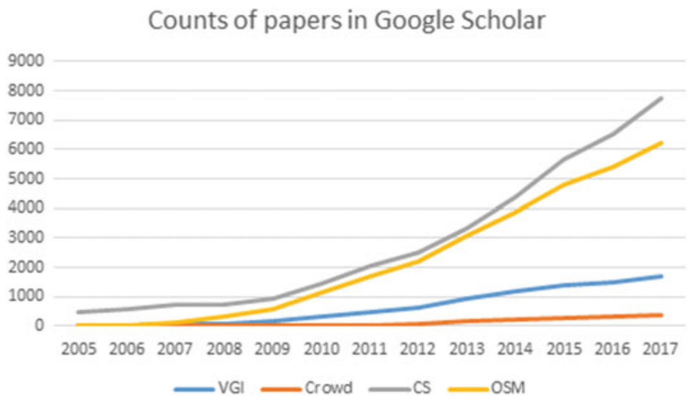

Fig. 18.1 Google Scholar results for papers matching the terms 'volunteered geographic information', 'geo crowdsourced' and 'crowdsourced geographic information' (Crowd); 'citizen science' (CS); and 'openstreetmap'

the provision of accompanying metadata is available for a wide variety of application fields (see, for example, Bastin et al. 2017, 2018; and Williams et al. 2018).

Notably, the term "citizen science" is not uncontested in the sense that the term "citizen" evokes a normative role of what it means to belong to and act as a member of a particular social group, including implications of what it means to participate in public science projects for "noncitizen" residents (e.g., Woolley et al. 2016). These perspectives are not just rhetorical, as labels matter in practical terms if actors such as refugees or resident immigrants participate in contributing. In contrast to the previous terms, volunteered geographic information highlights the active attitude of people when contributing data. VGI was proposed in 2007 and includes examples such as WikiMapia and OSM.

To evaluate the rapid evolution of terms related to user-generated content, Fig. 18.1 shows Google Scholar results for references that match the terms 'volunteered geographic information'; 'geo crowdsourced' and 'crowdsourced geographic information'; 'citizen science'; and 'openstreetmap' are reported. The growth over time is impressive. Moreover, the success of a single project, OSM, is also relevant and deserves more thorough exploration within this chapter.

18.3 Digital Earth Technologies for Citizen Science

The previous definitions allow for specification of the possible roles of Digital Earth as an enabler of citizen engagement—especially for citizen science. Digital Earth technologies provide citizens with advanced sensing devices (see the Chap. 11 on the Internet of Things) and mobile applications that allow for data collection by anyone who possesses a smart device or acquires a sampling tool. In addition, the use of existing social media platforms helps people collect data about a wide range of phenomena, including natural hazards, crop production and the spread of diseases. Following the Digital Earth vision, these data streams can be interconnected and real-time deliveries can be assimilated with data from complementary sources such as authoritative measurement stations or remote sensing imagery. Accordingly, data contributed by citizen scientists might help improve models about our environment (e.g., for air quality, water quality or extreme events) by ground truthing or validation—or by providing additional data points that are used for improved geographic predictions or forecasting. These possible contributions of citizen science could be considered the Digital Earth Nervous System—DENS (De Longueville et al. 2010).

The concept of VGI fits well into this kind of Digital Earth support for citizen science. VGI platforms can be viewed as a part of the Digital Earth infrastructure, but the uptake and use of VGI in combination with data from other sources are essential. In addition, crowdsourced data directly connects to this view, as data is passively collected before it is used as part of a dynamic and intertwined flow of stimuli and contextual information that is integrated into a gigantic knowledge base that keeps the pulse of our planet. User location information is a direct and obvious example. While protecting privacy, valuable information can be derived that, in combination with other data sources, can provide valuable decision support. For example, real-time locations can help optimize green transport or save lives in a crisis situation by individually guiding evacuees along safe routes or sending rescue teams to locations where they are most needed.

Transitioning from pure data collection, Digital Earth technology can also help other dimensions of citizen science. Once data is collected, Digital Earth could provide access to artificial intelligence that could be used for quality control, which is frequently demanded in citizen science. In this area of citizen science activities, automated algorithms can help assess the probability of a certain measurement or observation. For example, automated image recognition (based on machine learning) could analyze pictures of plants recorded by a participant and suggest the most likely species. This could also take into account when and where a record was made. Similarly, an algorithm might calculate risks based on findings from citizen science. For example, it might calculate the risks associated with a possible new sighting of an invasive alien species in an area where it has not been reported yet. Thus, automated support can help overcome the current difficulties in finding enough expertise to validate species information.

With respect to the next possible area of citizen science activities, Digital Earth technologies—especially visualizations—can help people analyze available data sets and display them in context. Offering multiple visualization techniques and map-based integrations with related information can help explore the latest information available and identify possible correlations or other dependencies. Visual approaches (with maps and graphs) might also help communicate the scientific findings to a particular audience, even audiences with low literacy rates. Interactive story maps can created to convey core messages in combination with the supporting data.

Through this highly dynamic situation in which data is contributed and can be used for modeling and storytelling in real time, the most advanced possibility of

Digital Earth as an enabler for citizen engagement can be reached. With this fully integrated view, any individual or group could access a Digital Earth representation on their preferred device to experience a certain situation, simulate possible decisions, and immediately assess the possible impacts. Such an advanced functionality can facilitate debates between any physically connected or remote group of people. In such settings, knowledge can be cocreated and experimented with and situations can be reassessed. In such a way, Digital Earth can create a safe space of interaction and cocreation to arrive at group decision-making before taking concrete actions in the real world.

Concerning the use of citizen-contributed knowledge, Digital Earth provides another essential enabler, namely, the possibility to track and trace data through processing chains and its use for decision-making. This traceability is fundamental to provide feedback to citizen scientists about the use of their data.

18.4 OpenStreetMap

18.4.1 Social Ecosystem

OpenStreetMap is one of the most well-known and researched examples of a volunteered geographic project in which data is crowdsourced at a global scale. Many people consider OSM to be an object or to be the free map of the world, which is contributed by volunteers and is available for everyone, being based on an open-content license (OpenStreetMap Wiki Contributors 2017). However, it is also commonly thought of as a data platform where as many as 5 million users contribute, edit, download and assess the data that are shared. As opposed to a map or platform, many others consider it an "online project," a perspective that refocuses attention on the efforts to create the map instead of the map or database itself. Others, who are often part of the project, speak of "OpenStreetMap" as a community, emphasizing the set of actors responsible for its existence. OSM should be thought of as a community of communities, (Solís 2017) in the sense that this community is increasingly diverse and incorporates the motivations of many different groups with varied approaches to OSM. Together with the technology products and systems, they form a complex sociotechno ecosystem that operates as a multiscalar network (Vespignani 2009). There are fluidities in the kinds of actors that participate in OpenStreetMap, which can be generally categorized and thought of (see Table 18.1) using typical descriptors such as sector-based characteristics: private enterprise, for-profit entities, nonprofit or civil society, and government or public institutions at various scales. It can also be categorized by community through their modality of engagement with OSM: those who directly create map data, locally and/or remotely, entities that add value through map-based services and third-party open source software, algorithms, scripts, or materials, consumers of the data, including individual users exporting for a discrete use, companies that run their navigation or social media platforms live

Table 18.1 Dimensions of characterizing OpenStreetMap as a community of communities

Sector-based categories	Modality of engagement	Social-based categories
Nonprofit/civil society • Humanitarian Sector (e.g., International Federation of Red Cross/Red Crescent) • Local nonprofit entities Education/Academic Sector • K-12 teachers • University students/faculty Government/Public Sector • Local municipalities (e.g., World Bank's Open Cities) • State /Regional governance (e.g., Transport planning entities) • National agencies • Multinational (e.g., World Bank's Open Cities) Private Industry/For-Profit or Commercial Sector[a] • Information Technology and Services • Computer/GIS Software (e.g., MapBox, • Internet Companies (including Social Media) • Use-Driven (e.g., Restaurants, Construction, Retail, Health Care)	Data contributors • Local mapping (e.g., Craftmappers) • Local and remote (e.g., YouthMappers) • Remote mapping • Dataset uploading (e.g., road networks) Providers of Map-based Services or Value Added to OSM[b] • General (e.g., Geofabrik, OpenTopoMap) • Functional Providers – *Edit/Compare* (e.g., *OSMCompare)* – *Live/real-time edits* (e.g., *Show me the way)* – *Quality Assurance* (e.g., *Keep Right, Osmose)* – *Export* (e.g., *Walking Papers, Field Papers)* – *3D Rendering* (e.g., *OSM Buildings)* – *Routing* (e.g., *OpenTripPlanner)* – *Interaction* (e.g., *Wikipedia overlay)* – *Services* (e.g., *OSMNames, OSM Landuse, OpenFireMap)* • Thematic Providers – *Biking, geocaching, hiking, sport* – *Art, history, archaeology, monuments* – *Public Transport* – *Other* • Educational (e.g., TeachOSM, LearnOSM) Consumers[c] • As Base Maps (e.g., Facebook, Wikipedia, Weather.com, Snapchat) • As Data (e.g., Pokémon Go) • As Media (e.g., films and TV) [d] • Internal systems (e.g., Uber)	**Purpose-driven** (e.g., Humanitarian OpenStreetMap Team) **Identity-focused** (e.g., GeoChicas) **Place-based** (e.g., Tanzania Development Trust)

[a]The OSM Wiki lists 80 entities in this category (https://wiki.openstreetmap.org/wiki/Commercial_OSM_Software_and_Services); iDataLabs identified 281 https://idatalabs.com/tech/products/openstreetmap

[b]Summarized with counts from OSM Wiki (https://wiki.openstreetmap.org/wiki/List_of_OSMbased_services)

[c]Adapted from https://wiki.openstreetmap.org/wiki/Major_OpenStreetMap_Consumers; see also https://wiki.openstreetmap.org/wiki/They_are_using_OpenStreetMap

[d]More detail at https://wiki.openstreetmap.org/wiki/Films and https://wiki.openstreetmap.org/wiki/TV_series

with underlying OSM data, and governments that download data for comparison in official geodataset validations. These categories are not mutually exclusive, as a single individual or organization often operates in more than one sector and engages in multiple modalities over the course of interaction with OSM, and thus, understanding this social ecosystem is highly complex. Furthermore, in the construction of communities in the OSM community, the way that social bonds formed around purposes (e.g., the Humanitarian OpenStreetMap Team's humanitarian mission), identity (e.g., YouthMappers academic actors and GeoChicas), or place must also be considered as another dimension of connectedness.

For example, one set of these communities that has experienced tremendous growth recently are the communities that engage with the OSM community with an express humanitarian or development purpose. Beginning with the incorporation of the Humanitarian OpenStreetMap Team (HOT) in the international civil society sector, which formed in the immediate aftermath of the 2010 Haiti earthquake, various groups have begun to distinguish and highlight the purposeful creation of volunteered spatial data rather than the creation of open data for its own sake. HOT has since registered as a nonprofit organization and has a structured governance comprising a core group of voting members that support a larger set of global volunteers with specific local and remote mapping campaigns. The Missing Maps project was later founded by HOT, Medecins Sans Frontieres/Doctors Without Borders, and the American and British Red Cross agencies. Similar to other purpose-driven efforts, this project aims to map the world's most vulnerable people. It has since grown to include participation from other organizations, and has developed a presence as a related OSM community in its own right, with close ties to HOT.

The participation of university actors intersecting with this purposefully humanitarian community was present, even if not consolidated, from the outset; in 2014, the academic community developed YouthMappers to explicitly bring together and nurture the community of students and their faculty that operate within and together with the broader set of OSM communities around youth-based identities. Founded by faculty from Texas Tech University, The George Washington University, and West Virginia University, with support from the US Agency for International Development's GeoCenter, and now administered by Arizona State University, YouthMappers organize as chapters on university campuses, run by student leadership under the guidance of university professor mentors. Chapters apply for recognition by the YouthMappers steering committee as existing student organizations that affiliate or as newly formed student-led groups. The network encourages students to participate in global remote campaigns of USAID, HOT and other humanitarian groups, develop and implement local mapping campaigns that create and use geospatial data for needs at the local or national levels, and seek and provide resources for students to expand their volunteerism through internships, leadership development, and research fellowships. Activities center on the concept of not just building maps, but building mappers and promoting exchange and solidarity among student peers across continents. Campaigns create data directly for development programming and seek to promote greater inclusion and participation of students from countries in development as well as female mappers via the #LetGirlsMap campaigns. By late 2018, the network had grown to 143 campus chapters in 41 countries, linking more than 5,000 OSM volunteers. Although the YouthMappers purpose falls along the humanitarian or development realm, where activities are defined as contributions to global targets such as the UN Sustainable Development Goals (Solís et al. 2018), the community has a strong identity-based composition, as participants are students in universities and learning through the mapping experience carries significant import (Hite et al. 2018; Coetzee et al. 2018). Similarly, consolidating community space for particular actors within the social ecosystem of OSM, GeoChicas formed at the State of the Map Latin America conference in 2016. GeoChicas is a group of women who volunteer map in OSM and work to close the significant gender gap within the OSM community. Their activities promote mapping campaigns that address women's issues such as mapping gender violence and promote female participation by creating more training spaces for women and ensuring harassment-free mapping. They also raise awareness of OSM technical matters such as tagging in support of women and girls in the OSM map and data platform.

An impressive example of a place-based community is Crowd2Map Tanzania, which was established in 2015 to improve the rural maps of Tanzania to fight female genital mutilation and improve development of the region. The community of volunteers creating OSM data in the context of Crowd2Map intersects with all of the above communities (HOT, Missing Maps, YouthMappers chapters in Tanzania, GeoChicas), especially local residents. This demonstrates how the communities of OSM engage and create a multiplicity of volunteer impacts within the social ecosystem of OSM.

End-user communities are important in shaping OSM institutionally and should not be underestimated because they are not actively involved in the construction and constitution of OSM. This community is much more difficult to track and assess, since OSM is free and open for anyone to use. In addition to the user-contributor communities noted above, governmental entities, including at the very small scale such as local civil protection agencies, local disaster response units, and local businesses, are using OSM data in their functions. At the country scale, actors such as national mapping agencies incorporate OSM data with official data sources, especially in times of urgency such as disaster response, e.g., the earthquake in Ecuador in 2016 where OSM data supplemented with official data was used to validate or gap-fill missing data. Multinational organizations such as the World Bank span local to global categories, considering the city-level action that work such as the Open Cities Project supports. The participation of governments and the public sector is significant due to the unique challenges for such actors and communities of actors for adopting crowdsourced geographic data, despite its potential value. The landscape of participation among governments has been highly dynamic in recent years, as the reliability and accuracy of volunteered data has been increasingly seen as appropriate for (to inform or accompany) official use. Obstacles remain; most recently, Haklay et al. (2018a, b) conducted qualitative comparative analysis of multiple use case studies to identify success factors for users with governance missions. The use cases included activities such as base mapping or focus on a particular area of interest, generating updates to authoritative datasets, upgrading public services, policy development or reporting, and disaster management or response. The authors find that individual champions and change agents are critical, organizational business models are necessary, technical capacity is essential, and conceptual buy-into acceptance of issues such as uncertainty, collaboration, and new ways of serving the public good must accompany this community's involvement in open Digital Earth landscapes.

On a broader scale, the user policies and open license of OSM provide a public good that commercial and for-profit enterprises are keen to leverage or even support in some cases. This is unsurprising in a rapidly growing context where geospatial information is valued as a multibillion dollar industry (Eddy 2014). With an Open Database License, adopted in 2010, OSM is enabled and simultaneously constrained for use in the private sector, and thus, calls for more "business-friendly" approaches are not uncommon (Gale 2015). The range of themes, applications, and industries in this sector are broad and growing and are difficult to comprehensively capture. The inclusion of the OSM layer as a base map in widely used proprietary geospatial software (such as ArcGIS Online) and examples of OSM powering services such as Craigslist and The Weather Channel show that the public may be consuming this volunteer-contributed content base without much awareness. Passive users are less affected by licensing frameworks than actors that seek to build services or add value and comingle data sources and types, who must contend with share-alike clauses. Explicit commercial contributors to the OSM ecosystem include companies that offer commercial OSM software and services that expressly add value to OSM in terms of architecture, analysis, visualization, and/or consulting on a multinational, regional or, very frequently, worldwide scope. Although Google Maps still dominates web mapping, OSM has captured approximately 0.1% of the market share of web mapping, which is impressive for a community that is completely powered by volunteer contributors (iDataLabs 2017). Top industries include IT software and services and Internet companies, with revenues reaching the $200 M range. Nearly one third of companies have fewer than 10 employees, and Germany, the US, France, and the UK currently account for 40% of estimated formal business activity. However, as OSM grows, its presence in lower-to-middle-income countries (LMICs) is increasing, as the ability to access scarce geospatial data and location-based information is gaining traction as an international economic development strategy in the context of digital development (USAID 2018). Open geospatial data such as OSM powers businesses in real estate, transportation, agriculture, and technology in 177 countries (Bliss 2015), and the corporate sector sees OSM as a priority in the open source community (Moody 2018). The increasing presence and influence of large-scale commercial or for-profit entities within the OSM community of communities is changing the countenance of the social ecosystem in ways that are sometimes contradictory and contested. The OSM Foundation, as the nonprofit entity that exists to protect, promote and support the project (though it does not own the data), continues to navigate this complex array of actors, visions, uses, and contributors in a dynamic landscape of volunteered geographic information.

18.4.2 Technological Ecosystem

One of the main reasons for the success of OSM is that the technology behind the project allows for everybody to contribute regardless of their level of expertise. More than a simple geospatial crowdsourced database, OSM is an ecosystem of data, software and web-based information stores. The tools and systems developed by different actors in the social ecosystem of OSM are generally characterized as being free and open source, i.e., available for further development by other people in the community. Access to the different applications is often possible using the same personal account as that for the OSM platform.

The geometric OSM data model is easy and simple, based on simple data types such as nodes, ways (polygons and polylines) and relations (logical collections of ways and nodes). The semantic model, i.e., the nonspatial attributes associated with the geometric objects, is more complex but services such as the taginfo (OpenStreetMap Contributors 2018a) help contributors to choose the most appropriate tags (key/value pairs). As an example, the most basic and common representation for a building is by means of a way and the pair: “building = yes”.

After signing up for free access to OSM (OpenStreetMap Contributors 2018b), users can begin contributing by mapping new data in OSM or editing existing data stored in the OSM geospatial database. In December 2018, there were more than 5 million users (OpenStreetMap Stats 2018). There are three ways to contribute:

(1) by physically surveying an area and inserting the information collected by GPS receivers and paper-based tools into the OSM database;
(2) by digitizing objects into the OSM platform using available aerial and satellite imagery; and
(3) by bulk-importing suitably licensed geospatial data.

The first two modalities are more generally used whereas the third must be coordinated with the OSM community.

Many guides and tutorials on how to map with OSM are available; excellent examples include those made available by the company Mapbox (Mapbox 2018) and the Humanitarian OpenStreetMap Team (HOT 2018).

Editing and visualization are the two basic functionalities for interacting with the OSM geospatial database. The choices are very broad for both and depend on the exigencies and skill of the user. As the OSM platform has an editing API, many editors have been developed, some with a simplified subset of functionality and others that operate on specific platforms such as mobile technology (OpenStreetMap Wiki Contributors 2018a). The three main editors are iD, which is the default editor for the user when accessing the OSM platform and is meant for beginners; MAPS.ME, which is an app for iOS, Android and BlackBerry designed mainly for travelers, with more than 50,000,000 installations, that provides offline maps and a straightforward editor (Maps.me 2018); and JOSM (Java OpenStreetMap Editor), which is a desktop application popular among expert editors because of its more advanced performance (JOSM 2018).

In addition to enabling individual contributions, the OSM technical ecosystem is designed to elicit and simplify collaboration among contributors. One fundamental tool for this purpose is the Tasking Manager developed by HOT (HOTOSM Community 2018).

The main purpose of this tool is the subdivision of a large area into smaller areas, which require less time and effort to map. Individual contributors work on smaller areas to avoid problems of overlap and confusion. Moreover, the Tasking Manager allows for a second level of contribution: validation of the mapping of other users. Validation is generally done by expert OSM users and consists of verifying the geometric and semantic accuracy of the mapped objects and reviewing the mapping for completeness.

The Tasking Manager has a graphical interface that shows the main characteristics for every project (status, project creator, last updates, difficulty, priority, types of mapping, organization, campaign, and contribution level required) and the map with activity and stats. Figure 18.2 shows the example of Typhoon Ompong: Cagayan and Batanes Structures (task: #5236) as published on 6 October 2018. The map helps contributors know where to edit or validate, depending on their role.

TeachOSM is another site eliciting collaboration that is useful, but not limited, to educators (TeachOSM 2018). It is another instance of the HOT Tasking Manager and is used mostly by the academic and educational community. It provides training documentation and resources that help instructors identify, assign, manage and grade mapping assignments.

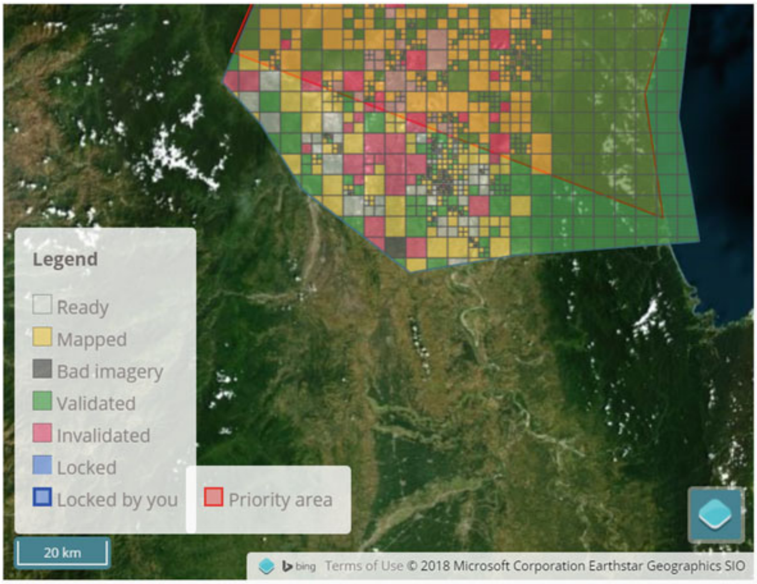

Fig. 18.2 Example of activity and status on the HOT tasking manager

The OSM ecosystem provides many opportunities for collaborating, and the possibilities of using these data are many and various. The license of the project, Open Database License (ODbL), permits free copying, distribution, transmission and adaption of part or the whole dataset as long as credit is provided to OSM and its contributors. If someone alters or builds upon OSM data, the results must be distributed under the same license.

As noted above, this free and viral license has been pivotal in the development of communities, research, and business around the project. Moreover, it has led to the creation of a very wide range of applications.

Many visualization tools have been created with different sensitivities and needs: rendering for cyclists, transportation maps, rendering for humanitarian purposes, maps of specific collections (hydrants, fire stations, etc.), 3D maps and artistic maps such as those provided by the US company Stamen (see Fig. 18.3).

Data can be downloaded in several ways. The first option is to download in .osm format directly from the OSM geoportal by selecting the area of interest and using the "export" button. As an alternative, the Planet.osm (OpenStreetMap Wiki Contributors 2018b) file is released weekly and contains the entire global dataset. It is a big file, almost 40 GB compressed. For the complete time-varying dataset, a full history planet dump is made available at irregular intervals.

For selected downloads, Geofabrik (Geofabrik GmbH Karlsruhe 2018) provides access to continental, national and regional data extracts as OSM raw data or in shapefile format and most of these files are updated daily. The same service is offered by OSMaax (HSR Hochschule für Technik Rapperswil 2018), through which OSM data are downloadable in the most common GIS formats. The HOT Export Tool (HOT

Fig. 18.3 Stamen watercolor rendering of OSM data (Tiber River in Rome)

2018) creates customized extracts of up-to-date OSM data in various file formats, with the limitation of at most 10 Million nodes.

Additionally, there are API calls to directly create, read, update and delete map data for OSM (OpenStreetMap Wiki Contributors 2018c), and this provides software developers and applications with the most up-to-date data available. The Overpass API service (OpenStreetMap Wiki Contributors 2018d) allows clients to send queries using a special API query language or a graphical interface and obtain the requested data (which can be huge). The ecosystem also includes free and open source GIS packages, for instance, QGIS. In this case, a plugin, QuickOSM, allows users to extract customized OSM data.

The availability of the data and this rich technological ecosystem has created opportunities to invent services and applications suited for different aims. In addition to "traditional" routing services (for cars, bikes and pedestrians), there are customizable ones. Among the many examples, Via Regina is a project related to "slow" tourism (Brovelli et al. 2015), i.e., tourism based on environmentally friendly forms of transportation, the appreciation of nature and the rediscovery of local history and cultural identity. Using OSM as a database, customized routes according to the user's preferred points of interest (religious, civil, museums, rural, archaeological, military, factory, panoramic, or geological) can be shown on the interactive map, as shown in Fig. 18.4 (I Cammini della Regina 2018). Before departure, the user can create a personalized itinerary according to her/his own choices, supported by other information such as the slope of the route and the presence of suitable tourist services (restaurants, hotels) in the area.

Furthermore, many other services unrelated to routing have been created. A detailed list of services is available on the wiki section of OSM (OpenStreetMap Wiki Contributors 2018e).

In conclusion, OSM is a very vital collaborative project with a flourishing and vibrant social ecosystem and a strong technologic support.

One of the main criticisms of this dataset is that, as a collaborative product created mainly by citizens without formal qualifications, its quality has not been assessed

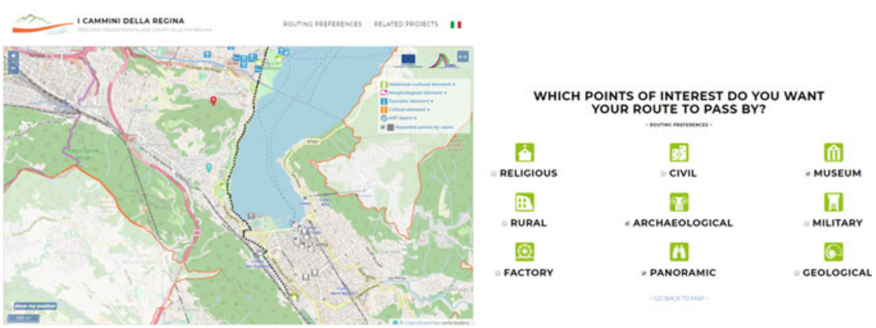

Fig. 18.4 Routing according to preferred points of interest (via Regina geoportal http://viaregina3.como.polimi.it/ViaRegina/index-en.html)

and therefore its usage can be detrimental for some applications. The assessment of OSM is a hot research topic and the majority of scholars have compared the database against authoritative ones. Whereas significant attention has been paid to OSM positional accuracy assessment and completeness, fewer authors have investigated its semantic, temporal and thematic accuracy and consistency (Antoniou and Skopeliti 2015) and none, to the best of our knowledge, have assessed all the elements of data quality. Some scholars have sought alternative quality metrics through "fitness of purpose" tests (Wentz and Shimizu 2018; Solís et al. 2018) in ways that prioritize how the data are used over abstract technical attributes of fidelity. The purpose for mapping has been suggested to influence productivity and quality in surprising ways: humanitarian mappers knowledgeable of the end use of the data may be on par with respect to productivity and error rates relative to mappers who operate without regard to purpose; however, they tend to make more and different *kinds of* errors, although they are more confident in the quality of their work. The implications of this so-called "do good effect", where new volunteers may think they are doing well just because they are doing good, holds significant implications for tailoring the training and quality control of new mappers motivated by humanitarian mapping purposes (Solís and DeLucia 2019).

It is impossible to draw a unique conclusion about the spatial accuracy and completeness, although recent case studies of OSM have indicated that they are comparable to those of regional-scale official datasets (Brovelli and Zamboni 2018). In other cases, for instance, in some developing countries, OSM is the only available dataset and therefore comparisons are not possible. The activism of the communities and attention paid to validation of the collected data (for brevity, many available tools are not mentioned) gives hope for continuous improvement of this product, as has occurred for other collaborative projects such as Wikipedia. As a practical reinforcement of our idea of "communities of communities" contributing in the scale-up of this resource, the OpenStreetMap community recently issued guidelines (OpenStreetMap Contributors 2019) for groups who are contributing collectively to the resource, making the ethic that quality matters to OSM creators and users more explicit and transparent.

18.4.3 Other Citizen Science Projects: Social Innovation and Public Engagement

OSM is a flagship example of citizen science. As noted above, although the primary purpose is to collect up-to-date topographic and other spatial data, it has additional benefits such as community building and active citizenship. Turrini et al. (2018) recently described the multiple benefits of citizen science more formally (Fig. 18.5). Their research examined how citizen science contributes to knowledge generation, learning and civic participation. The contributions can be clearly identified for the knowledge dimension, e.g., by the contributed data and quality control of OSM.

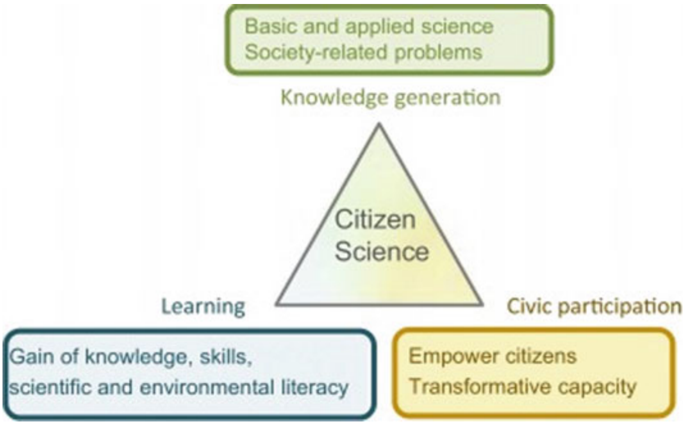

Fig. 18.5 The threefold potential of citizen science (*Source* Turrini et al. 2018)

With respect to learning, citizen science contributes to scientific literacy and to the improvement of topically related skills, e.g., those related to mapping. In addition, self-organized learning and education networks such as Geo4All (OSGeo 2015) for open geospatial software comprise this dimension. Lastly, civic participation is stimulated and facilitated. The YouthMappers community is an excellent example of this aspect of citizen science, as well as GeoChicas. The latter group adds different perspectives and experiences about conceptions of gender and ways of participation within the OSM community and analyze the roles, representation and participation of women in OSM to find a path of dialogue and close the gender gap. Improved gender inclusion also promises to impact the map and data and, ultimately, the knowledge products and decisions made with it (e.g., Holder 2018).

In addition to these multifold dimensions that materialize with different intensities in all citizen science initiatives, the concept of citizen science covers a much wider set of possibilities for (i) the public to understand and contribute to scientific research; (ii) academia to research new questions and carry out Responsible Research and Innovation (RRI); and (iii) governments and public administration to make better-informed decisions.

The different forms of contributions of citizens to science is likely the most debated and researched topic of citizen science. There are many different categorizations (see, for example, Shirk and Bonney (2015) for an overview), within specific contexts and justifications for existence. The framing introduced by Pocock and others (2017) is the most self-explanatory to describe the relationship to the research process, see also Fig. 18.6.

In addition, the relationship between academia and citizen science has been widely discussed; see, for example, the report of the League of European Universities (LERU 2016) or Mitchell et al. (2017). The form and shape of these discussions clearly depend on the way that citizen science is seen and embraced in different countries around the globe. There is great diversity across cultural regions and between more-

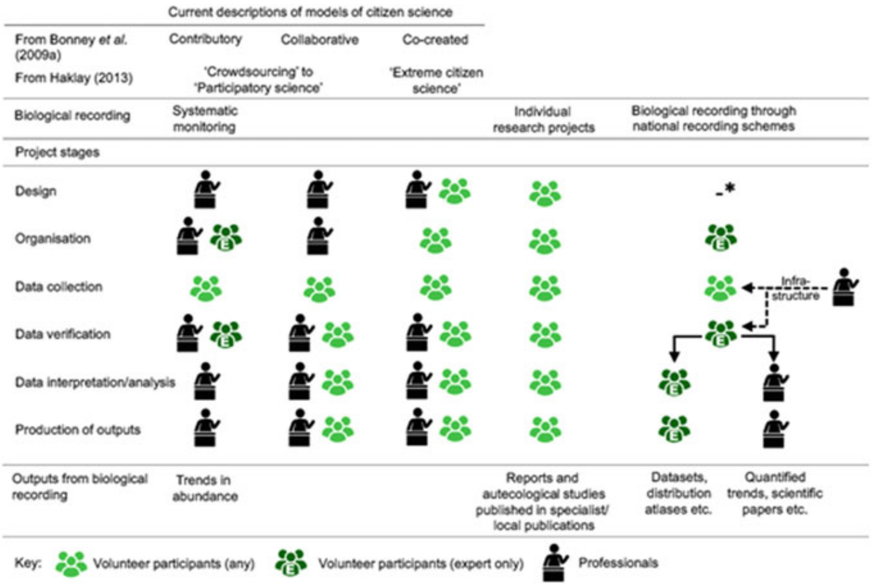

Fig. 18.6 Roy's categories of citizen science (*Source* Pocock et al. 2017)

and less-developed countries. It is also closely related to where the funding for citizen science comes from. For example, in Europe, the overarching topics of responsible research and innovation (RRI) and the open science agenda are strong promoters of citizen science—as is the funding of citizens' observatories in the context of innovative Earth Observation. In the US, citizen science is more often linked to open innovation (Congress.gov 2016).

In regard to the uptake of citizen science by governmental organizations, there are many different approaches (Schade et al. 2017). A possible overall model is summarized in Fig. 18.7. In this framing, the typical elements of citizen science (data gathering, quality control and analysis) are connected to the policy-making process. This imposes a need to provide feedback about the influence on political decisions, and creates an opportunity to consider citizen science to monitor the impacts of those decisions. Such an "accountability cycle" could be imagined at any administrative level, municipalities, regions, nations, macroregions or the entire earth. It can be distinguished by whether the contributing citizen science initiatives are initiated from the top down (i.e., on request by governmental institutions) or bottom-up (i.e., by an active citizenry that wants to raise an issue or challenge a governmental decision). Both approaches have success stories, and they face different challenges. Top-down approaches often have issues about acceptance or community uptake or buy-in. Bottom-up approaches often face difficulty in reaching the relevant decision makers or being taken seriously.

Given the multifaceted nature of citizen science, its relationships to the notion of Digital Earth are manifold. As set forth in the visionary work on the European

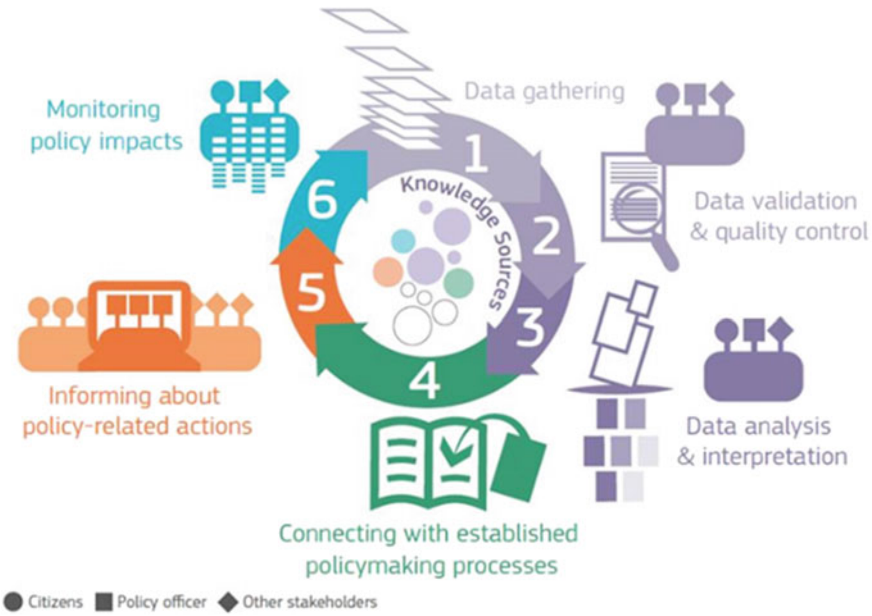

Fig. 18.7 Cyclic value chain of citizen science for policy (*Source* Schade et al. 2017)

Perspective to Digital Earth (Annoni et al. 2011), the Digital Earth Nervous System (De Longueville et al. 2010), the Digital Earth Living Lab—DELI (Schade and Granell 2014) and views beyond the next-generation Digital Earth (Ehlers et al. 2014), a clear direction of Digital Earth and related research concentrates on the possible contributions of and interrelationships with citizens—and citizen science is a very promising way to progress in this direction on local and global levels.

Digital Earth can be seen as an enabler of citizen science. With its enabling geospatial information infrastructures (see also Chap. 5) and Digital Earth platforms (see also Chap. 2), it offers citizen scientists a rich set of content and functionalities that can help develop and prepare citizen science initiatives. For example, technical solutions, recommendations and training material for geospatial data management could be offered by parts of the Digital Earth community (Chap. 5). Digital Earth technology can provide mapping tools and others forms of visualization, and can help any group of people explore, analyze, and model data collected by citizen scientists in combination with data from other sources. It can also provide access to machine learning algorithms and other forms of artificial intelligence (see also Chap. 10) that can help in quality control and quality assurance of citizen science data. With this capacity, Digital Earth technology can help address the continuing challenge of data processing scalability. With the potentially very high volume of citizen science data, it is impossible to rely on skilled community members and scientists alone to meet the need for quality-assured results. In addition, Digital Earth capabilities can help communicate core messages underpinned by research results. The story map of the European Year of Cultural Heritage is one example of many (Cultural Heritage 2018).

Digital Earth and Digital Earth research are also a beneficiary of citizen science. Citizen scientists can provide valuable input on priority items for research agendas and in terms of data provisioning, for example, from mobile apps or lower-cost sensors systems. Citizen scientists can also provide valuable contributions to field validation (e.g., to validate land use types that have been extracted from satellite imagery) or training of artificial intelligence algorithms (e.g., by crowdsourced applications that combine human reasoning with machine learning to extract damaged buildings in remotely sensed images). Concrete cases can be found on the GEO-Wiki platform (Geo-Wiki 2018).

The above examples only scratch the surface of the possibilities to advance Digital Earth research. Projecting these capabilities into the not too distant future, it can be imagined that new technologies will enable citizens to contribute to individual data and to our reasoning capabilities and interpretations via a global Digital Earth infrastructure for dedicated use. Possible uses might include new scientific discoveries in the earth and environmental sciences or in areas such as astronomy, social science and economics. Whereas most cases of citizen science apply to the former fields, possible applications might address more holistic approaches to overcoming challenges including energy, food and water. It has been illustrated that citizen science can contribute to all of the United Nations Sustainable Development Goals (European Commission, Directorate-General for Environment et al. 2018).

In exploring these new possibilities of citizen science within the context of Digital Earth, it cannot be forgotten that the indicated approaches must adhere to ethical and legal considerations. When operating on a global scale, the values and standards of the communities involved vary largely, as well as the cultures and habits of participants. Any realistic future scenario should adhere to local circumstances and define the possible contributions to (geographically) larger scale initiatives. The example of Let's do it World (Let's do it 2018) underlines some of the difficulties and Global Mosquito Alert (European Citizen Science Association 2018) confirms and, to some extent, complements these issues. Both initiatives aim at data collection and actions around our planet. However, they also allow for diversities, for example, in the data collection approach and additional community activities. By doing so, they provide a global framework and initiate movements while remaining open to the emerging (unpredictable) dynamics of those that react to the call for action. This openness and readiness to adapt to and accommodate specific needs is a key success criterion when dealing with local communities and stakeholder groups, and becomes even more important when the activity is spread across the globe.

18.5 Forms of Citizen Engagement and Distribution of Participation

Citizen science can be considered one form of citizen engagement, which is a broader concept encompassing other practices such as civic engagement, public participation and do-it-yourself (DIY) science (Figueiredo Nascimento et al. 2016). These practices involve different forms of contributions from citizens and collaboration with actors other than the academic community. A common feature of citizen science is the collaboration between the public and professional scientists in civic engagement rather than collaboration with academics, and the primary aim is to develop the knowledge, skills and values that can make a difference in the civic life of communities (Ehrlich 2000). DIY Science (Figueiredo Nascimento et al. 2014) includes nonspecialists, hobbyists and amateurs who do research outside institutional research centers in settings such as Makerspaces, FabLabs, and Hackerspaces, where people meet and work together to develop new projects and devices (Figueiredo Nascimento et al. 2016). Technically savvy people can carry out their own DIY science efforts using low-cost sensors and other devices including easy-to-program control boards, miniaturized computers (such as Arduino or Raspberry Pi) and 3D printers, and share information over collaborative websites (Haklay et al. 2018a, b).

Regardless of the differences in contributions, actors, and settings, these forms of citizen engagement provide opportunities for citizens to engage in science and innovation and, more generally, in the challenges that affect our society (Figueiredo Nascimento et al. 2016). As argued by previous authors, better use and integration of the inputs from citizens can expand the evidence used for policy-making and science, turning citizens into generators of innovation (Figueiredo Nascimento et al. 2016).

18.5.1 The "Power Law" Distribution of Participation

Digital technologies such as smartphones and tablets enable many people to engage but participation in online communities plots along a solid core/periphery model—provided that social software supports both low threshold participation and high engagement. Although the number of citizen science initiatives has grown, many projects fail to attract and retain enough participants. Participants tend to engage with projects for short periods of time, and successful projects rely on a small number of contributors who do most of the work (Dickinson and Bonney 2012; Curtis 2014; Sauermann and Franzoni 2015). For example, in GalaxyZoo, a very successful crowdsourced astronomy project, Lintott et al. (2008) show that a small number of participants complete a high number of classifications and that there is a tendency of participant withdrawal over time (Fig. 18.8). In their study of individual-level activity in seven different citizen science projects, Franzoni and Sauermann (2014) found that most participants contributed only once and with little effort, and the top 10% of contributors were responsible for almost 80% of classifications. This pattern

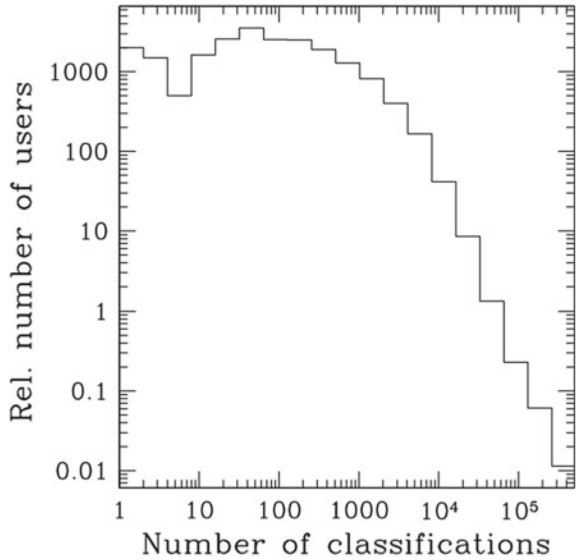

Fig. 18.8 The distribution of classifications among users. A small number completed more than 100,000 classifications each and the peak of the distribution is at approximately 30 classifications per user (*Source* Lintott et al. 2008)

of participation is known as a 'power law' distribution, or the 'Pareto Principle', and has been observed in several online communities such as Wikipedia, where most content is generated by a minority of users. Therefore, this phenomenon is not specific to citizen science projects. Franzoni and Sauermann note that the reasons for this uneven distribution of contributions are unclear. In their opinion, one reason could be that, as soon as the volunteers start contributing to the project, they realize that the match does not fit their expectation or is not suitable for their skills. One can argue that the specific demographics in citizen science may influence this distribution of participation.

18.5.2 Citizen Scientists Are a Minority and Have Specific Demographics

Digital technologies enable mass participation and increase the potential for considerable diversity among citizens in terms of age, gender, experience, race, and education, but participation in most citizen science projects is biased towards white men aged 20–65 from well-to-do socioeconomic backgrounds (Haklay 2015). For example, a study found that 87% of participants in a volunteer computing project were men, and a similar bias was identified in ecological observations of birds (Krebs 2010). A report by the Stockholm Environment Institute for the UK Government (DEFRA 2015) showed that the percentage of the UK population that had participated in environmental volunteering was biased towards white, male, middle-aged, higher income people. Low-income people, those with disabilities, and those of black and minority ethnic origin are traditionally underrepresented in citizen science, for example, in environmental volunteering (Ockenden 2007). Identity-based communities such as YouthMappers and GeoChicas can achieve higher inclusion rates among specific demographics but may not achieve other goals such as racial and ethnic or economic diversity.

At the international level, citizen science is concentrated in advanced economies, especially the US and northern Europe. Access to connectivity represents a barrier to wider participation, with a level of access of 87% in the UK, 81% in the US, and 65% in European countries such as Poland and Portugal (Haklay 2015). Haklay noted that many software applications developed for citizen science projects require continuous connectivity, but 3G and 4G coverage is partial even in highly urbanized environments such as London or New York City and less in remote nature reserves. Another barrier to broad participation is language. English is the main language in science, and many tools and technologies that support citizen science projects presuppose knowledge of English and are not available in local languages (Haklay 2015).

18.5.3 Not Only Science: Citizen Science for Digital Social Innovation and the Role of Local Authorities and Governments

It can be argued that citizen science should extend beyond the framing of citizen engagement in scientific research. The European Commission stated this need in relation to responsible research and innovation (RRI), which is an element of the EU Horizon 2020 program. RRI calls for researchers, companies, NGOs, and members of the public to collaborate during the research and innovation process to align both the process and its outcomes with the values, needs, and expectations of the European society (European Commission 2018). This view reflects the aspiration to cocreate the future with citizens and include diverse stakeholders to address social challenges.

Digital technologies such as social media and online platforms, open data, and open and standardized APIs have led to opportunities for different modes of citizen engagement and new forms of interaction among different stakeholders. Therefore, digital technologies and the Internet have the potential to enable forms of digital social innovation, that is, social and collaborative innovations in which different actors use these technologies to cocreate knowledge and solutions for issues of social concern (Bria 2015). In a study commissioned by the European Commission, Bria illustrated examples of digital social innovation involving citizen science, including the Globe at Night project in which citizens used a camera and geo-tagging functions on their smartphones to help the research project measure global levels of light pollution, effectively coupling open data and citizen science.

The growth of data generated by citizens can benefit scientists as well as other social actors. For example, the public sector could use data volunteered by citizens to address critical socioeconomic and environmental issues and inform policies. Two projects are worth mentioning: CuriousNoses (Curieuze Neuzen 2018), a citizen science project in which 20,000 citizens measured the air quality near their homes in Antwerp, Belgium in May 2018, and the Decentralised Network for Odour Sensing, Empowerment and Sustainability (D-Noses 2018), a large project in which citizens in 7 European and 3 non-European countries use innovative mapping tools to detect odor issues and cocreate specific solutions with several stakeholders including local authorities. Local authorities and governments can play a leading role in championing citizen science and social innovation projects. As noted by the Earthwatch Institute (n.d.), local authorities can champion citizen science to raise awareness of the surrounding environment and support environmental protection and education programs. Furthermore, local authorities and governments can enlist citizen scientists to participate in efforts to study social problems and cocreate actionable solutions. To this end, open data platforms can provide powerful tools for sharing information and developing collaborations to apply knowledge in the real world.

18.6 Conclusions

The rapid and profound nature of the technological innovations related to Digital Earth resources are matched, and even outpaced, by the social innovations unfolding in relation to creating and using them for citizen science. These dynamic configurations bring together new arrays of actors and diverse communities of interest to contribute to and apply the data and knowledge in ways that are only made possible by the massive participation of individuals and institutions.

In this chapter, we deliberately took a positive stance towards citizen science but some important operational challenges should not be overlooked. In the previous section, we addressed one of challenge, which is the difficulty of attracting and retaining a diverse base of contributors. Another main issue faced by citizen science is ensuring quality, especially the intrinsic quality of data, that is, the accuracy and believability of data provided by citizens (Prestopnik et al. 2014). Quality concerns are a large barrier to wider use of citizen science approaches by professional scientists and policy makers and the diffusion of citizen science project findings (Burgess et al. 2017; West and Pateman 2017). The reasons for this concern include participants' lack of formal scientific training and limited scientific knowledge, uneven levels of expertise and anonymity, as well as nonstandardized and poorly designed methods of data collection (Hunter et al. 2012). Research findings and data are sometimes not published because the ownership and property rights were not clarified during project initiation, leading to disagreements or misunderstandings among diverse participants with different norms and interests (Guerrini et al. 2018; Resnik et al. 2015). Therefore, it is important to understand how citizen scientists produce data, how accurate these data can be, and the factors that influence data quality. The literature suggests a number of approaches that can help projects ensure high-quality processes and results (Wiggins et al. 2011). Among others, reviews by experts can help establish scientific standards, and training of new participants can improve the consistency of research processes and results.

Despite these challenges, the current state of progress is encouraging given the results of humanitarian, environmental, and economic efforts but it has not fully overcome complex challenges related to quality, equity, inclusion, and governance. Outcomes unfolding in present contexts will determine the future extent to which Digital Earth created with and for citizen science is accountable to the needs of the planet and its inhabitants.

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Maria Antonia Brovelli Ph.D., is Full Professor of GIS at the Politecnico di Milano. Her main research interest is in open data, free and open source GIS and citizen science. As a researcher, she is involved in many networks and committees, like UN-GGIM AN, ESA ACEO, ISPRS and OSGeo.

Marisa Ponti Ph.D., is a scientific officer at the European Commission's scientific and knowledge management service, the Joint Research Centre (JRC), with a background in sociology and information management. Her interests cover citizen-generated data, games in citizen science and human computation.

Sven Schade is a scientific officer at the European Commission's scientific and knowledge management service, the Joint Research Centre (JRC), with a background in geospatial information science and knowledge engineering. His interests cover knowledge extraction from heterogeneous data sources, multi-disciplinary interoperability, and public participation in science for policy.

Patricia Solís Ph.D., is Executive Director at the Knowledge Exchange for Resilience and Research Associate Professor at Arizona State University. She has developed over fifty competitively funded projects promoting innovations in research, education and community collaboration in over sixty countries, including as Director and Co-Founder of YouthMappers.

Chapter 19
The Economic Value of Digital Earth

Max Craglia and Katarzyna Pogorzelska

Abstract In this chapter, we approach the economic value of Digital Earth with a broad definition of economic value, i.e., the measure of benefits from goods or services to an economic agent and the trade-offs the agent makes in view of scarce resources. The concept of Digital Earth has several components: data, models, technology and infrastructure. We focus on Earth Observation (EO) data because this component has been undergoing the most dramatic change since the beginning of this century. We review the available recent studies to assess the value of EO/geospatial/open data and related infrastructures and identify three main sets of approaches focusing on the value of information, the economic approach to the value of EO to the economy from both macro- and microeconomic perspectives, and a third set that aims to maximize value through infrastructure and policy. We conclude that the economic value of Digital Earth critically depends on the perspective: the value for whom, what purpose, and when. This multiplicity is not a bad thing: it acknowledges that Digital Earth is a global concept in which everyone can recognize their viewpoint and collaborate with others to increase the common good.

Keywords Economic value · Social value · Earth observation · Private sector · Public sector

19.1 Introduction: Framing the Issue

Previous chapters of this manual introduced the concept and definitions of Digital Earth (Chap. 1) and the data and technologies that contribute to it (Chaps. 2–12) and focused on the role of Digital Earth in supporting the achievement of sustainable development, particularly the UN Sustainable Development Goals (Chap. 13) linked to climate change (Chap. 14) and disaster risk reduction (Chap. 15). Each of these areas has both social value to present and future generations (Brundtland Commission

M. Craglia (✉)
Joint Research Centre, European Commission, Ispra, Italy
e-mail: massimo.craglia@ec.europa.eu

K. Pogorzelska
Joint Research Centre, European Commission, Seville, Spain

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1987) and economic value, i.e., the measure of benefits from goods or services to an economic agent (person, company or organization involved in an economic transaction) and the trade-offs the agent makes in view of scarce resources.[1] Given that each area of application of Digital Earth has both economic and social value and, by definition, this value varies according to different economic agents (the key question: value for whom?), how can we approach the economic value of Digital Earth?

Previous studies have dealt with the economics of issues linked to sustainable development. For example, Pezzey and Tonan (2017) addressed the economics of sustainability, Anand and Sen (2000) addressed human development and economic sustainability, the review by Stern analyzed the economics of climate change (Stern 2007), and Shreve and Kelman (2014) among others, reviewed the cost-benefit analyses of disaster risk reduction. As far as the value of Digital Earth is concerned, a review of the literature is not much help. A query on "the economic value of digital earth" on Google Scholar returns no entries, and a search on the web returns only the table of contents of this manual. A more fruitful approach may be to deconstruct Digital Earth into its constituent components. As indicated in Chap. 1, Digital Earth can be viewed from multiple perspectives; some emphasize the conceptual/representation aspects of Digital Earth (Gore 1999; Goodchild et al. 2012) and the data/information component (Goodchild 2013), others emphasize the information system component (Guo et al. 2009; Guo 2012; Grossner et al. 2008), and others emphasize the multidisciplinary body of knowledge and theoretical component (Goodchild et al. 2012; Guo et al. 2009). Each of these perspectives could be the subject of an economic analysis, but the one that has received greatest attention of late is data, described as the "new oil or the most valuable resource" of the digital economy (Economist 2017).

The rise of big data has recently been outpacing the growth in computer processing power and is set to speed up even further with the advent of the Internet of Things and billions of devices connected to the internet via 5G networks. For example, between 2002 and 2009, data traffic grew 56-fold, compared with a corresponding 16-fold increase in computing power (largely tracking Moore's law), as shown in Fig. 19.1 (Short et al. 2011; Kambatla et al. 2014).

The evolution of Digital Earth as a result of big (Earth) data, the Internet of Things, social media and new participatory approaches in which people contribute to sensing the environment were partially foreseen by Goodchild et al. (2012) and Craglia et al. (2012). What we did not expect was that the convergence of data and computing availability would lead to a major change in the development and use of artificial intelligence (largely since 2012) (Craglia et al. 2018) and that Earth observation would become such a big business for private sector companies and investors. Data seem to be the more significant change factor of the last decade, and therefore, this chapter focuses on reviewing the recently adopted approaches to assess the value of EO data, building on a study carried out at the Joint Research Centre by Pogorzelska (2018), as a lens through which to see the value of Digital Earth.

[1] https://www.investopedia.com/terms/e/economic-value.asp.

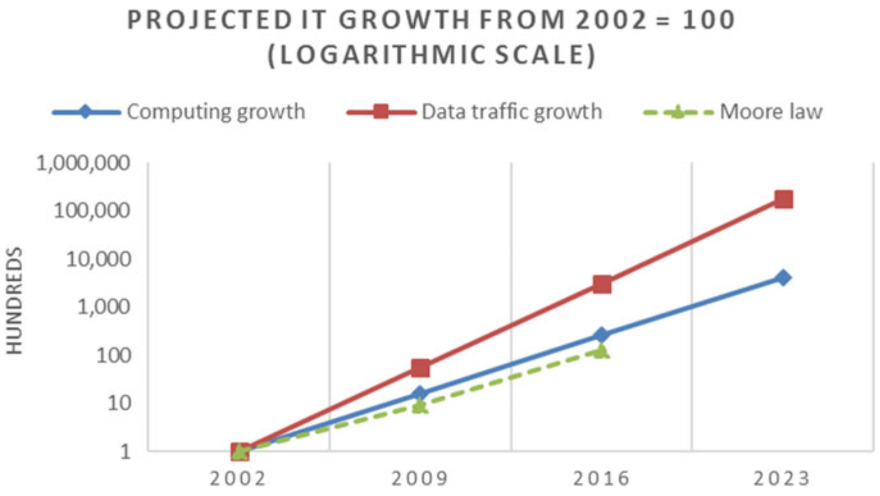

Fig. 19.1 Projection of data and computing growths (**logarithmic scale**). *Source* JRC based on Kambatla et al. (2014)

This chapter is organized as follows. After the Introduction, Sect. 19.2 outlines different viewpoints on the value of EO, Sect. 19.3 reviews approaches and methodologies to assess the value of EO, and Sect. 19.4 draws conclusions that are relevant to Digital Earth.

19.2 Different Viewpoints on the Value of Earth Observation

19.2.1 Definition of EO

In this chapter, we adopt the definition of Earth observation as developed by the Group on Earth Observations (GEO). EO is understood as "the gathering of information about planet Earth's physical, chemical and biological systems"[2] through a range of technological means such as satellites, aircrafts and drones, in situ measurements or ground-based monitoring stations. Remote sensing (RS) is a technique used in EO to observe objects from a distance without being in direct contact with them.

Various studies deal with EO as part of broader "geospatial data" or "spatial data". The adjectives "geospatial" and "spatial" are usually used interchangeably. The term "spatial data" is legally recognized in Europe as defined in the INSPIRE directive (European Commission 2007) and means "any data with a direct or indirect reference to a specific location or geographical area" (ibid, Art 3). Spatial data,

[2]GEO: https://www.earthobservations.org/g_faq.html. Accessed 7 Apr 2019.

apart from EO, encompasses data from other technology segments such as the global navigation satellite system (GNSS) and positioning, geographic information systems (GIS)/spatial analytics, and 3D scanning.[3] Since all of the above are relevant for Digital Earth, we use the GEO definition and therefore use EO as a broad label that also covers (geo)spatial data.

19.2.2 Value for Whom?

The value of data and information varies according to who values it and for what purpose, and often also carries a time dimension, i.e., some data may very valuable now (e.g., stock market prices or agricultural yield data) but almost worthless in a few hours (Blakemore and Craglia 2006).

The socioeconomic value of EO data is often greater when combined with other data. The value for a user of a digital map is greater when one can also navigate to a chosen destination as a result of combining EO data with location data. The value can be greater still if EO is combined with the social data of other participants in traffic because predictions of the traffic flow can be made and alternative routes can be proposed (to measure the value of a digital map, see, for example, Alpha Beta 2017). The value of EO data is easier to appreciate from the perspective of an individual in the mass market because of the daily use of EO–based solutions; assessment of the value of EO from the perspectives of the public and private sectors is more complex.

19.2.2.1 Public Sector Perspective

Governments have traditionally been the main users of various forms of geographic information, such as maps, for taxation, way-finding, navigation, and defense. With the expansion of commercial aviation and the launch of civilian space programs in the twentieth century, the public sector, often in partnership with the private sector or through private sector contractors, continued to remain the main producer and user of EO, largely for scientific purposes, weather monitoring and forecasting, and to support policy in the environmental, societal and economic domains. The public sector greatly relies on EO data—often combined with social and economic data—to help inform policies directed towards a range of environmental and socioeconomic objectives. The environmental policy objectives that rely on EO information revolve around the management of natural resources and battling environmental threats such as land, air and water pollution, deforestation, biodiversity loss, and climate change.[4] The EO-supported social policies touch on citizens' wellbeing and include areas such as security and defense, science, education, agriculture, safety and rescue, disaster

[3] Geospatial Media and Communications (2018), p 14.

[4] Science for Environment Policy: Earth Observation's Potential for the EU Environment, Copernicus: http://www.copernicus.eu/sites/default/files/library/FutureBrief6_Feb2013.pdf.

and disease response, health, transport and urban planning. Economic objectives include the development of innovations, knowledge and solutions that can increase competitiveness and create new products, services, and prosperity. In Europe, there has been a noticeable shift in EO policy to add objectives aimed at developing the digital single market and harnessing opportunities for economic growth and jobs in the private sector.

From the standpoint of the public sector, the value of EO mostly lies in informing policy making and decision making. EO can inform the full policy cycle: it helps identify needs and areas for policy intervention, formulate policies, and tailor regulatory responses that can use legal tools that rely on EO to support policy implementation and decision making. EO also supports policy monitoring and policy change.

There are numerous examples of how EO supports policy making. To identify policy intervention areas, satellite imagery allows for realizing the scale and rate of deforestation, for example, in the Amazon rainforest, which eventually led to passage of a regulation that resulted in a significant decrease in the pace of deforestation (see, for example, Finer et al. 2018).

As far as lawmaking is considered, the most visible use of EO is as a regulatory compliance tool (Purdy 2010), especially in enforcement of environmental legislation. There are at least three forms of the use of EO as a regulatory compliance tool: (a) as part of a targeted enforcement strategy to monitor specific laws, (b) in monitoring of individual sites or areas where environmental offenses have occurred, such as marine pollution (Wahl et al. 1996), and (c) as a form of historical evidence. There is a form of targeted regulatory monitoring, for example, in the agriculture sector in the EU, where legislation gives Member States the option of using data from "unmanned aircraft systems, geo-tagged photographs, GNSS-receivers combined with EGNOS and Galileo, data captured by the Copernicus Sentinels satellites and others" to monitor farm subsidy payments under agricultural cross-compliance schemes (European Commission 2018). The introduction of EO to replace or supplement on-field checks is aimed at reducing both the administrative burden on the EU member states and the cost of monitoring farm subsidies for potential fraud. For example, Australia incorporated satellite surveillance of tree clearing in the policy strategies of relevant legislation (Purdy 2010). EO data have also been increasingly used as evidence. Systematic archiving of satellite images provides regulators or a court with a relatively impartial snapshot of any location at any given time, providing accurate evidence that would often be otherwise unavailable. Such satellite imagery has been used as evidence in lawsuits. In the 2012 UK pollution case, satellite images were used as primary evidence to prove the breach of UK maritime pollution legislation by Maersk Tankers Singapore; in another case in the US, imagery was used to show false insurance claims (Rocchio 2006).

Regarding policy implementation, public institutions use EO for their decision making. Large financial institutions such as the World Bank or the Asian Development Bank often tailor their official development assistance (ODA) in accordance with EO-based environmental information.[5] Another example of the use of EO data

[5]ESA: http://eo4sd.esa.int/files/2017/10/1_esa_eo4sd_and_sdgs_oct_2017.pdf.

is the US federal decision making for drought disaster assistance, which heavily depends on drought indicators fed by EO data (Steinemann et al. 2015). Finally, EO supports the statistics necessary to monitor progress towards policy objectives (see UN 2017) and helps evaluate the outcomes and necessary changes to policies (see BRYCE 2017).

The last decade saw a huge increase in the number of EO satellites, including privately funded ones; combined with advancements in ICT, EO satellites changed the way that public institutions can use EO data and information. Due to the satellite-based infrastructure, EO data now provide insights into nearly real time geographical distributions of various phenomena that are commensurable across countries, regions and cities, allowing for timely and targeted responses to various needs or threats. Open and free access to data and analytical tools, advances in algorithms and data processing have started to enable the widespread use of this information. Harmonized and interoperable EO data infrastructures are often combined with other geo-referenced sociodemographic, economic and public administration data to make the indicators and analysis more robust and international reports more harmonized (OECD 2017). This eventually equips public institutions with tools that allow for better cooperation, particularly in face of challenges of a global scale. In this respect, the global cooperation achieved through the Group on Earth Observations (GEO)[6] is also important.

19.2.2.2 Private Sector Perspective

Whereas the EO upstream and end-user segments used to be significantly dominated by the governmental institutions, the private sector has been traditionally more pronounced in the EO downstream segment concerned with the creation of added-value products and services. Because the existing EO market was mostly driven by the demand from the public sector, particularly from the defense and security segments (ca. 60%, see Keith 2016), in 2014 there was still no functioning EO market (Smart 2014). The last few years witnessed the staggering growth of the EO market (European Commission 2017) in both the amount of money flowing to the EO sector economy and the number of new players at all levels of the EO value chain. These are good indicators of the advancement of the EO market towards maturity.

To large extent, the fast maturing of the EO market has been enabled and driven by technology developments in both the upstream and downstream EO segments. The miniaturization of satellites and the reusability of rockets were upstream-related technology developments, and increased analytical capabilities coupled with the enhanced ICT infrastructure reshaped the EO sector from the bottom. The former developments allowed for democratization of the access to space and vertical integration across different sectors; and the latter created a significant thirst for data outside the public sector and demand from the individual mass markets (e.g., digital imagery). These developments heavily impacted the dynamic in the whole EO sector.

[6] http://earthobservations.org.

They facilitated different forms of collaboration between the public and private sectors. Currently, innovative companies and businesses more actively contribute to the socioeconomic policymaking by proposing solutions based on the innovative technological developments (for the issue of building partnership between the sectors, see EARSC 2014).

Technology developments also enabled different business models and contributed to the growth of the individual mass market. The space industry has developed into a multibillion-dollar industry with global revenues increasing from $175 billion in 2005 to almost $385 billion in 2017—a growth rate of approximately 7% per year (US Chamber of Commerce 2019). According to Morgan Stanley (2018), the global space industry could generate a revenue of $1.1 trillion or more in 2040, with almost 50% of projected growth coming from satellite broadband internet access. While the demand for data has been growing at an exponential rate, particularly with the increasing demand for bandwidth from autonomous cars, the Internet of Things, artificial intelligence, virtual reality, and video, the cost of access to space (and, by extension, data) is falling rapidly. With the development of reusable rockets, the cost to launch a satellite has decreased from approximately $200 million to approximately $60 million, with a potential drop to as low as $5 million, according to Morgan Stanley (2018). The mass production of pico satellites such as CubeSat has brought costs down from hundreds of millions to several thousand dollars,[7] so that companies such as Planet can afford to send dozens of satellites in space every launch and operate a constellation of over 150 satellites orbiting the Earth. This is creating entirely new markets as an increasing number of companies offer daily high-resolution images of the Earth to monitor change. It also creates opportunities for companies providing launch and ground-segment facilities. In November 2018, Amazon Web Services announced the deployment of their first ground stations, with an aim of having 12 operational by mid-2019 and expanding their business to pay-as-you-go EO (Barr 2018). This announcement is potentially a big step in the expanding market for EO given the market size and reach of AWS.

The amount of private sector capital in the space sector is staggering, considering that this industry was dominated by large government-backed national space agencies until recently. According to Seraphim Capital, a venture capital fund, the amount of VC in the space sector was $3.25 billion in 2018, up 30% from 2017, with over 180 companies receiving backing, an increase of over 40% compared with the previous year. The launching sector received the highest investment flow of just over $1 billion in 2018 and data collection platforms (satellite constellations and drones) followed closely behind at $868 million.[8] Notably, China is also becoming a big player in the commercial space market since the government opened the country to private investment in 2014. In 2018, China became the world's top launch provider, with 39

[7] https://space.stackexchange.com.

[8] http://seraphimcapital.passle.net/post/102f50i/seraphim-q3-global-space-index-investment-remains-concentrated-in-launch-and-co.

launches versus 34 from the US, and its BeiDou GPS navigation constellation aims to rival the American (GPS) and European (Galileo) satellite navigation systems.[9]

While the development of the space industry is making the headlines, there are many other areas in which private sector companies are investing in geospatial data capture, processing, and value-adding, which are relevant to the further development of Digital Earth. Examples include well-established companies such as Trimble, which traditionally serviced the surveying and construction industry, and has now expanded into mining and precision agriculture; DigitalGlobe, which has moved from being a data supplier to a solution provider for specific sectors such as the automotive industry[10]; and new companies such as NextNav, which specializes in indoor positioning systems with a dedicated infrastructure of indoor antennae for applications including geo-advertising, public safety, and emergency services.

The increasing availability of EO with integrated multiple sensors from both space and the ground together with processing power and storage at diminishing costs, business models based on pay-as-you-go for everything-as-a-service and the development of AI algorithms to process the data and extract meaningful information are opening EO to a much wider audience of companies that are not experts in EO or geo-processing. A good example is Orbital Insight, a start-up established in 2013 that combines detailed imagery provided by companies such as Planet with public sector data and develops AI algorithms to provide solutions for specific sectors such as energy and advanced consumer intelligence.[11]

The above mentioned technology developments can also be linked to the creation of the distinguished ramification of the EO market, namely, the EO data market, which does not quite fit the traditional upstream or downstream EO segments but rather conveniently nests in between, being pulled by the gravity of the big data market. The commercial EO data market was estimated at EUR 1.5 billion in 2015 with the opportunity to grow to EUR 2.6 billion in 2025 (European Commission 2017). While upstream companies naturally expanded into this market segment and benefit from selling VHR EO or data products, the new influx from outside the EO sector is a relatively new phenomenon. The big IT techs such as Google or Facebook introduced new business models to the EO domain. They do not seek profits from selling EO data or EO-based services or products but profit from business intelligence based on combining EO big data with different streams of other data, especially location and social data. In such cases, IT platforms play the role of a content aggregator that can satisfy different customer needs while making profits from targeted advertising based on big data-based business intelligence. The recent developments by Amazon and Google are in this direction.

While the market is changing so rapidly, assessing the value of EO from both economic and social perspectives is not easy. In the next section, we review some

[9] http://seraphimcapital.passle.net/post/102fd5w/seraphim-space-predictions-2019.

[10] https://www.digitalglobe.com/markets/automotive.

[11] See Orbital Insight: https://orbitalinsight.com/products/go-energy/ or https://orbitalinsight.com/products/go-consumer/.

recent studies that estimated such value and then assess the extent to which they can inform the analysis of the economic value of Digital Earth.

19.3 Review of Approaches and Methodologies to Assess the Value of EO

Assessing the value of EO has been the subject of research for several years worldwide (Borzacchiello and Craglia 2011). The interdisciplinary and cross-cutting nature of the use of EO data resulted in a wide range of approaches to identify and measure the value of EO. A review of recent studies on the subject by Pogorzelska (2018) identified three main clusters of approaches. The first focuses on capturing economic value of EO and gathers micro- and macroeconomic methodologies. The second enters the discussion on EO value through the more interdisciplinary conceptual framework of the value of information (VOI). Since EO exhibits characteristics of an all-purpose infrastructure good, many have noted that measuring the value of EO in a comprehensive and exhaustive way is impossible; therefore, some approaches primarily focus on ways to maximize its value. The third cluster gathers methodologies concerned with maximization of the value of EO through enhancement of the data infrastructure and open access to EO data. These clusters are by no means exhaustive or exclusive. They represent different perspectives or entry points to the discussion and are often combined within one study. The methodologies used within one cluster may be used along with others or adapted to serve a specific purpose (e.g., VOI studies adapt micro- and macroeconomic methodologies to reflect value of EO-based information).

19.3.1 Value of Information (VOI) Approach

The studies framed by the value of information generally examine how EO-based information can be tied to decision making, how those decisions can be linked to societal outcomes, and how those societal outcomes produce value.

VOI studies underline that the value of information is tightly linked to its use. Barr and Masser (1997) claim that "information has no inherent value, it is only of value once used and that value is related to the nature of the use rather than the nature of the information [thus] information has very different values for different users." EO-derived information is valuable when it informs decisions aimed at achieving various environmental, social and economic benefits.

Since the value of EO-derived information changes depending on the specific use and the user, VOI studies also deal with different value propositions. Macauley (2005) proposed a framework to provide a common basis to evaluate information depending on the type of user. Macauley (2006) also provided a theoretical foundation for establishing the value of space-derived information and a framework that uses economic principles.

As far as the subsequent quantification of this value is considered, the VOI approach gathers a very diverse set of methodologies. There have been ongoing efforts in the fields of GIS and related systems as well as remote sensing to accelerate the development of methodologies to quantify the benefits arising from EO-based decisions. Meta reviews of the literature in this field have been carried out, for example, by Lance et al. (2006), Genovese et al. (2009), Richter et al. (2010). GEO-related work and research focused on remote sensing have been carried out, for example, by Fritz et al. (2008) and Rydzak et al. (2010).

While there is a widely recognized need for EO value to denote a quantitative measure, many agree that it does not need to be expressed in monetary terms (Borzacchiello and Craglia 2011). The VOI economists usually seek to monetize the difference between decisions made with and without the EO-derived information (Gallo et al. 2018). However, the benefits are often expressed in nonmonetary terms such as in reductions in mortality and morbidity, reduced damage to capital assets, improved community well-being, time saved, fuel saved, reduced carbon emissions and many other social and economic measurements (Kruse et al. 2018). Studies have identified a set of methodologies used to quantify the value of EO-derived information, e.g., McCallum et al. (2010), Borzacchiello and Craglia (2011), Slotin (2018). The range of the methodologies identified includes the following:

- Value-measuring methodology (VMM) was developed to calculate the return on investment (ROI) relating to decisions based on intangible values.[12] It was adapted by the International Institute for Applied System Analysis (IASA) to assess the benefits of the EuroGEOSS;
- Impact-based methodology—this methodology determines value by qualitatively assessing the causal effect of information availability on economic and social outcomes, or the costs in terms of inefficiencies or poor policy decisions due to limited or poor-quality information;
- Systems dynamics modeling—like the methodology above, it measures the impact of EO-derived information. The value of EO is described through system dynamics models, where a change in one variable (e.g., EO-based information affects other variables over time, for example, the FeliX model[13]);
- Bayesian belief network—this conventional statistical approach assumes that people's expectations are updated when new information is available (for use of the methodology, see, for example, Bouma et al. 2009);
- Regulatory cost-effectiveness—this methodology assesses the direct cost savings achieved when a regulatory framework is in place;
- Willingness-to-pay methodology—this methodology concentrates on monetization of benefits through surveys of individuals and private and public institutions

[12] The VMM was initially developed by the Federal Chief Information Officers Council (2002) and applied in a case study by Hamilton (2005).

[13] www.felixmodel.com.

that estimate their willingness to pay or the amount they are willing to accept for not having the data/information; and
- Case-based monetization of benefits—this method focuses on measuring (often monetizing) the benefits resulting from a specific EO-supported decision, solution, product or service. The approach usually relies on qualitative analysis to identify and measure the benefits that arise.

19.3.2 Economic Approaches

This cluster of approaches gathers macro- and microeconomic methodologies to capture the economic value arising in the context of EO. This set of methodologies has clearly become more relevant as the EO market has matured.

Macroeconomic

This group of approaches enters the discussion on the value of EO from the perspective of the economic impact of the EO sector on the economy and links the value of EO to the macroeconomic statistics characterizing the sector. The macroeconomic methodologies include the following:

- GDP impact assessment—this approach focuses on calculating the return on public investment in the EO sector. The following indicators are usually taken into account: investment of the upstream sector, spending by suppliers, wages/salaries of employees, employment impact, government tax revenues (income direct tax, VAT, employer social security contributions, employee social security contributions; see, for example, Strategy 2015);
- Economic impact assessment—focuses on the use of specific economic tools to assess impact, such as input-output tables and computable general equilibrium models (CGEM); and
- EO value chain approaches—these approaches focus on assessment of the value of EO across a whole value chain. A specific value chain is identified and qualitatively analyzed. The methodology usually relies on quantification of the value of EO as the increase in revenues and reductions in costs related to the EO-supported activities, compared with a situation where no EO-derived solutions are available (see, for example, PwC 2016).

Microeconomic

Microeconomic approaches focus on EO market characteristics and market approaches to value EO data and customer behavior. This cluster includes the following:

- Characterization of the EO market—this approach focuses on EO expressed through the statistics characterizing the EO market, the EO data market and specific markets for EO-based solutions, products and services;

- Stated/revealed preferences—these methods assess the value of EO-derived data/information though the amount that users are willing to pay or the amount they are willing to accept for not having the data/information;
- Market equivalent pricing—this is the market price that should have been received if the statistical or EO data outputs were sold in a market environment. This approach approximates market prices by looking at the market prices of similar data products, such as those from companies that offer data for prices, or business trends drawn from a range of sources including open government data;
- Cost-based derivation—this method determines value based on the full cost of producing the data, statistics or information; and
- Discounted cash flows (DCF) methodology—this method ascribes a value/price to a specific dataset (intrinsic value) based on a projection of its future cash flows that is discounted to today's value.

19.3.3 Approaches Concerned with Maximization of EO Value

This group of approaches recognizes that, although measuring EO value is difficult and relative, if not impossible, the improvements in the EO data infrastructure and open access to data are key prerequisites for maximizing the value of EO. This cluster often uses impact-based methodology to demonstrate how data infrastructure investments and removal of specific barriers to access data affect or may affect people's lives or the economy. With respect to this approach, Slotin (2018) argues that "[b]y linking to real-life outcomes, impact-based case studies show how investments in data systems can translate into meaningful outcomes for people." Many case studies show these impacts, including deliberate experiments such as randomized control trials and retrospective assessments of impact[14] (Slotin 2018).

19.3.3.1 Spatial data infrastructure

Spatial data infrastructures (SDIs) have been (largely) public sector-led investments by governments across the world to increase the availability and accessibility of geospatial data for public policy, an informed society, and market development. The development of SDIs has been documented by many studies, including by Masser (1999, 2005), Williamson et al. (2003), Crompvoets et al. (2008). For many years, the global community of researchers and practitioners of SDIs gathered through the Global SDI association,[15] which was formed in 2004 and dissolved in 2018. Now, global discussions on SDIs are held in many groups, including the International

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[14]See, for example, www.dataimpacts.org.

[15]www.gsdiassociation.org.

Society for Digital Earth,[16] the UN Committee on Global Geospatial Information Management[17] and the Group on Earth Observations, to coordinate efforts to develop a global Earth observation system of systems (GEOSS).[18]

In Europe, the adoption of the INSPIRE directive in 2007 (European Commission 2007) provided a major impetus towards the assessment of spatial data infrastructures and their socioeconomic impacts. A study on the expected economic impact of INSPIRE was carried out in 2003–2004 prior to adoption of the law (Inspire and Craglia 2003; Dufourmont et al. 2004). Progress in over 30 European countries on the implementation of SDIs was reported in a set of studies by Vandenbroucke and Janssen (2008). Crompvoets et al. (2008) collected a range of theoretical perspectives informing the work on SDIs and focused on the improvement of SDIs. Vandenbroucke et al. (2009) proposed the application of a network perspective to SDIs. The increased availability and quality of data and data sources are believed to help inform the actions taken by decision makers and the resulting socioeconomic benefits (Kruse et al. 2018).

19.3.3.2 Open access to data

Maximization of the value of EO through open access to data is similar to the previous approach. It primarily differs in the entry point to the discussion. Instead of focusing on the infrastructure, this approach focuses on the benefits of open access to EO data as a part of bigger data ecosystem. It considers access to data a key factor in determining EO-enabled creation of added value and promotes the openness of data.

Approaches that address the value of EO from the perspective of open data often focus on "unlocking the value of open data" via removal of specific barriers to data, not on measuring the actual value of EO. A study by McKinsey (2013) found that open data can help unlock 3.2 trillion to 5.4 trillion USD in economic value per year across seven chosen domains: education, transportation, consumer products, electricity, oil and gas, healthcare, and consumer finance.

From the economic perspective, the term "open data" falls back on the economic notion of a "public good". As a good, EO data are not homogenous. A public good is a type of good that, once produced for some consumers, can be consumed by additional consumers at no additional cost.[19] The definition includes the two main characteristics of a public good, nonrivalry and nonexcludability. "Nonrivalry" means that the consumption or use of the good does not diminish or remove the availability of the good to others. "Nonexcludability" means that everyone has access to a good since no exclusion mechanisms are in place. In contrast to public goods, private goods are often rivalrous, i.e., the consumption or use of the good diminishes or removes

[16] http://www.digitalearth-isde.org.

[17] http://ggim.un.org.

[18] https://www.earthobservations.org.

[19] For public good theory, see Holcombe (1997). For the theory of public expenditure, see Samuelson (1954).

the availability of the good to others, and excludable, i.e., prices, licenses and other exclusion mechanisms effectively control the number of beneficiaries, and property rights are applied to establish legitimate ownership. If nonpaying users cannot be excluded from benefits, then the market for the good fails as a result of free-riding (Harris and Miller 2011; Pearce 1995).

In general, EO data are largely nonrivalrous although some technical measures may be put in place to limit the number of users and applications. Although nonrivalrous, EO data tend to vary on the scale of excludability, which resulted in the heterogeneous landscape of the economic nature of EO data (for a proposition of mapping economic goods on the two axes of rivalry and excludability, see Harris and Miller 2011). This variation in excludability is reflected in the international legal provisions relating to access to RS EO data. The Remote Sensing Principles,[20] while promoting widespread access to satellite remote sensing data, contain a provision on the possibility of "provision of data on reasonable cost terms".[21]

The resulting regional and national regulatory frameworks allow for varying access to EO data. For example, the 2016 US Common Framework for Earth Observation Data states that "[a] core principle of the U.S. Government is that Federal Earth-observation data are public goods paid for by the American people and that free, full and open access to these data significantly enhances their value".[22] In the EU, the Copernicus Regulation provides that Copernicus data shall be made available on a full, open and free-of-charge basis. This general provision suggests that Copernicus data are a public good. Nevertheless, *lex specialis* provides for a series of possible access limitations that include (a) licensing conditions for third-party data and information; (b) formats, characteristics and dissemination means; (c) security interests and external relations of the Union or its Member States; (d) risk of disruption, for safety or technical reasons, of the system producing Copernicus data and Copernicus information; and (e) ensuring reliable access to Copernicus data and Copernicus information for European users.[23]

Similarly, other EU key regulations on data such as the Public Sector Information (PSI) directive (European Commission 2013) or INSPIRE directive (European Commission 2007) do not guarantee free access to governmental data. They all promote the idea of open data and encourage public institutions to open the vaults of their data, resulting in large amounts of data, including EO information, that exhibits characteristics of a public good (Uhlir and Schroeder 2007; Smith and Doldirina 2016). The opening of the vaults of PSI is often considered a boost for democratic accountability and for business to create value-added products, foster innovation and

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[20]RS Principles, Principle XII.

[21]Since the term "reasonable cost" is not defined, Harris and Baumann (2015) suggest that compared with many other EO data policies, the term should be interpreted as the marginal cost or the cost of fulfilling a user request.

[22]US National Science and Technology Council: Committee on Environment, Natural Resources, and Sustainability (2016) Common Framework for Earth Observation Data. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/common_framework_for_earth_observation_data.pdf.

[23]Copernicus Regulation, Article 23(2).

Table 19.1 Summary of studies, approaches and methodologies

Study	Approach	Main methodology
PwC 2016	Economic approach/GDP impact assessment (upstream and downstream space sector)	Revenue and reduction in costs attributable to the use of Copernicus-based solutions across 8 specific industries (value chains)
Geospatial Media and Communication (2018)	Economic approach/combination of micro- and macroeconomic approaches	– Characteristics of the global geospatial/EO market (size and trends) based on surveys and secondary sources; – Value impact of the EO solutions on the global economy; – The country readiness index for the absorption of the geospatial/EO solutions
Alpha Beta (2017)	VOI	Quantification of indicators relevant for estimation of the environmental, social and economic benefits arising from the use of digital maps for individual users and the private sector
OECD (2016a)	VOI	Quantification of indicators relevant for capturing knowledge and innovation spillover effects relating to EO
Miller et al. (2013)	VOI	The willingness-to-pay methodology—monetization of the benefits for the users of Landsat imagery. Survey-based
OECD (2016b)	Maximization of EO value/data access	Qualitative and conceptual analysis of the possible forms of data access
OECD (2014)	Economic approach	Indicator-based statistics on the digital economy (focusing on closing gaps in the measurement of the digital economy)
Cattaneo et al. (2016)—EDM Report	Economic approach: value of EO/the EU data market	Characterizes the European Data Market (EDM) through identification and measurement of a set of indicators within the private sector
EARSC and The Green Land case studies (2016a, b, and c)	VOI	Case-based monetization of benefits. Monetization of indicators relevant for estimation of the benefits/impacts arising from the use of a specific EO-based solution

create jobs (Fornefeld et al. 2009; Uhlir 2009). In addition, by alluding to the notion of public good and accountability, advocates of open data emphasize the need and legitimacy of science in the policy sphere (Arzberger et al. 2004).

Since increasingly large amounts of EO data exhibit characteristics of a public good (Smith and Doldirina 2016), the EO market has primarily developed around the value added to EO data in form of processed EO data or/and information as well as EO-derived services and products that also integrate other data (for adding value with the use of open data, see, for example Berends et al. 2017). To add value to EO data, the high uptake of EO data is critically important. Delponte et al. (2016) identified a set of barriers to space market uptake originating in the areas of policy, governance, technology, skills, and the market itself. To overcome these barriers, various public initiatives have been put in place. For example, the European Commission, in cooperation with the ESA, is providing financial support to develop the Copernicus Data and Information Access Services (DIAS).[24] The DIAS are expected to be an access point to Copernicus data and to provide processing resources, tools and other relevant data to boost user uptake and stimulate innovation and the creation of new business models based on EO data.

The Table 19.1 summarizes the studies reviewed and the approaches summarized above.

19.4 Conclusions

In this chapter, we approached the economic value of Digital Earth with a broad definition of economic value, i.e., the measure of benefits from goods or services to an economic agent and the trade-offs the agent makes in view of scarce resources. This definition implies that the benefits that can accrue to the economic agent (person, firm, or organization) can be more than economic in nature and can encompass environmental or social benefits.

The complexity of determining the value of Digital Earth is multilayered. A first level of complexity stems from the multiple definitions of Digital Earth introduced in Chap. 1: as a concept, an information system, a data organization principle, a multidisciplinary endeavor, and a science. With such multiple and heterogeneous perspectives, there is no single value of Digital Earth to measure and there is a whole range of values depending on the point of view. A second level of complexity is exposed when deconstructing Digital Earth into its key components: data, models, technology, and infrastructure. In this chapter, we focused on EO data because it is undergoing the most dramatic change at the beginning of this century. However, the value of EO critically depends on the value for whom, for what purpose, and when.

As indicated in Sect. 19.2.2.2, the commercial EO data market is reaching a level of maturity fueled by the availability of big EO data, cloud-based processing facilities, increased connectivity, and new business models based on everything-as-a-service.

[24] http://copernicus.eu/news/upcoming-copernicus-data-and-information-access-services-dias.

This maturity is indicated by the level of private investments in the EO market for all segments, including the launching of satellites, data processing, integration, and value adding. However, there are no published studies with repeatable methodologies on the economic return of these large investments.

With this in mind, we reviewed the available recent studies to assess the value of EO/geospatial/open data and related infrastructures and illustrated that the variety of purpose and applications requires multiple approaches. We identified three main sets of approaches that focus on the value of information, the economic approach to the value of EO to the economy from both macro- and microeconomic perspectives, and a third set aiming at maximizing value through infrastructure and policy. Each of these sets of approaches has something to offer to the understanding and valuation of Digital Earth. The conclusion that there is no single answer to the question posed at the beginning of the chapter is not a bad thing: it acknowledges that Digital Earth is a global concept in which everyone can recognize their viewpoint and collaborate with others to increase the common good. Ultimately, the true value of Digital Earth may rest in its values as a metaphor to increase global understanding and communication across disciplines and between science, policy, and civil society.

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Max Craglia is a lead scientist at the European Commission's Joint Research Centre. His main research interests relate to new forms of governance in digitally transformed societies, and to the social and economic impacts of geospatial information and artificial intelligence in Europe.

Katarzyna Pogorzelska is a Researcher in the European Commission's Joint Research Centre in Seville. She researches the question of the value of Earth Observation within the context of EU policymaking. She is an international lawyer with specialization in space law and sustainable development.

Part III
Digital Earth Regional & National Development

Chapter 20
Digital Earth in Europe

Mattia Marconcini, Thomas Esch, Felix Bachofer and Annekatrin Metz-Marconcini

Abstract In recent years, with the advancements in technology and research as well as changes in society, Digital Earth transformed. It evolved from its original concept of a 3D multilayer representation of our planet into a more practical system design to fulfil the demand for information sharing, which now embraces fields such as global climate change, food security and natural disaster prevention. In this novel scenario, Europe has become one of the major players at the global level; accordingly, the goal of this chapter is to provide a general overview of the major European contributions to the overall objectives of Digital Earth. These include the establishment of a European spatial data infrastructure through the Infrastructure for Spatial Information in Europe (INSPIRE) directive, the initiation of the Galileo and Copernicus programs that provide a wealth of big data from space, the launch of novel cloud-based platforms for data processing and integration and the emergence of citizen science. An outlook on major upcoming initiatives is also provided.

Keywords Information infrastructure · INSPIRE · Big data · Copernicus · Data access and information services - DIAS · Thematic exploitation platforms - TEPs · Citizen science · Digital europe · Horizon europe

20.1 Introduction

The original idea of Digital Earth (DE) first introduced by US Vice President Al Gore in 1998 envisioned a 3D multiresolution representation of our planet embedded with a variety of geo-referenced data to be transformed into understandable information (Gore 1999). Two decades ago, the major challenges in achieving such a vision were related to developing effective solutions for properly displaying, organizing and harmonizing data in space and time, as well as efficiently linking them to each other. Progress was necessary in the frameworks of Earth observation (EO), computational science, mass storage capacity and network speed, along with the definition of adequate metadata standards. At that time, the DE goal seemed difficult to achieve, if

M. Marconcini (✉) · T. Esch · F. Bachofer · A. Metz-Marconcini
German Aerospace Center (DLR), Wessling, Germany
e-mail: mattia.marconcini@dlr.de

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not impossible, but remarkable developments in data collection, hardware and software have led to several online web-mapping services (e.g., Google Maps, Microsoft Bing Maps) and desktop virtual globes (e.g., Google Earth, NASA's World Wind) that implement many of the features described by Gore in his speech just 10 years later, making DE real and accessible to millions of users (Annoni et al. 2011; Craglia et al. 2012). In this framework, the leading part was played by the United States, with key contributions from both the public and private sectors. However, with the advent of big data from space, the emergence of volunteered geographic information—VGI (e.g., citizen science, crowd-sourcing), the advancements in technology and research, as well as changes in society, the concept of DE also transformed (Goodchild et al. 2012). DE evolved into a more practical system design to fulfil the demand for information sharing and overcome the socioeconomic inequality in accessing and using the data (i.e., the digital divide) (Guo et al. 2016). Moreover, DE expanded its role in other fields related to global climate change, urban planning and management, agriculture and food security, and natural disaster prevention and response. This new vision will only become reality with effective integration of technologies from EO, global positioning and geo-information systems, sensor webs, virtual reality, and grid computing, as well as with proper gathering, harmonizing and sharing of data (also directly collected by nonexperts) through suitable information infrastructures. In this new paradigm, the role of Europe has gradually become more prominent, placing it at the forefront of DE implementation.

Notably, both research and commercial activities falling within the DE concept have been undertaken in the past 20 years at the single-country level in Europe; nevertheless, it is beyond the scope of this chapter to describe all these specific initiatives. Rather, our purpose is to provide a general overview of the major contributions to the overall objectives of DE from Europe as a whole. In this context, the first political initiatives embedding the DE concept date back to 2010 as part of the Europe 2020 strategy proposed by the European Commission (EC) (EC 2010), i.e., the executive branch of the European Union (EU), which, to date, is composed of 28 Member States. Europe 2020 aims to advance the economy in the EU, with a major focus on research and innovation. Among its 7 flagship initiatives, one has been specifically dedicated to the "Digital Agenda" (Annoni et al. 2011). In particular, this aims to improve the exploitation of information and communication technologies (ICTs) to foster innovation and develop a digital single market for generating smart, sustainable and inclusive growth in Europe.

In parallel, key European developments have provided major contributions to DE in the framework of information infrastructure, big data from space, geo-positioning and citizen science.

Effective data sharing is at the heart of DE and requires suitable and efficient dedicated information infrastructure, i.e., a framework of policies, standards and technologies that allow for finding, accessing, sharing and publishing information. The EC launched the spatial data infrastructure (SDI) initiative in 2001, which marked the beginning of SDI development in Europe. A few years later, this was followed by the "Infrastructure for Spatial Information in Europe" (INSPIRE) directive in 2007, a legal framework that requires EU Member States to share and properly document harmonized spatial and environmental data as well as establish a dedicated technical infrastructure. In particular, INSPIRE has become a model in the world; indeed, with respect to other SDIs solely supporting information discovery and access, it also addresses data harmonization, which allows them to be used seamlessly across national borders (EC 2018a).

Big data from space bring new opportunities in Earth Science and, in turn, to DE. These refer to the massive spatiotemporal Earth and space observation data collected by a variety of sensors ranging from ground-based to space-borne (EO satellites, navigation systems) and the synergetic use of data from other sources and communities (ESA 2019a). The first major European activity was the Envisat satellite mission started in 2002 and operated until 2012 by the European Space Agency (ESA) (ESA 2001). Envisat was the biggest and most complex satellite ever built and carried 9 EO instruments onboard, including imaging, atmospheric and temperature sensors (ESA 2019b). The mission (with an overall cost of ~2.3 billion euros) was the basis for the establishment of GMES, the Global Monitoring for Environment and Security initiative headed by the EC in partnership with ESA and the European Environment Agency (EEA). In particular, it first aimed to develop operational information services on a global scale using both space- and ground-based monitoring systems to support environment and security policy needs. GMES, officially endorsed in 2001, evolved over the next decade and, after the EU became directly involved in its financing and development, transformed into Copernicus in 2012. Specifically, Copernicus is the current EU's EO and monitoring program, which builds on existing national and European capacities; it includes both space and ground-based components and provides users with advanced data services (Copernicus 2019).

Concurrently, Europe has also been massively investing in the development and implementation of Galileo, its own civilian global navigation satellite system (GNSS). Galileo, whose conceptualization goes back to 1994, received major economic support from 2002 onwards. Two test satellites were successfully launched in 2005 and 2008, and the first satellite of the final constellation went into orbit in 2016. As of July 2018, 26 of the 30 planned active satellites have been launched and the system is expected to be completed by 2021. With respect to other existing GNSS, Galileo will provide higher precision positioning as well as a series of unique features aimed at improving people's security and safety in many fields.

Citizen science describes the nonprofessional involvement of citizens in a scientific process (Irwin (1995) and Bonney (1996)). Citizens can participate as observers or funders, by analyzing data or by providing data; moreover, they freely choose their degree of involvement based on personal interests, time or resources. After publishing a dedicated report in 2013 (Science Communication Unit; University of the West of England 2013), the EC officially began promoting and supporting citizen science due to its potential benefits for European researchers and society at large (EC 2017a). Since then, many projects have been funded that complement hundreds of dedicated citizen science activities in the different Member States.

In the following, major European contributions to DE are presented in detail. Section 20.2 is dedicated to an analysis of the information infrastructure in Europe, and Sect. 20.3 presents the many developments in the context of big data from space (including Copernicus and Galileo) and its exploitation. Section 20.4 provides an overview of the most relevant European citizen science projects; Sect. 20.5 introduces the two upcoming major programs supporting future digital innovation, Digital Europe and Horizon Europe. Finally, a brief conclusion is given in Sect. 20.6.

20.2 Information Infrastructure

A major element of the Europe 2020 Strategy—which set the objectives for smart, sustainable and inclusive growth of the EU by 2020—is the Digital Agenda. One of the seven pillars sustaining it is dedicated to the enhancement of interoperability and standards related to devices, applications, data repositories, services and networks (EC 2010). Therefore, efficient exploitation of spatial data infrastructures (SDIs) in combination with open data initiatives and portals have become a key component of Europe's efforts to assure more informed decision making as a basis for successful policy implementation.

The initial concepts related to the systematic realization—and later harmonization and linking—of SDIs emerged approximately two decades ago at the national level when governments began to initiate dedicated frameworks for enhanced utilization and sharing of data and information for applications in the public sector. These national spatial data infrastructures (NSDIs) primarily included technologies, standards, organizational and institutional structures, and Directives. The targeted applications were mostly aimed at sectors such as good governance, smart growth, or sustainable development (Nebert 2004). The NSDIs usually provide an institutionally sanctioned, automated means for remote search, access, use, and sharing of geospatial information by various providers and users (Pashova and Bandrova 2017). However, although the NDSIs in Europe often use similar technologies and standards, each country has many distinctive characteristics that result from specific national traditions, cultures and socioeconomic models.

To foster harmonization of the various national SDI developments at the European level, the EC started the first transnational SDI initiative in 2001 (EC 1995), which was succeeded in 2007 by the "Infrastructure for Spatial Information in Europe" (INSPIRE) directive (EC 2007, 2008). INSPIRE represents a legal framework implemented in a phased manner that defines a set of organizational rules and agreements for the establishment of an infrastructure for spatial information in the EU by the end of 2021. At the political level, the Directorate General Environment (DG Environment) is in charge of the overall coordination efforts, the Joint Research Centre (JRC) is responsible for the technical review, and EEA and Eurostat (the European Statistical Office) facilitate application and use case support.

According to the INSPIRE regulations, each Member State has to apply a minimum standard for open access to interoperable harmonized spatial and environmental data, along with related infrastructures, metadata and network services, which shall be completed with detailed documentation and reporting, as well as the establishment of a dedicated national coordination institution (EC 2018a). It is important to note that INSPIRE represents a transversal innovation that capitalizes on the manifold national and subnational SDIs that were already established and operated in the Member States across Europe. Hence, instead of creating any new centralized entity and data, INSPIRE focuses on making geoinformation seamlessly and easily searchable, accessible and interoperable across national borders through the harmonization and unification of standards, metadata and tools (EC 2015). A comprehensive overview of the INSPIRE initiative and contents is provided on the corresponding geoportal (http://inspire.ec.europa.eu/).

From the thematic point of view, INSPIRE covers 34 themes organized in three different annexes. These cover data and information related to the cadaster, land use and land cover, geology and soils, hydrology, agriculture, meteorology, transport and infrastructure, population, and environmental risks. In this context, one challenging factor is the requirement that all the data defined in the 34 themes of the three annexes can be utilized coherently and independently from the intended application. The key functionalities to fulfill this requirement and share the INSPIRE data and metadata are realized in the form of web-based services (Network Services) employing a service-oriented architecture (SOA) approach based on well-established standards such the Open Geospatial Consortium (OGC) (Döllner et al. 2019). Among others, the services include the catalogue service for web (CSW), web map service (WMS), web map tile service (WMTS), web feature service (WFS), web coverage service (WCS) and sensor observation service (SOS).

To control and evaluate the progress and extent of the INSPIRE implementation in the individual Member States, the directive provides two indicator-based mechanisms (Pashova and Bandrova 2017). Every three years, written reports must be submitted that address aspects such as coordination and organization structures, infrastructure management, monitoring of infrastructure and data use, data-sharing models and agreements, allocated budgets and arising costs, and gains and benefits at national and subnational levels. In addition, a dedicated set of performance indicators must be collected by the Member States on a yearly basis, describing the newly developed geo-information layers with all relevant metadata and related services. This reporting is administered by the INSPIRE committee, which is composed of representatives of all Member States, and the respective national contact points. According to the implementation plan, the Member States were obliged to transpose the directive into their national legislation by May 2009. Next, they had to provide their relevant national data collections "as-is" with the corresponding metadata through network services by December 2013, and all data listed in Annex I had to be accessible and interoperable by the end of 2017 (Döllner et al. 2019). Finally, the data covered by annexes II and III must be in place by end of 2021. In parallel to the Member State activities, stakeholder communities have been involved from the start of INSPIRE to actively help shape its implementation and critically review all technical developments.

The mid-term evaluation report published by the EEA in 2014 (EEA 2014) assessed an adequate progress of the implementation efforts and recommended some optimizations and improvements to close pending implementation gaps (often due to ineffective coordination at multiple levels) and foster exploitation of the profits through intensified integration of the private sector. Several alternative approaches were also applied to assess the progress in the development of SDI/NSDIs based on various political, institutional, organizational, conceptual, technical, and legal criteria (Pashova and Bandrova 2017). As a result, one of the outcomes was that Austria, Germany, Finland, France, Italy, the Netherlands, Poland, Portugal, and the UK are among the leading countries in SDI implementation.

Concerning the current challenges related to INSPIRE, the EU countries encountered many obstacles and shortcomings since the directive was put into effect almost 20 years ago. First, INSPIRE had to be initiated and established under complex conditions. Hundreds of national experts had to develop the technical specifications and standards for each specific thematic sector (including common and legally binding implementation rules), which had to be translated into more than 24 languages. Moreover, the various Member States showed a rather heterogeneous level of awareness and readiness in complying with the INSPIRE timelines, technical specifications and related recommendations. This effect was further amplified by the possibility given to each Member State to decide the most suitable strategy for implementing the INSPIRE framework based on specific individual needs. Consequently, the success of European-wide SDI realization strongly depends on the initiative, strategy and coherence of NSDI implementation at the national level.

However, the INSPIRE directive generally ensures that national and local governments provide high-quality and ready-to-use data and geoinformation to citizens, science and business across boundaries to support European environmental policies as well as initiatives such as e-Government and the EU interoperability framework. The INSPIRE datasets serve the European Water Framework Directive, the Habitats Directive, and the Clean Air Policy Package (EC 2015). INSPIRE makes quite valuable and direct contributions to the implementation of effective policies across Europe. The individual Member States also benefit from INSPIRE (Pashova and Bandrova 2017) due to the significantly enhanced access to geospatial information and the accelerated harmonization of their federal and municipal data inventories, improving the functionality and efficiency of public administration at all levels. This increased the effectiveness of several services that rely on geospatial data (e.g., disaster prevention and response, environmental impact analysis, risk assessment). In addition, the entry into force of INSPIRE could mitigate the drawbacks due to widespread national practices (and related business models) of selling geospatial data and incomplete and inconsistent policy frameworks.

As a means for offering easier access to spatial data in the EU, the Commission launched the new INSPIRE Geoportal on 18 September 2018 (http://inspire-geoportal.ec.europa.eu/). The redesigned portal is meant to become a "one-stop shop" for public authorities, businesses and citizens for discovering, accessing and using geospatial datasets relevant for specific application areas, particularly European environmental policy (EC 2018b). Moreover, the new Geoportal provides overviews of the availability of INSPIRE datasets by country and thematic area based on the metadata regularly harvested from the national data catalogs of different Member States. The Geoportal also allows for direct access to the so-called "priority datasets" (that were jointly selected by the Commission and the EEA) related to environmental reporting obligations in 6 different domains, "air and noise", "industry", "waste", "nature and biodiversity", "water" and "marine". The priority dataset list is a living inventory of environmental information needs and provides an instrument for i) monitoring progress on INSPIRE implementation; ii) incrementally building comparable INSPIRE maturity across Member States based on common settings; iii) planning tangible and usable INSPIRE deliverables for eReporting; and iv) promoting the reuse of the INSPIRE infrastructure for reporting purposes.

Of particular interest to the INSPIRE community are the novel funding opportunities offered to Member States by the Connecting European Facilities (CEF) instrument (EC 2018c); as an example, the recent 2018 CEF Telecom Public Open Data call (with an overall budget of approximately €18.5 million) key objectives include the generation of cross-border services providing access to harmonized thematic open datasets and the corresponding metadata.

For a comprehensive review of past and recent INSPIRE activities, the reader is referred to Cetl et al. (2019).

20.3 Big Data from Space

Given the key role of big data (including big data from space), in June 2015 the EC established the new "Space data for Societal Challenges and Growth" unit within the Directorate-General "Internal Market, Industry, Entrepreneurship and SMEs" (DG GROW). The unit is dedicated to implementing activities supporting the uptake of big data as a key economic asset to stimulate competitiveness and foster the growth of the European economy and employment (BDVA 2017). During the same period, its private counterpart was also established, namely, the Big Data Value Association (BDVA). The BDVA is an industry-driven international not-for-profit organization (counting 200 members all over Europe from large, small, and medium-sized industries and research and user organizations) that aims to develop the innovation ecosystem that will enable data and artificial-intelligence-driven digital transformation in Europe to deliver maximum economic and societal benefit. The importance of big data from space for the EC is further emphasized by the many dedicated calls for proposals included in the different Framework Programs for Research and Technological Development. Within Horizon 2020 (H2020—the current Framework Program), EO activities are recognized as a key element to accompany the remarkable EU investments in Copernicus (i.e., the European EO and monitoring program) and Galileo (i.e., the EU's civilian global navigation satellite system—GNSS) (BDVA 2017). Since 2014, H2020 has funded two work programs (i.e., 2014–2015 and 2016–2017) and is now running the third for 2018–2020. The "Leadership in Enabling and Industrial Technologies" actions for Space (LEIT-Space) comprise specific calls dedicated to EO that target the evolution of Copernicus as well as the exploitation of existing European space infrastructure for the development of novel products and services based on remote sensing, geo-positioning and other types of satellite-enabled data. Other H2020 focus areas also support the uptake of big data from space and related technologies. These are of particular interest in the Societal Challenge framework in support of the "Climate action, environment, resource efficiency and raw materials" challenge, where one of the key actions is dedicated to strengthening the benefits for Europe of the Global Earth Observation System of Systems (GEOSS) (BDVA 2017). In addition to these calls, other European intergovernmental organizations strongly foster the exploitation of big data from space, among which ESA has a leading position.

In the following, the most relevant initiatives with a prominent role of big data from space in Europe are introduced. An overview of Copernicus is provided, including details on its three main components and the newly established data access and information services (DIAS). Next, the EuroGEOSS initiative is presented, followed by a description of ESA's Thematic Exploitation Platforms (TEPs) and a brief review of Galileo and its major benefits.

20.3.1 Copernicus

The Copernicus program is a cornerstone of the EU's efforts to monitor the Earth and its diverse ecosystems, and ensure that European citizens are prepared and protected in the face of natural or man-made disasters (EC 2016a). Copernicus is Europe's eyes on Earth and a symbol of European strategic cooperation in space research and industrial development. It was established in 2012, building on the previous Global Monitoring for Environment and Security (GMES) program, and is coordinated and managed by the EC in partnership with ESA, the EU Member States and EU Agencies (Copernicus 2019). Copernicus aims to achieve a global, continuous, autonomous, high-quality, wide-range EO capacity by bringing together data collected in space, on the ground, in the sea and in the air to produce timely, reliable and easily accessible information. Moreover, it grants easy, autonomous and independent access to such information to support service providers, public authorities and other international organizations in improving the quality of life for European citizens. The program also drives economic growth, as it acts as a data source for several applications and services; recent estimates of the EC predict that its cumulative economic value will be on the order of 13.5 billion euros in 2008–2020 (EC 2016a). One of the major benefits of Copernicus relies on the policy for its data and products, which are released to all users and the public in general on a full, open and free-of-charge basis (EC 2014) (subject to appropriate conditions and limitations in specific cases), allowing for the development of several downstream services.

Copernicus comprises three different components: *Space*, In Situ and *Core Services*.

- The *Space* component includes the 5 families of dedicated Sentinel satellites as well as existing national and international missions (both commercial and public), known as the Copernicus Contributing Missions. The development of the *Space* component, including the launch and operation of the Sentinels and management of the ground segment, was delegated to ESA. The European Organization for the

Exploitation of Meteorological Satellites (EUMETSAT) coordinates the provision of space data and operational support for the climate change, marine environment and atmosphere monitoring services;

- The Copernicus In Situ component is responsible for gathering environmental measurements collected by data providers external to Copernicus, including ground-based, sea-borne or air-borne monitoring systems, as well as geospatial reference or ancillary data, collectively referred to as "in situ" data. It also identifies data access gaps or bottlenecks, supports the provision of cross-cutting data and manages partnerships with data providers to improve access and use conditions;
- The Copernicus *Core Services* produce value-added products available to the public that are generated based on the space and in situ data from the other two components. Products include six specific services: land monitoring, marine environment monitoring, atmosphere monitoring, emergency management, security, and climate change.

In the following, each component is presented in detail.

20.3.1.1 Space Component

The success of Copernicus is possible due to a well-engineered *Space* component for the provision of EO data to feed into a range of services to monitor the environment and support civil security activities. With more than 30 years of experience implementing missions to monitor Earth from space, ESA is responsible for developing and managing this core component of the program. The *Space* component includes ESA's families of dedicated Sentinel satellites and missions from other space agencies, referred to as contributing missions. A unified ground segment through which the data are streamed and made freely available for the *Copernicus Services* completes the *Space* component. ESA is establishing a mechanism to integrate, harmonize and coordinate access to all the relevant data from the multitude of different satellite missions (ESA 2019c). This is being carried out in close cooperation with national space agencies, EUMETSAT and, where relevant, owners of non-European missions contributing to the Copernicus objectives.

The Sentinels carry a range of technologies such as radar and multispectral imaging instruments for land, ocean and atmospheric monitoring (ESA 2019c).

- Sentinel-1 provides all-weather, day and night radar imagery for land and ocean services. The twin satellites Sentinel-1A and Sentinel-1B were launched on 3rd April 2014 and 25th April 2016, respectively, and the mission currently delivers high-resolution data globally every 6 to 12 days at a rate of 2.5 TB per day. In January 2019, more than 3.5 million products were available for download, with a total volume of more than 5.5 PB of data;
- Sentinel-2 provides high-resolution optical imagery for land services. The twin satellites Sentinel-2A and Sentinel-2B were launched on 22nd June 2015 and 7th March 2017, respectively. After March 2018, the mission has a revisit frequency

of 5 days worldwide. In January 2019, approximately 8 million products were available for download, with a total volume of more than 4.2 PB of data;
- Sentinel-3 provides high-accuracy optical, radar and altimetry data for marine and land services. The twin satellites Sentinel-3A and Sentinel-3B were launched on 16th February 2016 and 25th April 2018, respectively. The mission will reach a revisit time shorter than 2 days globally with an expected rate of 0.3 TB of data per day;
- Sentinel-4 and Sentinel-5 (whose launches are planned for 2021 and 2020, respectively) will provide data for atmospheric composition monitoring from geostationary and polar orbits, respectively;
- Sentinel-5 Precursor was launched on 13th October 2017 and bridges the gap between Envisat (which delivered data from 2002 to 2012) and Sentinel-5; and
- Sentinel-6 (whose launch is planned for 2020) will provide radar altimetry data to measure global sea-surface height, primarily for operational oceanography and climate studies.

The contributing missions include 30 past, existing and planned missions from ESA, the Member States, EUMETSAT and other European and international third-party mission operators that share part of their data with Copernicus (ESA 2019c). They are grouped in 5 different categories:

- Synthetic aperture radar (SAR) sensors, for all weather day/night observations of land, ocean and ice surfaces (e.g., TerraSAR-X, TanDEM-X, RADARSAT-2, ALOS/PALSAR, Kompsat-5);
- Very high resolution (VHR) optical sensors for targeting specific sites, mostly in urban areas and for security applications (e.g., WorldView-1/2/3/4, Kompsat-2/3, DEIMOS-2, SPOT-5/6/7);
- High-resolution and medium-resolution optical sensors for supporting regional/national land monitoring activities (e.g., Landsat-5/7/8, Proba, DEIMOS-1);
- Medium-low-resolution optical sensors for gathering information on land cover as well as for monitoring oceans, coastal dynamics and ecosystems (e.g., Proba-V, Oceansat-2);
- High-accuracy radar altimeter systems for sea level measurements and climate applications (e.g., Envisat RA-2);
- Radiometers to monitor land and ocean temperature (e.g., ODIN); and
- Spectrometer measurements for air quality and atmospheric composition monitoring (e.g., GOSAT).

Notably, the free and open access policy of Copernicus has triggered unprecedented opportunities for both academia and industry. The main challenges are the growing volume of data from the *Space* component and its heterogeneity (in terms of formats, semantics, measurements, resolutions, and modalities) due to the diversity of sensors employed. Accordingly, volume, variety, velocity and veracity apply to this type of datasets, which cannot be handled by traditional databases and processing methodologies; rather, they require advanced preprocessing, data harmonization, analytics, and uncertainty propagation analyses and the deployment of suitable knowledge models (BDVA 2017).

20.3.1.2 In Situ Component

The Copernicus In Situ component comprises a number of environmental local measurements collected from ground-based, sea-borne or air-borne monitoring systems. These are used to calibrate, assess and supplement the information provided by satellites, which is essential to deliver consistent and reliable data over time (EC 2015). The In Situ component includes data collected from sensors mounted onboard airplanes or weather balloons, positioned on riverbanks or high towers, drifting in the ocean on buoys or pulled through the sea by ships. Background topographic information (e.g., digital elevation models, administrative boundaries, transportation network maps) also falls under the In Situ umbrella, along with information collected by citizen scientists or volunteer contributors (e.g., OpenStreetMap) as well as data gathered by unmanned aerial vehicles—UAVs (i.e., drones) (EC 2015).

The In Situ component mostly includes contributions from the Copernicus Member States, since a consistent part of the data and monitoring infrastructure is owned and operated by single national governments. However, it also benefits from international efforts to collect and share information, in many cases from international research infrastructures. To guarantee reliable and sustainable provision of data for its services, Copernicus has to effectively coordinate with a variety of providers, from local conservation groups to global meteorological bodies. The goal of the In Situ component is to comprehensively explore the complex and manifold landscape of local data, identify gaps by comparing requirements against available information, support the provision of cross-cutting data, and establish and manage partnerships with data providers to improve the conditions of access and use (EC 2015). Timely implementation of the INSPIRE directive is expected to improve access to local datasets and considerably facilitate data discovery and access operations. INSPIRE will also improve the timeliness and quality of the Copernicus services.

All Copernicus service operators are granted direct access to data from the In Situ component as an integrated part of their workflows and according to their day-to-day operational needs (provided that they set up and manage the technical interfaces themselves). Since December 2014, under a delegation agreement with the EC, EEA has been appointed coordinator of this component (EC 2015).

20.3.1.3 Core Services

The Copernicus *Core Services* provide standardized multipurpose information common to a broad range of application areas relevant to EU policies in six different domains, namely, ocean (CMEMS 2019), land (CLMS 2019) and atmosphere (CAMS 2019) monitoring, emergency response (CEMS 2019), security (Copernicus Security Service 2019), and climate change (C3S 2019). The effective use of big data (from the *Space* and In Situ components) and advanced data mining techniques are two key elements to their success. The development of the preoperational version of the services was undertaken a few years ago through a series of projects launched by the EC and partly funded through the EU's 7th Framework Program (FP7). These projects were: MyOcean (ocean), Geoland2 (land), MACC and its successor MACC II (atmosphere), SAFER (emergency response) and G-MOSAIC (security). Most of them also contributed to the monitoring of climate change. In each of the target thematic areas, the range of products developed in response to users' needs is growing, along with the number of users. In addition, projects designed to explore the scope for downstream services supporting specialized topics have been launched, widening the range of available products. These will directly support national, regional or local activities as well as niche European and global markets. Below, additional details are provided for each of the existing *Core Services*.

Copernicus Atmosphere Monitoring Service (CAMS): CAMS is implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the EC. It has been fully operational since 2014 and provides businesses, policy makers and scientists with consistent and quality-controlled information on the atmosphere anywhere in the world; it also allows for assessing the past (based on the analysis of historical data records) and generating predictions for the next few days. The service monitors and forecasts parameters related to air pollution and health, solar energy, greenhouse gases and climate forcing. CAMS also compiles emissions inventories to support modeling and estimation of the CO_2 and CH_4 fluxes at the Earth's surface. The main application domains benefiting from use of this service include renewable energies, meteorology, climatology, environmental monitoring and health.

Copernicus Marine Environment Monitoring Service (CMEMS): CMEMS has been operational since 2015 and provides regular and systematic core reference information on the state of the physical oceans and regional seas. It delivers data and products that support major applications in the marine area such as maritime operations (e.g., search and rescue, transport and ship routing, marine safety), marine resources (e.g., fishery, aquaculture), coastal and marine environment (e.g., coastal erosion, sea temperature monitoring, water quality monitoring, pollution control). It also provides key information for weather, climate and seasonal forecasting (e.g., temperature, salinity, currents, wind, sea ice). By jointly exploiting satellite data and in situ observations, the service provides state-of-the-art analyses and forecasts on a daily basis, which offer an unprecedented capability to observe, understand and anticipate marine environment events.

Copernicus Land Monitoring Service (CLMS): CLMS has been operational since 2012 and comprises 4 main components: i) a *global* component providing a series of qualified biogeophysical global products on the status and evolution of the land surface (e.g., albedo, land surface temperature, top-of-canopy reflectance) at mid to low spatial resolution, which are used to monitor the vegetation, water cycle, energy budget and terrestrial cryosphere; ii) a *Pan-European* component aimed at generating land-use/land-cover maps (i.e., CORINE) and high-resolution layers (HRSLs) describing the 5 major land cover types, i.e., artificial surfaces, forest areas, agricultural areas (permanent grasslands), wetlands, and water bodies; iii) a *local* component providing specific and more detailed information that is complementary to the *Pan-European* component and is focused on identified hotspots (i.e., major EU city areas, riparian zones, grassland rich sites) prone to different environmental challenges; and

iv) an *imagery and reference data* component gathering satellite images and in situ data, forming the input for the creation of many information products and services (e.g., the Land Use and Coverage Area frame Survey—LUCAS database).

Copernicus Climate Change Service (C3S): C3S has been operational since 2018 and addresses the environmental and societal challenges related to the climate changes associated with human activities. C3S supports the adaptation and mitigation policies of the EU by providing consistent and authoritative information about the past, present and future climate, as well as tools to enable climate change mitigation and adaptation strategies by policy makers and businesses. The service complements the established range of meteorological and environmental services that each European country has in place and provides access to several climate indicators (e.g., temperature increase, sea level rise, ice sheet melting, ocean warming) and climate indices (e.g., based on records of temperature, precipitation, and drought events). C3S is implemented by ECMWF and relies on climate research carried out within the World Climate Research Program (WCRP) responding to user requirements defined by the Global Climate Observing System (GCOS).

Copernicus Emergency Management Service (EMS): EMS produces timely and reliable geo-spatial information derived from satellite and in situ data supporting the management of geophysical, meteorological and man-made hazards, as well as emergency situations and humanitarian crises. The service comprises 2 different components: i) an *on-demand mapping* component that provides maps for rapid emergency response as well as risk and recovery maps, bolstering the decision-making process in all the phases of the emergency cycle (i.e., preparedness, prevention, disaster risk reduction, emergency response and recovery); and ii) an *early warning* component including the European Forest Fire Information System—EFFIS (aimed at monitoring forest fires and forest fire regimes in the European, Middle Eastern and North African regions) and the European Flood Awareness System—EFAS (aimed at providing flood forecasts to support flood risk management).

Copernicus Security Service: This service tackles Europe's security challenges by providing key information to support crisis prevention, preparedness and response improvement in three application areas: (i) *border surveillance*—to increase the internal security of the European Union using near real-time data over land and sea, as well as fight cross-border crime and reduce the death toll of illegal immigrants at sea; (ii) *maritime surveillance*—to increase maritime security in the framework of navigation, fisheries control, marine pollution, and law enforcement by jointly exploiting Sentinel-1 and other sources of maritime information; and (iii) *support to EU External Action*—to assist third-world countries in crisis situations and prevent global and trans-regional threats with potential destabilizing effects using available geo-information for remote areas experiencing critical security issues.

20.3.2 Data Access and Information Services

To improve access to big data from space and maximize the benefit to different user communities (on an equal basis to all Member States and countries participating in the program), the EC recently funded the development of 5 competitive cloud-based platforms known as data and information access services (DIAS) (CREODIAS 2019; MUNDI 2019; ONDA 2019; SOBLOO 2019; WEKEO 2019). The DIAS allow for centralized access to Copernicus data and products and offer advanced computing resources and tools (open source and/or on a pay-per-use basis) for online processing and analysis (Copernicus 2019). This will create the possibility to easily build new applications and offer added-value services. Each platform also provides access to additional commercial satellite or nonspace datasets, and premium offers in terms of priority or support. By providing a single access point for all Copernicus data and information, the DIAS allow for users to develop and host their own applications in the cloud (ensuring protection of intellectual property rights), without the need to download bulky files from multiple access points and process them locally. This will enable simpler and more user friendly exploitation and data combination, and thus promote innovation. Furthermore, competition between the DIAS will ensure that the best service is delivered to the users and avoid customer lock-in on a specific platform among the 5 (Copernicus 2019). A DIAS functionally consists of 3 types of services:

- **Back office services** that provide access to Copernicus data and information (unlimited, free and complete), as well as to any other data offered by the DIAS provider, in a scalable computing environment where users can build and operate their own services;
- **Interface services** encompassing tools that facilitate users in the development of applications. This environment is developed and managed by the DIAS service providers (according to their specific business models) and offers scalable computing and storage resources to the users at competitive commercial conditions;
- **Front office services** that are provided by third parties (e.g., EU Projects, ESA, EUMETSAT, developers and companies) and are based on exploitation of the Copernicus data and products available through the back office services.

The success of DIAS strongly depends on the strong relationship between the different Copernicus actors as well as on the involvement of Member States and participating countries, information and communication technology (ICT), the EO industry and third parties interested in using Copernicus data and information. The support to and integration of the DIAS into the workflows of ESA and EUMETSAT is expected to further enrich the environment offered by the platforms. Moreover, the integration of DIAS and DIAS-based services into the European Open Science Cloud (EOSC) will make it possible to connect the EO domain to other fields of science at a European level, facilitating the transition from research to commercialization (BDVA 2017).

20.3.3 Thematic Exploitation Platforms

ESA is Europe's gateway to space and its main mission is to shape the development of Europe's space capability and ensure that investments in space continue to deliver benefits to the citizens of Europe and the world. For more than 20 years, EO satellites developed or operated by ESA have provided a wealth of data, which is increasing like never before, especially due to the Sentinel missions. This expanding operational capability of global monitoring from space and data from long-term EO archives, models and in situ networks allow for unprecedented insight into the interconnections of the Earth system between oceans, ice, land and atmosphere. However, while the amount of big data from space represents a key opportunity for academia and industry, it also poses major challenges to achieving comprehensive exploitation of the data. Several initiatives are currently supported by ESA through different programs, among which the development and implementation of the Thematic Exploitation Platforms (TEPs) started in 2014 has a prominent role (ESA 2019d). The TEPs supply a collaborative virtual work environment that provides—through one coherent interface—access to the following:

- relevant big data from space;
- computing resources and hosted processing;
- a platform environment that allows for users to integrate, test, run, and manage applications without the need to build and maintain their own infrastructure;
- standard platform services and functions including collaborative tools, data mining and visualization applications, development tools (e.g., Python, IDL), communication tools (e.g., social networks), as well as documentation, accounting and reporting tools; and
- repositories of advanced processing applications (including those developed by other users).

Moreover, the user community is present (and visible), directly involved in the governance of the platforms and enabled to share and collaborate (ESA 2019d).

Seven different TEPs have been developed, each addressing a specific area of environmental research, namely, geohazards (GEP 2019), forestry (F-TEP 2019), hydrology (H-TEP 2019), food security (Food Security TEP 2019), as well as costal (C-TEP 2019), polar (Polar TEP 2019) and urban areas (U-TEP 2019). In the following, additional details are provided for each TEP.

Geohazards TEP (GEP): The GEP aims to support the exploitation of satellite EO information for geohazards and is based on the Supersites Exploitation Platform (SSEP), originally initiated in the context of the Geohazard Supersites & Natural Laboratories (GSNL) initiative (SSEP 2016). The core user communities for the GEP are the groups of practitioners working on the Seismic Hazards Pilot (CEOS 2019a) and the Volcano Pilot (CEOS 2019b) of the Committee on Earth Observation Satellites (CEOS). The former is a three-year demonstration project intended to showcase the benefits of EO satellite data in the context of seismic hazard research, whose major goals are to (i) support the generation of globally self-consistent strain rate estimates and mapping of active faults at the global scale; (ii) support and continuation of the GSNL for seismic hazards and volcanoes; and (iii) develop and demonstrate advanced science products for rapid earthquake response. The main objectives of the Volcano Pilot through the GEP are to (i) demonstrate the feasibility of integrated, systematic and sustained monitoring of Holocene (i.e., the current geological epoch) volcanoes using space-based EO; (ii) demonstrate the applicability and improved timeliness of space-based EO products for reducing the impact and risk of eruptions; and (iii) build the capacity for exploiting EO data in volcanic observatories in Latin America to showcase global capacity development opportunities.

Coastal TEP (C-TEP): Sustainable coastal development requires accurate and easily accessible knowledge about the dynamic processes shaping coastal zones as well as suitable long-term analysis and automatic trend detection tools. The C-TEP provides a dedicated service for observation and monitoring of the coastal environment. The integration of satellite and near real time (NRT) EO data, in situ data and model predictions in the virtual platform provide an effective means to characterize and understand the many linked coastal processes across a wide range of space and time scales. Key applications include coastal bathymetry, coastal change monitoring, and early warning for pollution discharges, harmful algal blooms and storm surges.

Forestry TEP (F-TEP): The F-TEP vision is to be a one-stop shop for forestry remote sensing applications. The platform offers online processing services and tools (e.g., versatile satellite image analysis, GIS software) for generating value-added forest information products by means of simple and easy-to-use push-button functionalities. It also supports the generation of forest and land cover maps, change maps, and the estimation of continuous forest variables (e.g., growing stock volume). The F-TEP serves users with expertise in forestry rather than EO as well as remote sensing professionals and service providers. These include UN REDD (i.e., the United Nations program on Reducing Emissions from Deforestation and Forest Degradation) and other international programs, national forest inventories, universities and research centers, forest managers, land use planning and nature conservation agencies, as well as value-adding industry and sustainable development NGOs. The platform is closely coordinated with the Food and Agriculture Organization of the United Nations (FAO), the JRC and the Global Forest Observation Initiative (GFOI).

Hydrology TEP (Hydro-TEP): As water affects all societal and environmental domains, there is a major need for integrated, open water information services offering efficient access to cross-regional and multidisciplinary water information. This is even more critical in the developing world, where data are generally sparse. The Hydro-TEP aims to facilitate exploitation, processing and visualization of different types of data (EO, in situ, socioeconomic or meteorological) to better comprehend water-related challenges by combining a holistic understanding of the water cycle with evidence-based governance and increased public awareness. The main services supported by the platform are water quality monitoring, floods and drought risk, climate change forecasts and hydropower and aquaculture assessment. Current users of the Hydro-TEP comprise water authorities, regional mandated authorities, river basin organizations, and universities and research centers.

Polar TEP: The polar regions are remote and hostile environments where collecting data is strongly hindered by the extreme weather conditions, lack of infrastructure and long periods of darkness during the winters. As a consequence, satellites are the only source of consistent, repeatable, year-round and wide-area coverage information. Polar TEP enables users to access and exploit this information to support their operations and science as efficiently as possible. The main current applications include iceberg risk assessment, derivation of ice sheet and ice stream surface velocities, and ice concentration and thickness estimation. An initial pilot project was carried out to demonstrate the potential of the platform to investigate the current and future iceberg risk in Baffin Bay. Different datasets, processors and models have been deployed and integrated to allow for investigating linkages between iceberg populations, observed and modeled changes in ice sheet movement and calving rates, ocean circulation and iceberg trajectories. Current user communities of the Polar TEP include scientific researchers, industry, local indigenous populations, and regional and national governments.

Urban TEP (U-TEP): From the beginning of the 2000s, more than half of the global human population is living in urban environments, and the dynamic trend of urbanization is growing at an unprecedented speed. The U-TEP aims to open up new opportunities to facilitate effective and efficient urban management and safeguard livable cities by systematically exploring the unique EO capabilities in Europe in combination with the big data perspective arising from the constantly growing sources of geo-data. The platform is envisaged to initiate a step change in the use of EO data and geospatial analytics by enabling any interested user to easily exploit and generate thematic information on the status and development of the built environment based on multisource data collections (e.g., EO imagery, statistics, surveying, and volunteered geographic information). The capabilities of participation and sharing of knowledge by using new media and ways of communication will help boost interdisciplinary applications with an urban background. The U-TEP provides a unique portfolio of thematic products and services and, by the end of 2018, was successfully used to process more than 3 PB of EO data and activate a community of more than 300 institutions from all around the world (including the UN, the World Bank, the Organization for Economic Co-operation and Development—OECD, the World Food Program and the Bill and Melinda Gates Foundation).

Food Security TEP: The challenge of increasing the food supply to feed a growing global population makes the sustainability of agriculture and aquaculture as critical as ensuring food security. Food production systems need to optimize the use of water, energy and fertilizers, reduce pollution and soil degradation, and maximizing high-quality agricultural yields and fish harvest under increasingly unstable environmental conditions. To support future sustainable and efficient farming and aquaculture, the Food Security TEP (i) offers direct access to key satellite products and derived data; (ii) allows for on-the-fly computation, visualization and manipulation of basic key indices; and (iii) provides high-accuracy, quality-checked biophysical parameters that are suitable for use in operational scenarios. The Food Security TEP builds on a large and heterogeneous user community that includes small-scale farmers and agricultural industry, public science and the finance and insurance sectors, local and national administrations and international agencies. A forum of experts from this community (i.e., the Partnership for Growth and Sustainability) supported ESA in defining the project requirements, and enables the team to continually develop the platform in accordance with their needs.

20.3.4 EuroGEOSS

The Group on Earth Observations (GEO) is a partnership of more than 100 national governments, 100 participating organizations and the EC. It envisions a future where decisions and measures for the benefit of humankind are informed by coordinated, comprehensive and sustained EO. A central part of the GEO's Mission is to build GEOSS, i.e., a set of coordinated, independent EO information and processing systems that interact and provide access to diverse information for a broad range of users in the private and public sectors (GEO 2019). EuroGEOSS is the European component of GEOSS and complements the other three ongoing GEO initiatives, namely, AfriGEOSS in Africa (initiated in 2013), AmeriGEOSS in the Americas (initiated in 2014), and AOGEOSS in Asia and Oceania (initiated in 2015). EuroGEOSS will be a gateway for European EO programs and projects to GEOSS, with Copernicus as a major element (GEO 2019). Its added value will comprise the following (EC 2017b):

- the user-driven systematic coordination, integration and scaling up of existing services (based on a wide range of data sources) to address sustainable development goals—SDGs, GEO societal benefit areas—SBA (e.g., biodiversity and ecosystem sustainability, food security and sustainable agriculture, sustainable urban development, energy and mineral resources management) and other GEO priorities in the European context;
- the leveraging of global datasets through the GEOSS common infrastructure (GCI) and their exploitation within a European context; and
- additional support to Copernicus to address new communities within GEO and act as an incubator for possible new Copernicus services and applications supporting European priorities.

It is not the objective of EuroGEOSS to establish new data platforms in Europe. Rather, it builds on the GCI and DIAS to take advantage of multiple, existing or upcoming capacities in Europe, including the INSPIRE database, the Copernicus *Space* component, Copernicus *Core Services* products, output products from services offered by the TEPs, citizen observations, and additional data/products from agencies and organizations (e.g., ESA, EUMETSAT, ECMWF) (EC 2017b).

The exploitation of EO data and products, including Copernicus, and the subsequent market creation will be boosted by global cooperation approaches regarding data collection, processing and codesign of information products within the GEOSS context. A more coherent European action towards GEO would complement existing national and supra-national strategies, leverage EO European investments including those from the commercial sector and reduce fragmentation within Europe.

The initial phase of EuroGEOSS was supported through H2020. The EuroGEOSS roadmap 2017–2019 foresaw an initial phase to establish EuroGEOSS during the fourth quarter of 2017, a consolidation phase to start addressing EuroGEOSS pilot applications in 2018 and a third phase in 2019 to showcase the EuroGEOSS added value (EC 2017b).

At the heart of the EuroGEOSS is the ambition to foster the European user dimension in the process of scaling up existing multidisciplinary pilot applications. Emphasis is placed on the “last mile” of the innovation process, enabling preoperational services that could extend/reinforce other GEO initiatives and flagships. For this purpose, reviews of European user needs will be conducted on a regular basis to consider all possible European user communities involved in ongoing GEO tasks as well as other communities in Europe identified by EuroGEOSS members (EC 2017b). The initiative will take full advantage of the many user platforms and consultation processes that are conducted at continental, national and local levels by the members of the European GEO Caucus. EuroGEOSS will aggregate user demand at regional levels from both GEO-aware and GEO-unaware European users. This process will ensure pilot applications driven by structured, consolidated user needs of regional significance.

20.3.5 Galileo

The original idea for Galileo—Europe’s own global navigation satellite system (GNSS)—dates back several decades. Galileo was agreed upon in 1994 and, after many delays and setbacks, became available in December 2016 and is foreseen to reach full operational capability by 2021 (Reillon 2017). The system is operated by the European GNSS Agency (GSA) and ESA, with the program oversight by the EC and the political oversight by the European Council and the European Parliament.

Galileo allows for users to determine their location and the location of other people or objects at any given moment, and the ability to determine their velocity and the current system time. It is interoperable with GPS and GLONASS, (i.e., the US and Russian GNSS, respectively), and by relying on a large constellation of satellites and exploiting multiple frequencies, it will provide better service to the users, with real-time positioning accuracy in the meter range (Hecker et al. 2018c). At full deployment, Galileo will comprise 30 satellites (24 operational, plus 6 in-orbit spares) 26 of which have been launched as of July 2018. This large number, together with the optimized constellation design and the availability of three active spare satellites per orbital plane, ensure that the loss of one should not have a discernible effect on the users. Moreover, contrary to all other GNSS, Galileo will provide good coverage even at latitudes higher than 75°N (i.e., corresponding to the most northerly tip of Europe) (Hecker et al. 2018c).

Galileo has several other unique technical features. The two most relevant are the Search and Rescue (SAR) return data link for user notification and the signal authentication for civil users. Both represent important technologies that are expected to provide high added value to EU citizens and worldwide users.

To support the SAR function, satellites are equipped with a transponder, which is able to transfer the distress signals from a user's transmitter to regional rescue coordination centers, which then initiate rescue operations. The system sends a response signal to the users, informing them that the situation has been detected and help is on the way. This latter feature is new and is considered a major upgrade to the existing systems, which do not provide user feedback (Hecker et al. 2018c). The Galileo SAR service represents Europe's contribution to the worldwide satellite-based distress signal detection and localization system COSPAS-SARSAT (where COSPAS is an acronym for the Russian "Cosmicheskaya Sistema Poiska Avariynyh Sudov", which translates to "Space System for the Search of Vessels in Distress" and SARSAT is an acronym for search and rescue satellite-aided tracking). Currently supported by 44 countries, COSPAS-SARSAT was established by Canada, France, the former Soviet Union and the United States in 1979 and provides help to people in danger in the context of aviation, vessels, worldwide expeditions, and people equipped with personal locator beacons (COSPAS-SARSAT 2019). Galileo complements COSPAS-SARSAT with additional satellites and sensibly improves the coverage and accuracy of the located emergency position. Moreover, several research projects supported by the GSA under Horizon 2020 are creating end-to-end solutions based on the Galileo SAR service and leveraging its return link.

Galileo is the only GNSS envisaged to provide open and free signal authentication (Galileo GNSS 2017), i.e., a technical mechanism that allows for verifying if the received navigation signals truly originate from the stated source. Galileo is expected to start transmitting the "Open Service Navigation Message Authentication" in mid-2019 (EGSA 2019a). This feature will help effectively mitigate deliberate signal manipulation and strongly increase the security for Galileo-based timing and positioning applications (especially in critical and safety-relevant fields).

Since all other GNSS constellations are operated by organizations with a military background, there has been concern that navigation signals might be degraded or rejected for civil use (even in specific regions only). Dedicated techniques have been developed similar to the GPS' "Selective Availability", which intentionally reduced the quality of its open signal until the year 2000 (Hecker et al. 2018c). Although these tactics were rarely used in the past, their employment cannot be completely precluded, with potentially dangerous consequences as GNSS are increasingly used in safety critical applications and highly relevant infrastructure. Operated under civil control, Galileo ensures Europe's strategic autonomy with respect to satellite positioning under all circumstances, thus avoiding the abovementioned dependencies and risks. This will also strengthen the EU's position, which can actively influence the GNSS strategy and pave the way for long-term investments and technologies.

The range of applications that Galileo is expected to support is vast and spans different market segments in both the private and public sectors (EGSA 2019b). The most relevant comprise the following:

Emergency, security and humanitarian services: Galileo's SAR service will help save lives, e.g., in the event of an airplane or boat crash. The system will also be an invaluable asset for border control authorities and coastguards (e.g., ensuring faster rescue operations) and to support security-related applications (e.g., helping locate missing persons, stolen property or lost pets).

Environment and weather: Galileo will support geology, geodesy and meteorology research in mapping and measuring of oceans, tides and sea levels, and tracking icebergs, pollutants and dangerous goods. Moreover, it will allow for improving the quality of atmospheric measurements (especially the level of water vapor, which is particularly important in the context of weather forecasting), to advance the study of the ionosphere and space weather, and to better monitor (and hence comprehend) the movements of animal populations.

Agriculture: Galileo will become an asset for the agriculture community. Through the joint exploitation of in situ information, it will allow for improved parcel yield due to customized treatments, improved monitoring of the distribution and dilution of chemicals, and more efficient property management.

Fisheries: Galileo will provide fishermen with improved navigational aids and allow for more accurate and effective exchange of information between vessels and stations. The SAR service will be particularly important to the fishery industry.

Energy: Galileo's high-quality time synchronization will result in better services for the transportation and distribution of energy; modern energy networks strongly rely on accurate location systems (e.g., in case of failure, power grids monitoring instruments will be synchronized with maximum accuracy). Furthermore, by exploiting Galileo's services, marine drilling activities will become safer in the gas and oil fields (where precise time measurements are fundamental when employing seismic streamer or gun arrays).

Once fully operational, Galileo will offer 4 different high-performance services worldwide (EGSA 2019c):

- *Open Service (OS)*: open and free of charge positioning and timing services;
- *Commercial Service (CS)*: complements the OS by providing an additional navigation signal and added-value services in a different frequency band (the CS signal can be encrypted to control access to the service);
- *Public Regulated Service (PRS)*: restricted to government-authorized users to support sensitive applications requiring high-level service continuity; and
- *Search and Rescue Service (SAR)*: in support of COSPAS-SARSAT.

Although Galileo is running behind its original schedule, many application domains are already profiting from its entry into operation and many more will do so in the near future. This is also due to the system interoperability with other GNSS, which results in more satellites in view and thus more measurements and improved accuracies (Hecker et al. 2018c).

Furthermore, it is foreseen that Galileo and the European Geostationary Navigation Overlay Service—EGNOS (a system based on a network of ground stations and 3 geostationary satellites that combines GPS and Galileo signals to improve the accuracy and robustness of navigation in Europe), will provide consistent economic benefits to the European space industry, as well as for a variety of downstream GNSS-based services and applications. These are estimated to be on the order of ~ 130 billion euros for 2014–2034 (against the total Galileo costs of ~ 16 billion euros from the early 1990s until 2020) (Hecker et al. 2018c).

20.4 Citizen Science

The term citizen science (CS)—coined by Irwin (1995) and Bonney (1996) in the mid-1990s—describes the nonprofessional involvement of citizens in a scientific process. The concept of CS has been rapidly adopted in the international and European policy landscape as well as by the scientific research community and has received considerable attention in recent years. However, CS is not a new phenomenon. Depending on the definition, the concept of the participation of citizens in scientific processes can be traced back to the eighteenth century (Mahr et al. 2018). The field of CS is diverse, and there is no universally accepted definition. According to SiS.net (2017), CS can be described as a method to practice scientific research at larger scales, as a movement that democratizes scientific research processes or as a social capacity to produce knowledge. Various approaches of determining a definition for the term CS are discussed by Eitzel et al. (2017). The EC has used various definitions for CS in its policy documents. In EC (2016b), the definition of the Oxford English Dictionary (OED 2014) is applied: CS is *"scientific work undertaken by members of the general public, often in collaboration with or under the direction of professional scientists and scientific institutions"*. Instead, in the H2020 work program 2018–2020 (EC 2018d) the definition *"Citizen Science* [...] *covers a range of different levels of participation: from raising public knowledge about science, encouraging citizens to participate in the scientific process by observing, gathering and processing data, right up to setting scientific agenda and co-designing and implementing science-related policies"* is used. In this context, the European Citizen Science Association (ECSA) developed ten principles of CS, which complement the above-mentioned definitions (ECSA 2015; Robinson et al. 2018). For a general overview of the most relevant CS activities in addition to those discussed in this chapter related to the European framework, refer to Chap. 18.

20.4.1 Citizen Science in the European Policy Landscape

The EC emphasizes the opportunities of CS in its Open Science Policy by stating "Citizen Science can contribute to the Commission's goal of Responsible Research and Innovation, as it reinforces public engagement and can redirect research agendas towards issues of concerns to citizens" (EC 2016b). CS is recognized by the EC as an important pillar of the Open Science (OS) concept and, together with Open Access, is at the forefront of new frameworks for research and innovation. The assignment of CS to OS, which is implied by this statement, is controversial. Science Europe (2018), an association of European research funding organizations (RFOs) and research performing organizations (RPOs), argues that CS is increasingly considered an independent discipline whereas DITOs (2018) and Hecker et al. (2018a) see them as equal disciplines that enrich and partly depend on each other.

In 2013, the EC dedicated an entire report to environmental CS, which highlighted the role of new and emerging mobile technologies for CS and the perception of the quality of research by CS and discussed the influence of CS on European environmental policymaking (UWE 2013). Together with the outcomes of a green paper on CS by socientize (EC 2013) and the resulting white paper on CS for Europe in 2015 (Sanz et al. 2015), the results of the report prepared the ground for the aforementioned statements on CS in the EU Open Science Policy "*Open Innovation, Open Science, Open to the World—a Vision for Europe*" (EC 2016b) and were streamlined into the *EC Action Plan for Environmental Reporting (Action 8)* (EC 2017c) and the *Horizon 2020—Work Program 2018–2020* (EC 2018d). The level of consideration of CS in the upcoming Horizon Europe Program is still under discussion.

For the practical implementation of CS, JRC is the EU organization with the highest activity level (Science Europe 2018). The JRC is collaborating with several other EU institutions (including EEA) in the Environmental Knowledge Community (EKC), which investigates the creation and exchange of knowledge in environmental policy making processes and the role of CS in environmental policy making (Schade et al. 2017). The EKC operates a Knowledge and Innovation Project (KIP) on CS, with a focus on how CS data could be used qualitatively to complement European environmental monitoring and reporting processes. Another activity of the JRC that directly addresses European policy making is the development of a CS platform (EC 2019a). The platform will support CS projects and foster the consideration of their needs in the European policy making process.

The EC observes the development of CS projects with the Open Science Monitor (EC 2019b), which currently utilizes the repositories of SciStarter (https://scistarter.com/) and Zooniverse (https://www.zooniverse.org/). In 2016, a detailed EU-wide survey on CS was conducted (see Fig. 20.1). It showed that the majority of CS projects were initiated in Central and Western Europe and that the primary subject of most projects was in life sciences. In 2018, JRC published an inventory of environmental CS projects based on a study of a consortium of the EC (DG Environment, DG JRC), Bio Innovation Service (FR), Fundacion Ibercivis (ES) and The Natural History Museum (UK) (Bio Innovation Service 2018). It identified 503 projects (444 with participating actors from European countries, 12 European initiatives, 29 global initiatives and 18 from other regions; see Fig. 20.2). Even though both studies have a different focus and might not cover all activities, they show that the CS engagement of Eastern European countries has increased.

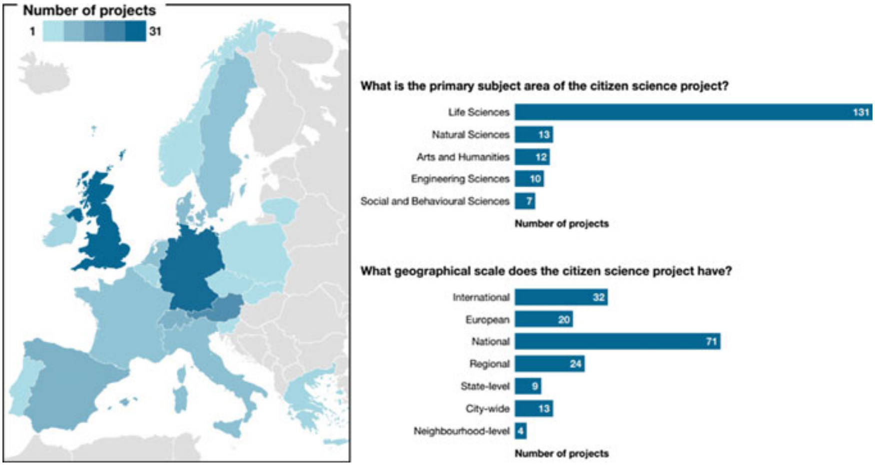

Fig. 20.1 Map of CS activities taking place across Europe; field of study of the project; and geographical scale of the project based on an EU-wide survey of CS conducted in 2016. *Source* European Commission (2016b) as cited in Science Europe (2018)

20.4.2 FP7 and H2020 Citizen Science Projects

With its Research and Innovation programs, the EU is an active funder of CS initiatives. The Seventh Framework program (FP7) was the EU funding program from 2007 to 2013, its successor H2020 is the framework program for 2014 to 2020, which will be followed by Horizon Europe. Some of the projects aim to enable CS participation and raise the general awareness of environmental and societal challenges; other projects focus on the involvement of citizens to engage in specific research questions. The following summary provides an incomplete overview of funding sections with instances of CS-related projects:

CAPS (Collective Awareness Platforms for Sustainability and Social Innovation): The CAPS seek new models to create awareness of emerging sustainability challenges. They aim to offer collaborative solutions based on modern information and communication technologies. A range of CAPS have been funded and are listed at https://capssi.eu. Among them, two of the most interesting are:

- *MakingSense*, which offers a toolkit of open source software and hardware, digital maker practices and open design that enables citizens and local communities to engage in pressing environmental questions (www.making-sense.eu); and
- *SOCRATIC*: whose main objective is to provide citizens and organizations with collaborative space and allow for them identify innovative solutions to achieve the United Nations Sustainable Development Goals (SDGs) (www.socratic.eu).

SwafS (Science with and for Society): The SwafS program objective is to build effective cooperation between science and society. The "Responsible Research and Innovation" program supports the design and implementation of innovative ways to

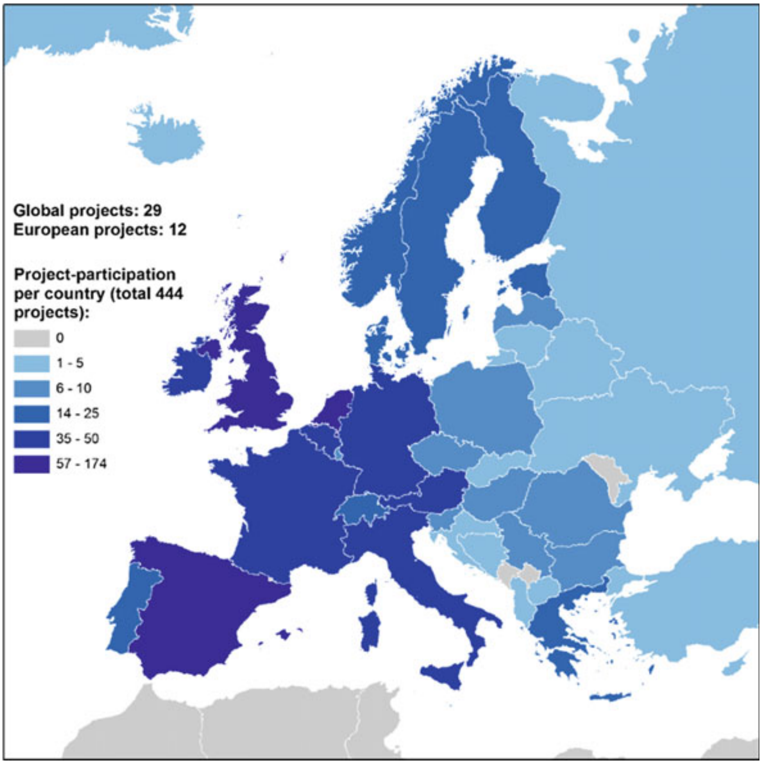

Fig. 20.2 Map of the environmental CS activities taking place across Europe based on the "Study on an inventory of CS activities for environmental policies". Twelve projects were listed as being on the European scale, and 26 were on a global scale. In addition, 444 projects had participants from European countries (multiple countries can be assigned to one project). *Source* own illustration based on EC (2018e)

connect science and society more broadly (http://ec.europa.eu/research/swafs/). In this framework, two representative activities are:

- *DITOs (Doing It Together Science)*, which connects research institutions, museums, science galleries and art institutions to engage people with CS in Europe (http://togetherscience.eu/); and
- *SPARKS*, which is an awareness-raising project dedicated to familiarizing and engaging European citizens with the concept and practice of Responsible Research and Innovation (RRI) (http://www.sparksproject.eu/).

Citizen Observatories: Citizen observatories commonly exploit the capabilities offered by the citizens' own devices (EC 2018e). Under the FP7 Environment Theme, 5 CS observatories were funded: COBWEB (biosphere monitoring), CITI-SENSE (air pollution monitoring), WeSenseIt (flood and drought monitoring) OMNISCIENTISTS (odor monitoring) and Citclops (coastal and water quality monitoring). Four others have been established through the H2020 Societal Challenge 5 (climate action, environment, resource efficiency and raw materials), namely, SCENT, Ground Truth 2.0, the GROW Observatory and Landsense (which contributes to EO analyses in the framework of land use and land cover monitoring (https://landsense.eu/)). Projects have also been undertaken to improve the coordination between CS observatories in Europe and support the integration of their outcomes in European policy (Gold 2018) (e.g., WeObserve www.weobserve.eu).

COST (European cooperation in science and technology): COST aims to connect research initiatives across Europe with initiatives outside Europe to enable researchers and innovators to develop ideas in any field of science and technology in cooperation with their peers. This includes the fostering of citizen participation in research activities (www.cost.eu). Interesting activities include:

- *Citizen Science COST Action CA15212*, which aims to investigate and extend the impact of the educational, policy, scientific and civic results and achievements of CS to use it for social innovation and socioecological transition (http://cs-eu.net/); and
- *Networking Lake Observatories in Europe (NETLAKE) COST Action ES1201*, which was funded from 2012 to 2016 and aimed to monitor 25 European lakes with the support of CS methods (NETLAKE 2017).

Notably, the FP7 *socientize* project aimed to promote the usage of science infrastructures and considered society itself as infrastructure for e-science by utilizing technology, innovation and creativity. *Socientize* compiled the aforementioned green and white papers on CS for Europe (Sanz et al. 2015) (www.socientize.eu).

20.4.3 Initiatives and Platforms in EU Member States and Public Organizations

In addition to CS projects and actions that are mainly based on funding by EU programs, many initiatives developed in Europe with national funding or through private and institutional engagement. A prominent role is played by the ECSA, a nonprofit association aimed at encouraging the growth of CS in Europe. It was launched in 2013 and consists of European and international individual and organizational members (Science Europe 2018). To foster policy advances and initiate and strengthen CS in Europe, the ECSA published ‘Citizen Science as part of EU Policy Delivery-EU Directives’ (ECSA 2016) and developed ten principles of CS (ECSA 2015; Robinson et al. 2018) for use in discussions with the EC. Several governments of EU Member States and public organizations actively support CS, particularly environmental protection agencies. One example is the Scottish Environment Protection Agency (SEPA), which fosters CS initiatives with a large support infrastructure, including best-practice guidance to support public authorities (Pocock et al. 2014). CS platforms and capacity-building initiatives increase the visibility of projects and help cultivate networks in the CS community (Hecker et al. 2018b). They produce training materials, distribute new developments and establish contacts to policy makers, scientists and stakeholders (Bonn et al. 2016, Richter et al. 2018). Examples of such platforms are *Bürger schaffen Wissen* (www.buergerschaffenwissen.de, Germany), *Österreich forscht* (www.citizen-science.at, Austria), *Schweiz forscht* (www.schweiz-forscht.ch, Switzerland), *Observatorio de la Ciencia Ciudadana en España* (http://ciencia-ciudadana.es, Spain) and the *Scottish Citizen Science Portal* (https://envscot-csportal.org.uk/, Scotland). A consortium of the nonprofit research associations Helmholtz and Leibniz, together with university partners, leads the *Bürger schaffen Wissen* (GEWISS) program in Germany. It published the green paper Citizen Science Strategy for 2020 (Bonn et al. 2016), which describes the understanding, requirements and processes of CS in Germany. For an extensive overview of European CS projects, we refer the reader to the *Inventory of citizen science activities for environmental policies* (EC 2018e) and the accompanying report (Bio Innovation Service 2018).

20.5 Digital Europe and Horizon Europe

To support future digital innovation (a fundamental prerequisite for effective implementation of DE in the coming years) in the framework of the next long-term EU budget for 2021–2027, the Commission is proposing two major programs: Digital Europe and Horizon Europe (EC 2018f, 2019c).

Digital Europe builds on the Digital Single Market strategy launched in May 2015 with the main objectives of increasing the EU's international competitiveness and shaping Europe's digital transformation for the benefit of citizens and businesses. The program will promote the large-scale deployment of digital technologies across economic sectors and will support the digital transformation of public services and businesses (EC 2019c). With a budget of €9.2 billion, Digital Europe will boost frontline investments in key relevant contexts:

- *high-performance computing*: €2.7 billion will be invested in projects aimed at strengthening supercomputing and data processing in Europe, with a goal of deploying a world-class supercomputer and data infrastructure with exascale capabilities (i.e., billion calculations per second) by 2022–2023 and post-exascale facilities by 2026–2027;
- *artificial intelligence (AI)*: €2.5 billion will be allocated to activities supporting the uptake of AI across the European economy and society, taking into account all the correlated socioeconomic changes and ensuring an appropriate legal and ethical framework. The idea is to create open 'European libraries' of algorithms to support both the public and private sectors to identify the most suitable solutions for their needs. The establishment of digital innovation hubs across the EU will also make it possible for small business and local innovators to access testing facilities;

- *cybersecurity*: €2 billion will be dedicated to boosting cyber defense and the EU's cybersecurity industry. This will be carried out by financing state-of-the-art cybersecurity equipment and infrastructure as well as by supporting the development of the necessary knowledge and skills;
- *advanced digital skills*: €700 million will be invested to form the current and future workforce through training courses and traineeships aimed at providing the necessary advanced skills to access supercomputing, artificial intelligence and cybersecurity; and
- *ensuring wide use of digital technologies*: €1.3 billion will support the digital transformation of public administration and related services, as well as their interoperability within the EU. Digital innovation hubs will become "one-stop shops" for both public administrations and small/medium-sized enterprises by providing access to technological expertise and experimentation facilities.

In addition to Digital Europe, financing for research and innovation in next-generation digital technologies will continue and be reinforced under the upcoming Horizon Europe program. Horizon Europe is the successor of H2020 and will be the biggest research and innovation funding program ever, with an overall budget of approximately €100 billion (EC 2018f). The new program will reinforce the Union's scientific and technological bases to help address major global challenges and contribute to achieving the United Nations SDGs; moreover, at the same time, it will boost the Union's competitiveness, including that of its industries. Horizon Europe will help deliver on the Union's strategic priorities and support the development and implementation of its policies. The program is designed around three main pillars: (i) the *Open Science* pillar, which supports researchers through fellowships, exchanges, and funding to projects defined and driven by researchers; (ii) the *Global Challenges* pillar, which directly supports research addressing societal challenges; and (iii) the *Open Innovation* pillar, which aims to make Europe a front runner in market-creating innovation.

Horizon Europe is expected to generate the following:

- new (and more) knowledge and technologies, promoting scientific excellence and impact. It will continue facilitating cross-border collaborations between innovators and top scientists, as well as allow for trans-national and cross-sector coordination between public and private investment in research and innovation;
- positive effects on growth, trade and investment flows as well as on quality jobs and international mobility for researchers in the European Research Area. The program is expected to increase the GDP by an average of 0.08–0.19% over 25 years (which corresponds to a potential return of up to €11 for each euro invested over the same period); and
- significant social and environmental impacts created by translating scientific results into new products, services and processes, which will help successfully deliver on political objectives, as well as social and eco-innovation.

The Digital Europe and Horizon Europe programs will work hand-in-hand: Horizon Europe provides key investments in research and innovation, and Digital Europe builds on these results to create the necessary infrastructure and support deployment and capacity building, which will provide input for future research in AI, robotics, high-performance computing and big data.

AI is foreseen to become the main driver of economic and productivity growth and will contribute to the sustainability and viability of the industrial base in Europe. Accordingly, the Union aims to develop trusted AI based on ethical and societal values, building on its Charter of Fundamental Rights; people should trust AI and benefit from its use for their personal and professional lives. Thus, the Communication "Artificial Intelligence for Europe" of 25 April 2018 proposed a dedicated strategy that supports the ambition for Europe to become the world-leading region in developing and deploying cutting-edge, ethical and secure AI (EC 2018g). Furthermore, in the related coordinated Action Plan of 7 December 2018, the Commission explicitly proposed the development and deployment of dedicated AI capacities, taking direct advantage of Copernicus data and infrastructure to foster geo-location-based services to support agriculture, air quality, climate, emissions, the marine environment, water management, security and migration monitoring, and citizen science (EC 2018h). These will be accompanied by initiatives supporting AI-based exploitation of EO data and information in both the public and private sectors.

20.6 Conclusions

Most of the visionary features of the original DE view formulated by Al Gore in 1998 were implemented in practice only 10 years later in several web-mapping platforms and desktop virtual globes. This led to an evolution of the DE concept, in light of the concurrent advancements in technology and research, as well as changes in society. DE expanded its role in other fields (e.g., related to global climate change, natural disaster prevention and response) and transformed into a more practical system design to fulfil the demand for information sharing and overcome the socioeconomic inequality in accessing and using the data. In a few years, Europe became one of the key players in DE at the global level. Through the INSPIRE Directive, it created a legal framework for the establishment of a European SDI relying on single NDSIs. By jointly supporting data discovery, access and harmonization, INSPIRE has become a model in the world and its complete entry into force in 2021 will become a milestone for the implementation of transnational services. Furthermore, the EO mass data collected within the Galileo and Copernicus programs place Europe at the forefront of the big data from space paradigm. Galileo will enable higher precision positioning, with consequent key improvements in a variety of applications (especially once full operation begins in 2021). Moreover, its SAR and signal authentication features will improve people's security and safety in many fields. Copernicus provides continuous monitoring of our planet through a comprehensive set of sensors mounted onboard the Sentinel satellites (whose families will grow in the next decade) as well as a number of environmental local measurements. From such a wealth of data, the ultimate goal of the program is to generate key information for the users; this is directly carried out by the different core services and made possible through novel cloud-based platforms such as the DIAS and the TEPs. The last 5 years saw the increasing emergence of CS in Europe, which proved to be an effective tool to support researchers and society at large, with hundreds of projects and initiatives funded throughout the different EU Member States. The implementation of dedicated platforms facilitated the uptake of CS in different fields and raised awareness of environmental and societal challenges. Further advancement is expected in the near feature, e.g., by giving citizens the possibility of collecting and contributing real-world data through novel (and connected) sensors directly immersed in their environments. Europe has clear plans for the future and is creating a basis to establish an overall framework in which DE will gain even more importance. This will be possible by means of the Horizon Europe and Digital Europe programs. The former will support research and innovation by strengthening the scientific and technological bases of the Union and fostering its global competitiveness and innovation capacity; the latter will procure high-tech resources and skills for use by European businesses and the public sector. In both cases, the effective integration of cutting-edge AI will be one of the main challenges in the next years.

In conclusion, the European experience illustrates that big data from satellites are a fundamental aspect for the future of DE, as they will allow for analyses that were unimaginable just few years ago. To maximize their benefit, the implementation of processing platforms that enable advanced processing are essential (the integration of novel AI-based methodologies is one of the priorities), as well as the establishment of effective SDIs to share derived products and guarantee access to them beyond national borders. In this framework, the role of citizens can become a key asset through their involvement in directly collecting and sharing data and actively providing feedback.

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Mattia Marconcini is a project manager and scientific researcher at the Earth Observation Center of the German Aerospace Center. He has extensive experience in advanced urban remote sensing, machine learning, pattern recognition, land-cover classification and change detection. Among others, he convenes the European chapter of the International Society for Digital Earth.

Thomas Esch is a project manager and leader of the Smart Cities and Spatial Development team at the Earth Observation Center of the German Aerospace Center. He has vast experience in urban remote sensing, SAR applications, sustainable development, land management, and energy efficiency. Among others, he is the leader of the ESA U-TEP project.

Felix Bachofer is a project manager and scientific researcher at the Earth Observation Center of the German Aerospace Center. He has extensive experience in urban remote sensing and spatial analysis, with focus on East Africa and SE-Asia. Among others, he is currently addressing urban development and climate change interrelations using multi-sensor remote sensing.

Annekatrin Metz-Marconcini is a project manager and scientific researcher at the Earth Observation Center of the German Aerospace Center. She has extensive experience in advanced urban remote sensing, machine learning, geographic information systems, energy efficiency and land management. Among others, she is currently addressing global automatic land-cover classification and change detection.

Chapter 21
Digital Earth in Australia

Zaffar Sadiq Mohamed-Ghouse, Cheryl Desha and Luis Perez-Mora

Abstract Australia must overcome a number of challenges to meet the needs of our growing population in a time of increased climate variability. Fortunately, we have unprecedented access to data about our land and the built environment that is internationally regarded for its quality. Over the last two decades Australia has risen to the forefront in developing and implementing Digital Earth concepts, with several key national initiatives formalising our digital geospatial journey in digital globes, open data access and ensuring data quality. In particular and in part driven by a lack of substantial resources in space, we have directed efforts towards world-leading innovation in big data processing and storage. This chapter highlights these geospatial initiatives, including case-uses, lessons learned, and next steps for Australia. Initiatives addressed include the National Data Grid (NDG), the Queensland Globe, G20 Globe, NSW Live (formerly NSW Globe), Geoscape, the National Map, the Australian Geoscience Data Cube and Digital Earth Australia. We explore several use cases and conclude by considering lessons learned that are transferrable for our colleagues internationally. This includes challenges in: 1) Creating an active context for data use, 2) Capacity building beyond 'show-and-tell', and 3) Defining the job market and demand for the market.

Keywords Digital infrastructure · Data cube · National computational infrastructure · National collaborative research infrastructure strategy · Queensland globe

Z. S. Mohamed-Ghouse (✉) · C. Desha · L. Perez-Mora
International Society of Digital Earth (ISDE), Sydney, Australia
e-mail: zaffar.mg@spatialvision.com.au

Z. S. Mohamed-Ghouse
Spatial Vision, Melbourne, Australia

C. Desha · L. Perez-Mora
Cities Research Institute, Griffith University, Brisbane, Australia

H. Guo et al. (eds.), *Manual of Digital Earth*,
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21.1 Introduction

In this chapter, the authors demonstrate the need for local, champion-based initiatives to support mainstreaming, integration and take-up globally. This includes progress made in the digital earth agenda, and the creation of a repository that can be used by researchers, policy makers, decision-makers and the community at large. The chapter describes the lessons learned in Australia, which are likely to be immediately transferrable and of benefit to other initiatives around the world. The chapter outlines precedents and examples of innovation arising from the need to better manage local resources, and addresses the complexities of environmental stewardship and the extraction and processing of natural resources.

In the global move towards automation, employment and productivity (Manyika et al. 2017), Australia must overcome a number of challenges to meet the needs of its growing population in a time of increased climate variability, from sustainably managing and restoring natural environments to developing resources and optimizing our agricultural potential. Increasingly frequent environmental extreme events such as chronic drought, extreme bushfires, and flooding have catalyzed internationally regarded innovation in this field, in addition to the requirement for large-scale infrastructure planning along the eastern seaboard and in northern Australia (Australian Government 2015), and the national need to report on performance—in relation to people and planetary systems—through the United Nations Sustainable Development Goals (Griggs et al. 2013). Within this context, senior mentors in the field Steudler and Rajabifard reflect that sharing information through a spatial data infrastructure (SDI) can facilitate improved decision-making, where themed images and temporal overlays can quickly engage different communities in common understanding and appreciation of issues and potential solutions (Steudler and Rajabifard 2012; Rajabifard and Crompvoets 2016).

Fortunately, Australians have unprecedented access to current and historical data about land and the built environment that is internationally regarded for its quality. Australia has been at the forefront in the development and implementation of Digital Earth concepts over the last two decades (Woodgate et al. 2017). In recent years, several key national initiatives have also formalized the Australian digital geospatial journey, shaping its world-leading initiatives and credentials in digital globes, open data access and quality:

- The Cooperative Research Centre for Spatial Information (CRCSI), launched in 2003 and recently transitioned to 'FrontierSI', has driven numerous initiatives in research and technological innovation, market and product development, workforce planning and preparedness, and outreach. Three seminal *Global Outlook* reports (Woodgate et al. 2014; Coppa et al. 2016, 2018) provide excellent content for a more detailed exploration of the Australian geospatial progress, in addition to a White Paper on the context and priorities of the future of spatial knowledge infrastructure (Duckham et al. 2017).
- The National Innovation and Science Agenda (NISA), launched in 2015, comprises 24 initiatives. With a AUD $1.1 billion direct allocation of federal funds,

it influences approximately AUD $10 billion per annum in government-related expenditure on innovation (Coppa et al. 2018:6).

- The 2026 Agenda (co-chaired by Cockerton and Woodgate 2016, 2017, 2019), developed from extensive consultation, provides the vision and direction to enable the geospatial community to deliver national and global services supporting the NISA. This landmark initiative involved the CRCSI (now FrontierSI), the Spatial Industries Business Association-Geospatial Industry Technology Association (SIBA-GITA), the Australia New Zealand Land Information Council (ANZLIC—Australia and New Zealand's peak government Council for spatial matters), the Australian Earth Observation Community Coordination Group, Data61 (CSIRO), Landgate, Geoscience Australia, Department of Natural Resources and Mines (Queensland Government), and the Department of Prime Minister and Cabinet.
- Substantial digital infrastructure projects in broadband services around the country, including the National Broadband Network (NBN) and Australia's Academic and Research Network (AARNet), owned by the Australian universities and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), which provides internet services to the Australian education and research communities and their research partners. AARNet is widely regarded as the founder of the internet in Australia and is renowned as the architect, builder and operator of a world-class high-speed, low-latency network for research and education (AARNet 2018).

Domestically, the country has directed efforts towards world-leading innovation in big data processing and storage (for example, see Dhu et al. 2017), without ownership of substantial resources in space (AAS 2009) and with only-recent establishment of a Space Agency. Furthermore, Australia is large enough for the Earth's curvature to be important, and its tectonic movement is significant enough to require a dynamic cadaster. Hence, Australia's digital earth history has been grounded in an emphasis on a planar geometry—where geodetic coordinates (latitude and longitude) are mathematically projected onto a two-dimensional plane using a Universal Transverse Mercator system—in comparison with other chapters in this manual that emphasize the globe.

Within this context, in 2017 the federal government established Digital Earth Australia (DEA), building on the Geoscience Australia 'Data Cube' supported by CSIRO, the National Computational Infrastructure (NCI), and the National Collaborative Research Infrastructure Strategy (NCRIS). This includes funding of AUD $15.3 M/year going forward within the federal budget. When completed, it will provide 10-meter resolution image data nationwide, allowing for multitemporal analyses throughout the stack of co-registered data for as far back as 30 years and as detailed as 16-day intervals.

Looking ahead, Australia has identified its most promising growth sectors for the spatial industry: transport, agriculture, health, defense and security, energy, mining, and the built environment, with the environment requiring special consideration (ACIL 2015; Cockerton and Woodgate 2017). ***A significant challenge concerns building capacity for widespread uptake of geospatial technologies and tools across***

these key growth sectors, where open-data use, real-time crowd-sourcing of information, and visualization are integrated within core decision-making processes.

Within this context, this chapter provides commentary on key geospatial initiatives, case-uses, lessons learned, and next steps for Australia, drawing primarily from published material in the public domain and experiences of the Authors. The chapter presents a summary of a number of initiatives, including the National Data Grid (NDG), the Queensland Globe, G20 Globe, NSW Live (formerly NSW Globe), Geoscape, the National Map, the Australian Geoscience Data Cube and Digital Earth Australia. It also highlights key products and projects currently being undertaken by Digital Earth Australia. The chapter includes exploration of several use cases in agriculture, property, education and training, and disaster management, and concludes with a consideration of lessons learned and next steps in Australia.

21.2 An Historical Context of Geospatial Initiatives

It has been a busy two decades for the Australian geospatial community, with a number of key products developed by state and federal governments. As illustrated in Fig. 21.1, these initiatives are indicative of a growing awareness of and appetite

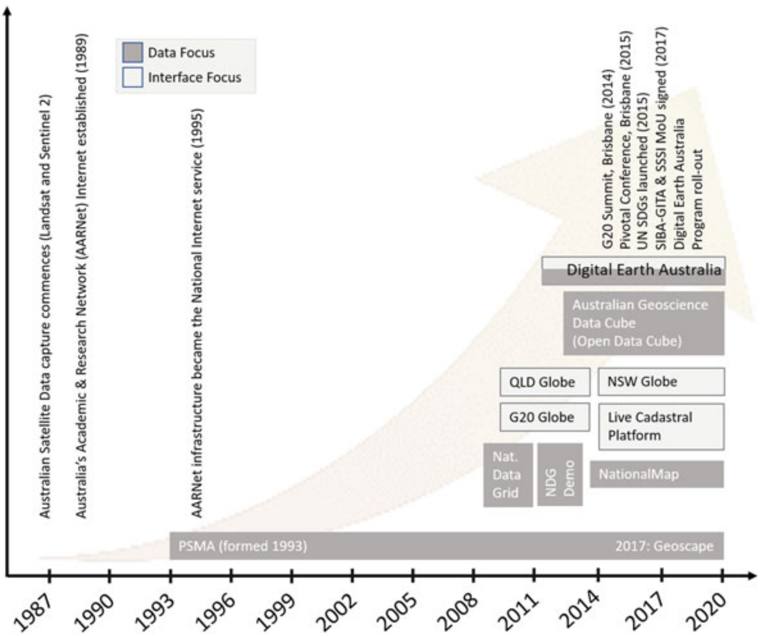

Fig. 21.1 Illustration of the history of digital earth in Australia

for access to data that can result in meaningful decision-making, addressing three important principles for Digital Earth (Desha et al. 2017):

(1) Open data: Harnessing the potential of open, transparent, rapid access to comprehensive data and information to harvest the plethora of data sets for meaningful problem solving. Australia ranked first on the Global Open Data Index that measures how well nations publish open government data against 14 key categories (Wallace 2017a).
(2) Real-world context: Decision-making support frameworks that integrate spatial information and sustainable development aspirations, including the United Nations' sustainable development goals. Australia's Open Data Cube (ODC) objectives include building the capacity of users to address these goals in addition to those of the Paris and Sendai agreements (Coppa et al. 2018:84).
(3) Informed visualization for decision support: i.e., making visual sense of the complex, dynamic and increasingly interrelated systems of today and the future. Among the world's 23 unique virtual globe platforms and four virtual globes that are visualization applications only, Australians have access to an expanding array of support tools (Keysers 2015), with exciting prospects for user functionality improvements.

In the following paragraphs, we briefly introduce the features of these products, how they have evolved over time, how they are being used to increase end-user take up of geospatial products and services, and the contributions that led to the formation of Digital Earth Australia (Sect. 21.3). Several use cases are also provided in Sect. 21.4.

21.2.1 National Initiatives

21.2.1.1 2008–2010: CRCSI's National Data Grid (NDG)

The National Data Grid (n.d.) was developed by the CRCSI to support the spatial enquiry needs of modelers and decision support systems, as conceptualized in Fig. 21.2. The developers had a vision to develop a shared infrastructure that could provide an economical and effective means to integrate spatial information from a variety of sources and formats to support commonly required query, analytical and modeling tasks.

The resultant NDG was essentially an integrated data platform that adopted a grid cell (i.e., raster) based approach to managing spatial information, which could assist professionals with little or no knowledge of geospatial science in performing simple and replicable spatial queries and analyses. It included three components (CRCSI 2009):

- National Nested Grid: a set of standard nested grids with an innovative indexing system to facilitate and promote spatial consistency in a cost-effective manner.

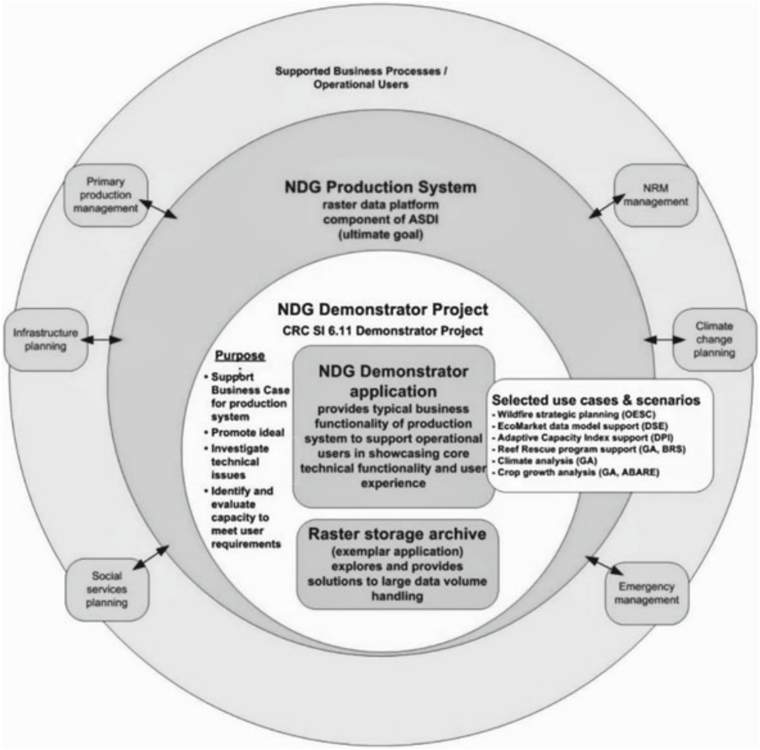

Fig. 21.2 A conceptualization of the national data grid (*Source* CRCSI 2011)

- National Data Grid Demonstrator Application: a publication data store with a web-based function, rich data querying and data visualization environment for users to access and publish grid cell data.
- National Data Grid Raster Storage Archive: a high-capacity backend data store for efficient and cost-effective storage and management of large datasets.

To raise awareness about the full potential of the NDG, the CRCSI funded the development of an online proof of concept 'NDG Demonstrator' (Spatial Vision 2011). Built upon an earlier collaboration into a 'Platform for Environmental Modeling Support' (Chan et al. 2008), several scenarios including crop growth, a biodiversity index and climate evaluation were used to showcase the core technical components and opportunities to interact with the product for national and jurisdictional agencies and the public, and opportunities to address scalability issues (CRCSI 2011). IP created in the NDG project was also subsequently used in a pivotal \$3.4 M initiative funded by the Australian Space Research Program to build Earth observation infrastructure enabling processing of the national LANDSAT imagery archive of more than 30 years of data.

21.2.1.2 2014: NICTA's NationalMap

National ICT Australia (NICTA) developed 'NationalMap' for the Department of Communications and Geoscience Australia as a public tool for accessing and mapping open data and users' private data (National Map, n.d.). The NationalMap provides a map-based view of data but does not store data. Selected data viewed on the map is typically accessed directly from the relevant government department or agency.

The initiative was designed with a focus on interoperability and open source code, supporting the government's commitment to policy visualization and open data (NAA, n.d.). It was developed as open source software (available as a GitHub project) using user-centered design methods. Now managed by the Department of the Prime Minister and Cabinet, the open source software is available as a GitHub project. The web front-end uses NICTA's TerriaJS software, which was initially developed by Data61 for NationalMap and has subsequently been used for other projects.

An example of NationalMap use documented in Australia's Digital Continuity 2020 Policy is the Australian Renewable Energy Mapping Infrastructure (AREMI) platform owned by the Australian Renewable Energy Agency (NAA, n.d.). AREMI uses NationalMap to create an open-source, three-dimensional mapping platform to convert and visually display information that works in any modern browser without plug-ins or specialized software on the user's computer. It facilitates evaluation of renewable energy project developments through gathering relevant spatial datasets in one location at the same time. End-user flexibility is key; financiers and investors can ascertain the potential viability of ventures, and project developers can freely access ground and resource measurements to assist with site assessment and design. State and local governments can also use the information to assist with community and stakeholder engagement, tracking and promoting projects, and reviewing and assessing environmental and regulatory planning approvals.

NationalMap requires data to be formatted in a particular way to be machine readable and presented spatially. The Australian Government is continuing to work with agencies to assist with data formatting requirements and compatibility with Australian and international data standards, and have produced the AusGEO CSV standard as a guide to provide consistent formatting.

21.2.1.3 2017: PSMA's Geoscape: Australia's National 3D Data Set

PSMA Australia is an independent and self-funded entity, formed in 1993 by the state governments of Australia to collate, transform and deliver the national government's geospatial data as national datasets (PSMA 2009). The company undertook its first major initiative in 1996, supporting the national Census by providing Australia's first digital national map at the street level.

In 2017, the company launched Geoscape as a suite of digital datasets that represents buildings, surface cover and trees across urban and rural Australia, as shown in Fig. 21.3. Using a reliable geospatial base, the national dataset spatially represents

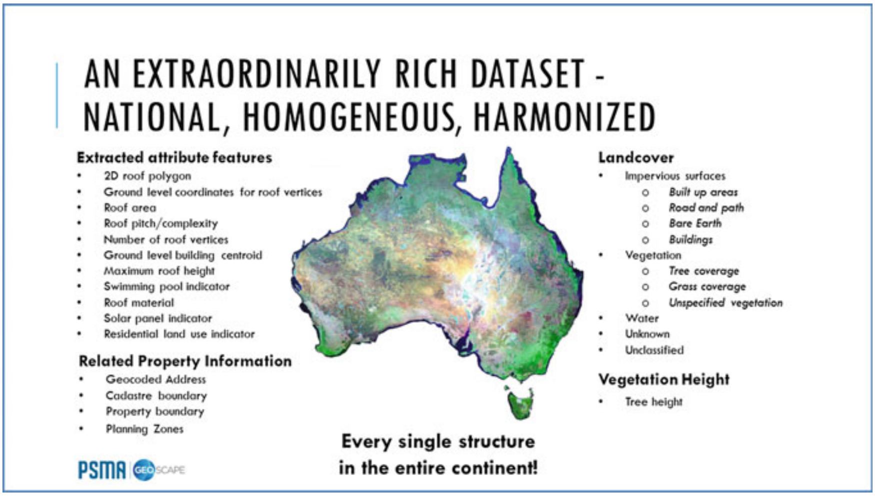

Fig. 21.3 Geoscape product summary (*Source* Paull and Rose 2017)

every building with a roof area greater than 9 m^2, for use by industry and government. This is equivalent to approximately 15 million buildings spanning 7.6 million km^2 across the entire country (Schubert 2017).

The data set links numerous land and property features related to physical structures, land and vegetation, and geographical locations. This includes links to important geospatial reference datasets including geocoded addresses, property data, administrative boundaries, 3D building attributes, land cover details, tree heights, and information on roof materials, swimming pools, and solar panels. It is regularly updated, providing a narrative of the changing landscape, and has links to other PSMA products including G-NAF (addresses), Cadlite (cadastre and property) and Administrative Boundaries (suburb/localities). As PSMA's CEO Dan Paull reflects in a Geoscape Blog (2017), *"Time and location-stamping have moved data from position to precision, giving a more accurate reflection of the built environment. Organisations can now make sharper decisions with more efficiency and greater confidence."*

Working in partnership with DigitalGlobe for satellite imagery, the company has used a combination of satellite imagery, crowd-sourcing and machine learning to develop a new process for recognizing and extracting insights from images. The result is an analytics-ready product that is globally replicable and depicts the full built environment (PSMA 2017a). At the time of writing, the roll-out of mapped locations was underway (see https://www.geoscape.com.au/rollout/).

The following are two examples showcasing the capabilities of Geoscape:

- The Greater Launceston Transformation Project: Geoscape provides the essential foundational data to enable a cost-effective, accurate solution for smart cities and smart suburbs in the Tasmanian city of Launceston. The *Sensing Value* company is layering datasets including Geoscape to provide scenario modeling capabilities and visual representations of entire land areas. This is being used to, '*model, understand and demonstrate the impact of development decisions, mobility patterns, energy consumption, land use and other strategic and operational insights for urban and regional planning*' (PSMA Australia 2017b).

- GeoVision™: Developed in collaboration with *Pitney Bowes*, this product is a suite of datasets including Geoscape that combines information on the 3D built environment with information such as addresses, postcodes and ABS Census data. (PSMA Australia 2017c). End users include retail, utilities and construction clients seeking to accelerate decision-making and increase efficiency as well as banking, financial services and insurance users. It aids insurers in risk modeling for setting insurance premiums and assists with telecommunications infrastructure planning.

21.2.1.4 2017: Australian Geoscience Data Cube—'Open Data Cube' (ODC)

The Australian Geoscience Open Data Cube—otherwise known as the Open Data Cube, (ODC)—aims to realize the full potential of Earth observation data holdings by addressing the big data challenges of volume, velocity, and variety that otherwise limit its usefulness (Lewis et al. 2016). The result of several years of iterations of partnership between Geoscience Australia (GA), the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the National Computational Infrastructure (NCI), it is the first case in which an entire continent's geographical and geophysical attributes have been made available to researchers and policy advisors. (NCI Australia 2018). It provides users with access to free and open data management technologies and analysis platforms, with the ability to observe historical changes in land use and patterns over time using the infrastructure shown conceptually in Fig. 21.4.

The foundations and core components of the AGDC are (Lewis et al. 2016):

(1) Data preparation, including geometric and radiometric corrections to Earth observation data to produce standardized surface reflectance measurements that support time-series analysis and collection management systems that track the provenance of each Data Cube product and formalize reprocessing decisions;
(2) The software environment used to manage and interact with the data; and
(3) The supporting high-performance computing environment provided by the Australian National Computational Infrastructure (NCI).

This data cube approach allows for analysts to extract rich new information from Earth observation time series, including through new methods that draw on the full spatial and temporal coverage of the Earth observation archives. As noted in the introduction, due to the size of Australia, the Earth's curvature is important and its tectonic movement is fast enough to require a dynamic cadastre. With an emphasis on a planar geometry, the Data Cube's flat base is actually an illusion that enables a useful platform to engage with the data.

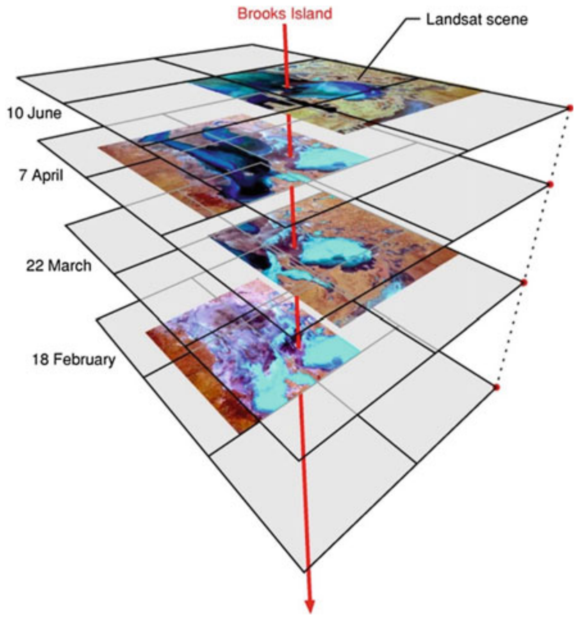

Fig. 21.4 Conceptual illustration of the data cube, showing Landsat scenes reformatted as spatially consistent tiles of data (*Source* Lewis et al. 2016)

To enable easy uptake and facilitate future cooperative development, the code was developed under an open-source Apache License, Version 2.0. This approach enables other organizations including the Committee on Earth Observing Satellites (CEOS) to explore the use of similar data cubes in developing countries. Advances in cloud computing and the availability of free and open technologies such as the Open Data Cube (ODC) mean that developing countries without the local infrastructure to process large volumes of satellite data can access data and computing power to build relevant applications and inform decision making.

21.2.2 State Initiatives

21.2.2.1 2013: The Queensland Globe and G20 Globe

The Queensland Globe was created in 2013 by the Queensland Government's Department of Natural Resources, Mines and Energy and was released by the Department as part of the State's open data initiative aimed at increasing the number of publicly available datasets (https://qldglobe.information.qld.gov.au/). As the first Australian example of combining Google Earth and government spatial data into a standalone application, it used the familiar Google Earth viewer to find and download free reports and information such as cadastral maps and coal seam gas well and water bore reports.

Subsequently, Google announced they were no longer going to support Google Earth Enterprise, and the new Queensland Globe was developed using the Esri JavaScript API 4.x and Esri REST web services application hosted on Amazon Web Services (AWS) Beanstalk. Its web services were published using ArcGIS Server from departmentally hosted servers. The Globe currently includes 652 data layers from almost every Queensland Government department and is now accessed straight from a browser, so users are no longer required to download Google Earth.

An adaptation of the Queensland Globe, the G20 Globe was produced for the G20 Summit held in Brisbane in 2014. Profiling Queensland to world leaders including Barack Obama and Vladimir Putin, the G20 Globe illustrates the global economic ecosystem from the perspective of Queensland. It shows the value of spatial technology for exploring economic activity in our globally interconnected world across six economic sectors, including agriculture, construction, resources, tourism, science and innovation and education and training. As an exemplar, the G20 Globe reveals the opportunities and competitive advantages in agriculture, construction, resources, tourism, science and innovation in Queensland. It demonstrates the value of open data and the capacity to merge it with digital technology so users can follow economic stories that begin with domestic supply chains and are linked to expansive market demands around the world.

At the time of the G20 summit, Queensland University of Technology went a step further than the Queensland Globe and G20 Globe, developing a state-of-the-art interactive digital display called the CUBE (Fig. 21.5) to teach school children geography and science in an innovative way. Consisting of 48 multi-touch screens across two stories, the Cube is open to the public to view and facilitates opportunities for discovery, visualization and contribution to research projects as ‘citizen scientists’ by experiencing real project scenarios and exploring 21st century challenges (QUT, n.d.).

Fig. 21.5 QUT’s CUBE interactive displays, launched in 2014 and used for community engagement

21.2.2.2 2018: NSW Globe and Live Cadastral Platform

In New South Wales, the state government's Spatial Services initiated NSW Globe and a cloud-based 'cadastre as a service' platform to upgrade its maintenance of the NSW cadastre, including an application that lets the public access cadastral data in real time (Bishton 2018). The new API-based system is targeted at the automated backbone of the development application submission process for councils, reducing duplication of data and effort. Previously, plans were accepted in hard copy and manually scanned whereas the new submission process automatically extracts data and metadata from digital plans, and images are converted to validated LandXML. The DCDB remains the system of record, updated via the new API, and the LandXML and GeoTIFF files are stored in the cloud.

The system is part of a digital transformation of the surveying industry, and the benefits of this system include more efficient land subdivision and reduced cost of development to market. The public will also be encouraged to contribute data to the platform, which supports the NSW Government's spatially digital agenda. Other initiatives such as dMarketplace, a sharing place for data, include a rating scheme for data sources (Wallace 2017b).

21.3 Digital Earth Australia

In 2017, the Australian government launched *Digital Earth Australia* (DEA) to implement the open source analysis platform developed as part of the ODC initiative discussed above. The DEA program contributes code, documentation, how-to guides, tutorials, and support to domestic and international users of the Open Data Cube. As a platform, it uses spatial data and images recorded by orbiting satellites to detect physical changes in unprecedented detail.

Drawing on data from as far back as 1987, DEA translates almost three decades of Earth observation satellite imagery into information and insights about the changing Australian landscape and coastline, providing a ground-breaking approach to organizing, analyzing, and storing vast quantities of data (DEA 2017). Using high-performance computing power provided by the National Computational Infrastructure and commercial cloud computing platforms, DEA organizes and prepares satellite data into stacks of consistent, time-stamped observations that can be quickly manipulated and analyzed to provide information about a range of environmental factors such as water availability, crop health and ground cover. By preparing the data in advance, DEA reduces the cost and time involved in working with the vast volumes of Earth observation data. This analysis-ready data (ARD) are made freely available to users and will enable businesses to innovate and develop information products and applications that can be applied to global challenges.

21.3.1 Product Development for Enhanced Access

DEA provides a suite of information products to the Australian government and businesses. Table 21.1 provides a summary of key products and the following paragraphs describe some of them in more detail (report extracts) to illustrate how, by providing easy access to Earth observation data, DEA can help unlock innovation and capability in government, industry, and the research community (DEA 2018). In the future, there are many opportunities to include other data sets that may be in the public or private domains, such as data collected by sensors installed in machines used by farmers.

Severe floods are a feature of the Australian climate and landscape and are likely to continue with increasing regularity and severity. Water Observations from Space (WOfS) helps understand where flooding may have occurred in the past, which allows for mitigation measures to be considered for reducing future impacts, including proper disaster planning and initiatives supporting communities' preparedness and disaster resilience. WOfS is also an invaluable information source for the Australian Flood Risk Information Portal, which enables flood information held by different sources to be accessed from a single online location.

The fractional cover (FC) product can provide insights for land managers regarding which parts of a property show heavier grazing. DEA is working with the Australian Bureau of Statistics to explore whether this product can provide useful information for land accounting and environmental reporting, and with the Clean Energy Regulator to incorporate FC into its monitoring of Emissions Reduction Fund projects and in potential future ground fraction products that may be of use to industry partners such as FarmMap4D (FarmMap4D Spatial Hub 2018).

Changes in the NDVI over time can be used to identify areas where there has been a sudden decrease or increase in the amount of vegetation. Sudden decreases in the NDVI can be caused by a range of processes including tree clearing, cropping, or severe bushfires. Sudden increases in the NDVI can result from vegetation responding to increased water availability, crop growth, or greening of irrigated pasture.

The knowledge provided by products such as those highlighted in Table 21.1, can contribute to a broad range of applications, including environmental monitoring for migratory bird species, habitat mapping in coastal regions, hydrodynamic modeling, and geomorphological studies of features in the intertidal zone. The surface reflectance tool allows for a more accurate comparison of imagery captured at different times, by different sensors, in different seasons, and in different locations. It also indicates where the image contains missing data, is affected by clouds or cloud shadow, or has been affected in other ways.

Table 21.1 An overview of key DEA products developed in Australia, drawing on data gathered since 1987

Product	Description summary	Key References
Surface Reflectance (Landsat and Sentinel 2)	• Starting point for many analyses, translating information recorded by an Earth-observing satellite into a measurement of the characteristics of the surface of the earth	Li et al. (2012); Geoscience Australia (2018e), (2018f)
Fractional Cover (FC)	• Identifies areas of dry or dying vegetation and bare soil, and allows for mapping of the living vegetation extent (e.g., where animals spend time grazing). • Informs a broad range of natural resource management issues	Scarth et al. (2010); Geoscience Australia (2018b)
Water Observations from Space (WOfS)	• The world's first continent-scale map of the presence of surface water. • Provides insight into the behavior of surface water over time. • Highlights where water is normally present, seldom observed, and where inundation has occasionally occurred	Mueller et al. (2016); Geoscience Australia (2018a)
Normalized Difference Vegetation Index (NDVI)	• Assesses the extent of living green vegetation. • Provides valuable insight into the health and/or growth of vegetation over time. • Supports the mapping of different land cover types across Australia	Geoscience Australia (2018c)
Intertidal Extents Model (ITEM)	• Information regarding the extent and relative elevation profile of the exposed intertidal zone (between the highest and lowest tide). • Complements existing data with a more realistic representation and understanding	Sagar et al. (2017); Geoscience Australia (2018d)
High and Low Tide Composites (HLTC)	• Mosaics produced to allow for visualization of the Australian coastline and reefs at high and low tides	Geoscience Australia (2018g)
Dynamic land cover dataset	• Nationally consistent and thematically comprehensive land cover reference for Australia	Geoscience Australia (2018h)

Source References shown in table

21.3.2 Implementing Projects to Enhance Take-up

The DEA platform enables anyone, anywhere, to use the data to inform better decision-making. The platform has the potential to contribute immediate and direct economic benefits to companies, organizations and individuals conducting feasibility studies and assessments, evaluations, monitoring and management activities. A number of high-impact projects have used this platform, and GA aims to increase its use by the wider community, including in regional and remote Australia. The spectrum of Geoscience Australia's current projects is illustrated in Table 21.2, synthesized from the Geoscience Australia Road Map (GA 2018).

21.4 Australian Use Case Examples

In this section, we highlight several use cases spanning agriculture, education and training, and disaster management, including initiatives within the capacity-building work of the ISDE Australia chapter research node. For each use case, we highlight the project objectives, lessons learned and opportunities going forward.

21.4.1 Agricultural Sector—FarmMap4D

The FarmMap4D (formerly known as the NRM Spatial Hub) property management planning platform demonstrates how world-leading time-series remote sensing of ground cover through an online interface can optimize grazing pressure and land conditions, and allow for land managers to make better, more informed decisions. Managers can use the product to view and overlay map layers and generate maps and reports to support more effective land management and planning.

This single source of information is accessed by project managers, contractors, and property managers. The Hub combines the latest geospatial mapping technologies with time-series satellite remote sensing of ground cover in a novel way. For the first time, the sheep and beef industries can use and compare their own data paddock data with government data in a consistent and interactive way, as illustrated in the screenshot of the interface in Fig. 21.6.

Russell-Smith and Sangha (2018) provide an overview of how FarmMap4D can be used to consider emerging opportunities for developing a diversified land sector economy in Australia's northern savannas.

Table 21.2 Current and future DEA projects

Project category	Key current projects	Future projects 'on the horizon'
Land cover & Land use	UN land cover classification system feasibility study Forest cover; Dynamic land cover dataset; Fractional cover; Review of current crop mapping approaches; Irrigated versus Nonirrigated crop extents; Water quality monitoring for sustainable development goals	Water observations from space, Sentinel-2; National intertidal digital elevation model; National wetlands extents map; National land use map integration with DEA; Irrigated versus Non-irrigated crop extents; Broad commodity type crop mapping; NEXIS enhancement; Land degradation Monitoring; NRM requirements analysis; Urban features; Groundwater-dependent ecosystems
Marine & Coastal	National mangrove mapping; Shallow water habitat mapping	Marine turbidity; Ocean color statistical summary; Sea surface temperature statistical summary; Coral bleaching; Coastal change characterization
Change detection	Current projects; Change detection for CER land projects; New approaches to statistical analyses of time series data; Burn extents	–
Analysis-ready data	Sentinel-2 surface reflectance; Landsat ARD Intercomparison and sensitivity analysis; Landsat surface brightness temperature; Surface reflectance validation; Aquatic surface reflectance; Observation density quality assessment; Improving the location accuracy of synthetic aperture radar	Sentinel-1 ARD; Himawari-8 ARD; Sentinel-3 ARD; MODIS ARD; VIIRS ARD; Climate Data; Evapotranspiration
Platform improvement	Automation and orchestration; Cloud storage drivers; Scalability and performance; Documentation; Science algorithm portability	–

(continued)

Table 21.2 (continued)

Project category	Key current projects	Future projects 'on the horizon'
Data visualization & Delivery	NEII viewer extension; Data publication governance; User experience design; ODC web services development; NCI web services development; GSKY services for national map	Virtual products Web processing Data dashboard
Data management	Collection Upgrade and transition analysis; Automation of the landsat processing pipeline; Cloud computing architecture pilot; Regional copernicus data hub development	Collection one upgrade (actual upgrade); DGGS support; DGGS implementation support; Near real-time landsat processing
Government engagement	Department of the environment and energy needs analysis; Tasmanian government transition to DEA	Interdepartmental grad program
Industry & community engagement	Industry and economic value strategy	FarmMap4D need analysis
International engagement	Support for the group on earth observations; Support for the committee on earth observation satellites; Support for regional development projects; Cambodia open data cube; Open data cube community development	–

Source Adapted from Geoscience Australia (2018)

21.4.2 Education Sector—Research Group (ISDE Research Node, Australia)

Griffith University's researchers (in Queensland) are working to connect digital-spatial ('place based') design and decision-making enquiry for resilient and regenerative cities, building capacity to collectively address planning and governance for future resilience in the face of unprecedented pressures (see Smith et al. 2010; Steffen et al. 2011), including climate change, population dynamics and resource scarcity. Building upon research and experience in sustainable development and engineering, the researchers draw on a strong multidisciplinary research capacity and strengths in educational pedagogy, rapid capacity building and education for sustainable development. The group includes educational and behavioral psychology researchers,

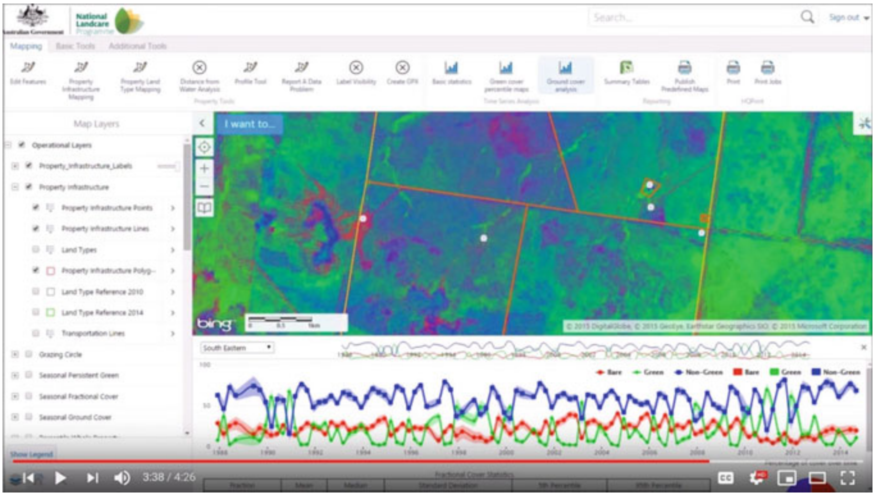

Fig. 21.6 Screenshot of the FarmMap4D interface (*Source* https://www.farmmap4d.com.au/)

industry-facing laboratory technical and management staff, and a growing team of doctoral (PhD) candidates.

21.4.2.1 Capacity-Building System

The Cities Research Institute (CRI) is collaborating with the International Water Centre (IWC) to create an innovative approach to capacity building for Digital Earth products and services, building on the IWC's success with the water modeling community in Queensland. With an aim of effectively disseminating Digital Earth knowledge and the benefits of use to the Australian professional community for business development and growth, the team is developing a 'Digital Earth Capacity System' through which participants can learn about new and emerging capabilities of Digital Earth globally and in Australia, as well as importance, relevance and applications, as illustrated in Fig. 21.7.

Participants engage with Digital Earth experts on trends and opportunities for Australian organizations and 'learn from doing' by working with Digital Earth Australia data to assess problems over time. The courses also include case studies of real examples of Digital Earth tools and applications that helped solve complex problems and enhance sustainability. It ranges from introductory courses to advanced support. Building on the data that has been created, participants develop the capacity to understand and use DEA data for applications including the development of evidence-based policies and developing visual aids for strategic decision-making.

Fig. 21.7 Illustrative photos of capacity-building environments within a community of practice context

The expected benefits for government collaborators include the following:

- Coursework being aligned with priority themes and focused on relevant topics
- Independent courses available to wider professional and public policy audiences
- Direct feedback from participants on the best ways to access and apply the tools
- Effective dissemination of knowledge and upskilling of the workforce to facilitate enhanced use of the available high-quality data.

Potential learning outcomes for participants include the following:

- Live interaction via remote immersive collaboration
- Practice in visualizing, interpreting and communicating big data sets
- The ability to engage in professional development from remote locations
- Remote, always-available access to learning resources about using products.

21.4.2.2 Remote Immersive Collaboration Spaces—DENs

The same group of researchers are prototyping two unprecedented cost effective and interactive “Digital Earth Node (DEN)” rooms, facilitating remote-immersive collaboration where the data itself stays local to the users (utilising image rather than data transfer) while collaboration occurs anywhere. In an increasingly connected world, it is a challenge to create virtual meeting spaces to facilitate deep thinking and decision-making that overcome the need to travel, where people can generate, harvest, interpret and share data as though they were physically side by side.

In response to this challenge and in liaison with colleagues in the International Society of Digital Earth (ISDE), ‘Digital Earth Node’ (DEN) engagement spaces have been designed to promote productive thinking and timely decision-making. The following paragraphs summarize the ‘preto-typing’ (i.e., conceptual) and ‘prototyping’ (i.e., pilot) undertaken to conceptualize, design and build the pilot facilities on two Griffith University campuses in Queensland, Australia, and connect them with other facilities elsewhere (see also Desha et al. 2018). The achievements to date are highlighted with regard to building the potential for immersive thinking environments, as well as next steps for future space development and refinement.

Smart visualization and communication are critical components of any effort to ensure that decision-makers have timely access to complex information and enable holistic problem solving. This has been documented by authors such as Van Wijk (2005) and the ISDE network (Goodchild 2010; Goodchild et al. 2012; Craglia et al. 2012; Roche 2014) and discussed within the geospatial and geo-design communities by seminal speakers including Dangermond (2010), Benyus (2014) and Scott (2017).

Table 21.3 summarizes the key differences that the research team have defined to date in the Digital Earth Node (DEN) rooms and other regularly used interactive video-conferencing tools and facilities. Essentially, the DEN rooms use readily available hardware that is also used for video conferencing, including web cams, audio feeds, touch screens and interactive technologies. However, a breakthrough in software has resulted in the software 'doing' the heavy lifting, resulting in almost no differences in the delay for the end-users and unprecedented flexibility in the extent of potential real-time editing and review.

A schematic of the room layouts is shown in Fig. 21.8. The individual room designs are mirrored as closely as possible to provide the user with an 'extended room' experience.

Table 21.3 Scope distinctions between conventional video conferencing and the DEN rooms

Video conferencing facility	Digital Earth Node (DEN) rooms
Interactive viewers	Immersive layout *with* interactive viewers
Remote connection "feels like you are really *there*"	Sense of proximity "feels like you are really *here*"
Catered to short interactions (usually up to 2 h)	Catered to long interactions (up to many hours)
Heavy hardware + share-screen software	Light hardware + heavy-lifting software

Source Desha et al. (2018)

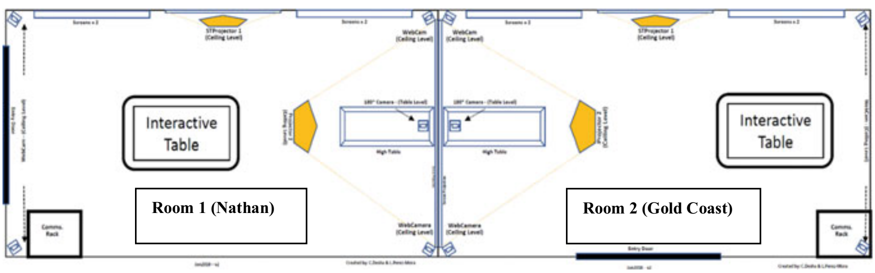

Fig. 21.8 DEN prototype configuration showing 'Room 1 (Nathan)' and 'Room 2 (Gold Coast)' (*Source* Desha et al. 2017)

Looking ahead, society must transition towards multidisciplinary and multinational approaches to address the planet's increasingly complex challenges. This requires a process change in collaboration around the world, without further impacting greenhouse gas emissions from the collaboration (primarily through travel). Considering the *Pivotal Principles* for such problem solving in the 21st century referred to in the Introduction to this chapter, the next logical step is to provide Digital Earth Node (DEN) facilities around the world that create 'remote but realistic' personal experiences between researchers and decision-makers to facilitate deep thinking and problem solving.

Efforts towards this end-goal include using the prototypes to inform the installation of a Disaster and Resilience Management Facility (DRMF) within a new building on Griffith University's Nathan Campus (Brisbane) by connecting the prototype DENs with ISDE chapters internationally and focusing on two primary research agendas to engage with the DEN rooms to explore how this technology and scientific knowledge could be harnessed for human and ecological wellbeing:

- Green infrastructure: Using nature and learning from nature to inform the design of resilient cities through analysis of geospatial data sets.
- Crisis communication in disaster management: using technologies to improve response times to optimize the allocation of resources.

We anticipate that this network of global nodes will connect academics, leaders and decision-makers around the globe in a fast, reliable and immersive manner. Colleagues around the world will be able to engage in pragmatic, real-time and rigorous enquiry into challenges and opportunities facing humanity, with application opportunities spanning sectors including education, research, emergency services, crisis management and global communication. This innovative network will be instrumental in developing spatial capabilities to catalyze human and planetary wellbeing. Such precedents of the possibilities will have immediate implications for deep-thinking engagement internationally and provide remote collaboration opportunities that are engaging and better for the planet.

21.4.3 Disaster Management—NSW Volunteer Rescue Association

With the reality that one minute can mean the difference between life and death, the New South Wales Volunteer Rescue Association (NSW VRA) has been exploring opportunities to make the most of existing 'state of the shelf' and emergent geospatial technologies to improve outcomes with regard to what is anecdotally referred to as, 'the right person and/or the right resources being in the right place, at the right time' (Desha and Perez-Mora 2018). This includes recognition that there may be associated critical infrastructure disruption during disasters that makes rescue more critical, including disabled communication networks, internet, and limited or no access to power. Such circumstances require creative solutions to manage the timely collation and exchange of conventionally ‘heavy’ data files such as video, photos, location-based mapping assistance and real-time or near-real-time management of large databases.

In 2017, the researchers were introduced to VRA personnel through the Griffith University EcoCentre. Inspired by the Digital Earth agenda and the work of researchers including Van Wijk (2005), Craglia et al. (2012), and Goodchild et al. (2012), they visited other researchers in Japan (Chubu University) and Europe (Joint Research Centre) to experience precedents and discuss possibilities for improving communication in disaster response.

Seeking a solution to these challenges, the researchers and their Digital Earth Node technical team have been working on developing software solutions to improve the way hardware is used and leased, including engaging researchers in different areas to generate better ways to use hardware in the form of a more efficient communication tool. In collaboration with the NSW VRA, data from a number of different sources have been collated and analyzed, including the organization’s database and historical anecdotal and solicited feedback from members of the volunteer community of professional volunteers and highly trained emergency management personnel. These data were used to ground-truth potential software solutions, allowing for the team to test solutions for improving the way personnel communicate in remote areas, how personnel deploy information and how personnel manage others in times of need.

Following software development, the first stage of deployment occurred in July 2018 when the team developed a software solution to improve the communication between executive managers and key decision-making personnel and their squads and squad members. This software now allows for the NSW VRA to collect data while in the field during a call out.

The data arising from deployment will be analyzed and processed to establish the next stage of this complex project, the deployment of a DEN (Digital Earth Node) remote immersive collaboration facility in regional NSW (Dubbo). This immersive tool will allow for decision making personnel to locate units or key personal in the field while they are being deployed during challenging times such as floods and bushfires. This will provide better ways to analyze what is happening in the field and aid in deployment of resources to the right locations at the right time. The system will also be able to track activities in real-time and with accuracy to ensure the safety of these professional volunteers.

The data will also be analyzed in an event block to enable a comprehensive report at the end of each incident response. Drawing on the analysis of the data collected by the DEN and devices in the field, the NSW VRA will be able to generate precise reports based on the human behaviors and decisions made. The findings will also allow for the Association to understand how they should improve the way they train their decision-making personnel and prevent mistakes during future events.

The research team is connecting with colleagues in international chapters of the International Society of Digital Earth (ISDE) to ensure that best practices are shared around the planet with other emergency management response teams. Thus, professional international expertise to fix unsolved or permanent challenges will reach remote areas of Australia. Ultimately, everyone, everywhere should have access to a fully comprehensive system that allows for our 'local heroes' to save more lives and provides them with the best safety approach during their high-risk activities.

21.5 Conclusions

This chapter highlighted achievements and opportunities for Australia considering three decades of data capture and enquiry, from local and largely champion-based ad hoc initiatives to mainstreamed integration and take-up globally. This included an historical exploration of practices and experiences in Australia arising from the need to manage local resources better, addressing the complexities of environmental stewardship. With regard to data management and interfaces for meaningful end-user engagement and enquiry, a number of initiatives stand out as exemplar projects for potential adoption elsewhere.

Australian current and future priorities were summarized through a text analysis of the Geoscience Australia roadmap, and two examples from the Australian ISDE chapter highlight the imperative of enhancing end-user take up of the Digital Earth technology through strategic capacity-building initiatives. The authors discussed the mechanisms and challenges of harnessing interoperable information in the form of geospatial data and through systems and processes to add value to the information. Considering these experiences, the benefits of open data and data sharing are realized through careful planning, design and integration, with a focus on upfront iterative design and end-user engagement. Releasing high-value data is an iterative process that requires collaboration and communication with agencies to show the benefits of open data and to support useful data sharing.

Reflecting on the history and examples provided, several 'turnkey' capability (workforce and market) considerations are summarized here for Australia's future and for non-Australians considering their own Digital Earth:

(1) ***Challenges in creating an active context for data use***: Decision-makers and researchers are currently grappling with how to harness the common repository to create saleable products (apps and APIs), where analytics is a well-established and supported opportunity for industry, beyond delivering funding for such initiatives via government grants (i.e., teaching the people how to fish).
(2) ***Challenges in capacity building beyond 'show-and-tell'***: In a rapidly emergent industry, it is critical to create the demand for products and services as well as build the capacity to deliver these goods and services. Trust is paramount in this process and must be prioritized when governments test and pilot products and services. There is a need for industry buy-in and for industry investors. In Australia, there is currently no public-private-partner (PPP) model in data adoption beyond advocating for industry to 'look how good the tool is.'
(3) ***Challenges in defining the job market and demand for the market***: In a country where the number of geospatial professionals is insufficient, capacity building is critical and must be addressed urgently (FrontierSI 2018). This includes public

and private sector considerations with regard to the types of skills required and the need for a capacity-building framework to aid in data utilization. We need to find demand for the market, potentially through the development of an active 'Community of Practice' across different key sectors, to enable more serious business workflow integration around technology, for example, for farm and water management.

In addition, several considerations relating to efforts and investments made on data and technologies are summarized:

(1) **Considering open source versus business continuity**: The initial version of the Queensland Globe was created using a Google open source platform, then could no longer be supported by Google. It took time for the Queensland government to find a reliable partner and Esri (proprietary software) was chosen to support the continuity of the project. In hindsight, a hybrid approach could take advantage of open source and proprietary platforms.

2) **Sharing knowledge within the context of an open source platform**: Despite progress, most end-users—whether government, business or citizens—do not have the knowledge and/or skills to find, download and use open data directly. This Digital Earth platform relies on a number of technologies and, although the code developed is open source, there is no community of practice to enable or coordinate technical expertise. Hence, coordination and capacity building are needed to help practitioners access and work with the data.

3) **Measuring the success of Digital Earth products**: This chapter provided numerous examples of products and the utilization of such products must be evaluated beyond the initial excitement and celebration of their existence. Ways to measure utilization are being explored, including conducting economic benefit analyses. Such metadata about utility is important to demonstrate value and ensure continued maintenance and updating of the Digital Earth Platform to meet the future needs of the community.

4) **Enabling access and utility remotely**: In a globally connected world, remote immersive collaboration has the potential to create communities of practice with reduced cost of travel and greenhouse gas emissions, in addition to ensuring data security in discussions and collaboration. This is particularly important when governments internationally are interested in using Australia's Digital Earth platforms to communicate decisions, upgrade infrastructure, and oversee the safety and wellbeing of citizens.

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Zaffar Sadiq Mohamed-Ghouse is the Chair of Australia Chapter of International Society for Digital Earth (ISDE) and a member of the ISDE Bureau. He holds academic appointments at UNSW and University of Melbourne, and is Executive Director at Spatial Vision. He provides strategic consulting to Governments in Australia, Asia and Middle East. He is the President of SSSI, Australia.

Cheryl Desha leads the 'Digital Earth and Green Infrastructure' theme, within Griffith University's Cities Research Institute (Queensland, Australia). Her team builds capacity for place-based, nature-inspired, and nature-loving urban development, towards cities where people and nature thrive. She is a Council member of the International Society of Digital Earth.

Luis Perez-Mora is the Data and Information Technology Logistics Manager in New South Wales' Volunteer Rescue Association (Dubbo), and an Adjunct Industry Fellow with Griffith University's Cities Research Institute (Queensland, Australia). He applies emergent technology, knowledge and skills to improving 'right time, right place' emergency response and emergency management.

Chapter 22
Digital Earth in China

Jiantao Bi, Yongwei Liu, Ainong Li, Min Chen, Ruixia Yang, Wenwen Cai, Yang Hong, Bingfang Wu and Cheng Wang

Abstract In the promotion of economic digitalization as an important force driving the realization of development through innovation, countries around the world have made forward-looking arrangements in frontier technology research and development, open data for sharing, privacy security protection, and personnel training. China also attaches great importance to the development of Digital Earth technologies and applications. In this chapter, we introduce the development of Digital Earth in China in recent years and provide readers a broad overview of Digital Earth technologies and applications in China.

Keywords Digital Earth in China · Big data · New generation information network · Internet + · Cloud computer · 5 Generation

22.1 Introduction

Research on technologies related to Digital Earth has been the focus of attention in fields such as science and technology, the economy and society. Many countries have raised Digital Earth and big data research to the national strategic level. In the promotion of economic digitalization as an important force driving the realization of development through innovation, countries around the world have made forward-looking arrangements in frontier technology research and development, open data

J. Bi (✉) · Y. Liu · W. Cai
Chinese National Committee, International Society for Digital Earth, Beijing, China
e-mail: bijt@radi.ac.cn

J. Bi · Y. Liu · R. Yang · B. Wu · C. Wang
Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China

A. Li
Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, China

M. Chen
Nanjing Normal University, Nanjing, China

Y. Hong
Peking University, Beijing, China

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for sharing, privacy security protection, personnel training and other areas. China also attaches great importance to the development of Digital Earth. In 1999, the first Digital Earth Symposium was held in Beijing, which began Digital Earth research all over China. In 2006, the Chinese National Committee of the International Society for Digital Earth (CNISDE) was established. As the national member of the ISDE, the CNISDE promotes the ISDE's ideals for national acceptance. Since 2006, Digital Earth has experienced high-speed development in China. Focusing on the development of Digital Earth in China caters to and promotes information technology development and acts as an endogenous driving force to promote economic transformation and upgrading as well as sustainable development.

22.2 China's Digital Earth Strategy and Policy

In recent years, the Chinese government has attached great importance to information technology development, especially for Digital Earth technologies. It has strengthened the top-level design and overall layout and made a strategic decision on building Digital Earth in China. Digital Earth is a new strategy for information technology development in the new era, a new measure to meet the people's growing demands for a better life, and a new driving force leading high-quality economic development. Digital Earth in China covers information technology construction in various fields such as the economy, politics, culture, society and ecology. In his congratulatory letter to the first Digital China Summit held in April 2018, President Xi Jinping noted that the information technology innovation in today's world is changing with each passing day, and in-depth development of digitalization, networking and intelligence plays an increasingly important role in promoting economic and social development, modernizing the state's governance systems and capabilities, and meeting the people's growing demands for a better life.

As Digital Earth development in China enters a peak period, the digital economy will also naturally add momentum to China's economic development. To speed up the development of Digital Earth in China, China will continue to improve the policy environment by formulating and introducing a series of policy documents on the development of Digital Earth in China. Information technology has become a major force for the government to serve the people and adds new momentum for economic development. The development of Digital Earth in China has brought changes to people's daily lives and the production of enterprises.

22.2.1 National Macro Strategic Plans for Digital Earth in China

In recent years, relevant departments in China have successively issued major strategic plans for national information technology development to indicate a road map and timetable for the development of Digital Earth in China and clarify that the general goal of Digital Earth development in the new era is to adhere to and achieve the synchronous promotion of the "Two hundred-years Goals" to fully support the development of the causes of the country, to promote balanced, tolerant and sustainable economic and social development and to provide solid support for the modernization of the national governance systems and capacities. The development plans note that China must adhere to people-centered development thinking and take the improvement of the people's well-being as the starting point and foothold for the development of Digital Earth in China, to better benefit the people. The three strategic tasks of Digital Earth in China are to greatly enhance the ability of information technology development, focus on improving the level of information technology development in economic and social fields and continuously optimize the environment for information technology development.

(1) ***"Broadband China" Strategy***. On August 17, 2013, the government of China issued the "Broadband China" strategy implementation plan and deployed the broadband development goals and paths for the next 8 years, meaning that the "Broadband Strategy" went from a departmental action to a national strategy, and broadband became the national strategic public infrastructure for the first time. By 2020, China aims to finish the construction of a high-speed and smooth broadband network infrastructure with advanced technology to cover urban and rural areas and offer convenient services.

(2) ***Outline of the National Information Technology Development Strategy***. The outline is a regulation formulated to promote modernization through information technology development and to build network power. The outline stipulates that, by 2020, the core key technologies will reach the international advanced level, the international competitiveness of the information industry will be greatly improved, the digitalization, networking and intelligence will make significant progress in key industries, the networked collaborative innovation system will be fully formed, e-government affairs will firmly support the modernization of national governance systems and capacities, and information technology development will become a leading force driving the modernization construction (The State Council 2016). The internet bandwidth for international export will reach 20 Tbps to support the implementation of the "Belt and Road" initiative and achieve network and information connection with neighboring countries. The China-ASEAN Information Port will be built and the online Silk Road will be established to significantly improve the international competitiveness of information and communication technologies and products and internet services.

(3) ***"Thirteenth Five-Year" National Information Technology Development Plan***. Aiming to implement the Outline of the Thirteenth Five-Year Plan and the

Outline of the National Information Technology Development Strategy, the plan is an important part of the "Thirteenth Five-year" national planning system and an action guide for information development work in various regions and departments during the "Thirteenth Five-year." It was issued and implemented by the government of China on December 15, 2016. The plan noted that by 2020, "Digital Earth" development will achieve remarkable results, the level of information technology development will rise sharply, the information capability will rank among the top in the world, and the information industry ecosystem with international competitiveness and security under control will be in place. Information technology and economic and social development will be deeply integrated, the digital gap will be significantly narrowed and the digital dividend will be fully released. Information technology development will fully support the causes of the government and the country, promote balanced, tolerant and sustainable economic and social development and provide solid support for the modernization of the national governance systems and capacities (Gov.cn 2016).

(4) ***Big Data Strategy***. Data are basic national strategic resources. China attaches great importance to the role of big data in economic and social development. The government proposed the "implementation of the national big data strategy" and the issued the Outline for Actions Promoting Big Data Development to fully promote big data development and accelerate data development to strengthen the state. The Big Data Industry Development Plan (2016–2020) was also formulated, proposing that the income from big data-related products and services will exceed RMB 1 trillion by 2020, with an average annual compound growth rate of approximately 30%; 10 internationally leading core enterprises in the industry of big data will be cultivated; 10–15 comprehensive big data pilot areas will be built; and 1–2 open source communities with standardized operation and an international influence will be established.

(5) ***Network Power Strategy***. The network power strategy includes three aspects, namely, network infrastructure construction, new development of the information and communication industry and network information security (Chen 2016). The proposal for the "Thirteenth Five-Year" Plan approved by the government proposed implementation of the network power strategy and the closely related "internet +" action plan. Accelerating the network power strategy has a direct effect in improving China's international competitiveness and contributes to the economic and technological development and transformation of China.

22.2.2 Policies and Plans for Development of Digital Earth in China

(1) ***White Paper on China's Digital Economy Development (2017)***. On July 13, 2017, the China Academy of Information and Communications Technology released the White Paper on China's Digital Economy Development (2017) at the 16th China

Internet Conference. The white paper noted that, in the next few years, China will deploy 5G, next-generation internet, the Internet of Things (IoT), industrial internet and other technologies on a large scale. With the construction of various network infrastructures and the application of related technologies, development of Digital Earth in China will enter a peak period. It will lay the foundation for development of the digital economy, industrial transformation and upgrading, and the integrated development of various industries in China (China Academy of Information and Communications Technology 2017).

(2) ***Action Plan for Promoting Large-Scale Deployment of Internet Protocol Version 6 (IPv6)***. On November 26, 2017, the government issued the Action Plan for Promoting Large-scale Deployment of Internet Protocol Version 6 (IPv6), proposing that in the next five to ten years, China will form a next-generation internet independent technology system and an industrial ecology, build the world's largest IPv6 commercial application network, realize deep integration and application of next-generation internet in various economic and social fields, and become an important leading force in development of the world's next-generation internet.

(3) ***"Internet +" Action Plan***. The development of the plan was led by the National Development and Reform Commission and the Ministry of Industry and Information Technology. China introduced and is still developing a series of policies for promoting innovative development of information technology and e-commerce. In the government work report on the two sessions in 2015, Premier Li Keqiang proposed the requirement of "developing an internet + action plan" to promote the integration of mobile internet, cloud computing, big data, and the Internet of Things with modern manufacturing and the sound development of e-commerce, industrial internet and internet finance as well as to guide internet companies to expand the international market (Ning 2015). Representing a new economic form, "internet +" supports industrial intelligence, enhances the momentum of new economic development and promotes improvements in quality and efficiency and the upgrading of the national economy.

(4) ***Three-Year Action Plan for Cloud Computing Development (2017–2019)***. In April 2017, the Ministry of Industry and Information Technology developed and issued the Three-Year Action Plan for Cloud Computing Development (2017–2019). The targets of the plan are for China's cloud computing industry to reach a worth of RMB 430 billion, make breakthroughs in a number of core technologies, achieve cloud computing service capability at an international advanced level and significantly drive the development of the new-generation information industry. The international influence of cloud computing enterprises will be significantly improved and two or three leading enterprises with a large share in the global cloud computing market will emerge. The capability of guaranteeing cloud computing network security will be significantly improved, and the network security supervision systems and laws and regulation systems will be gradually improved (The Ministry of Industry and Information Technology 2017).

(5) ***"Thirteenth Five-Year" Special Plan for Scientific and Technological Innovation in the Information Sector***. The special plan formulated the implementation plan for "Scientific and Technological Innovation 2030—Major Projects" and started

the implementation of major new-generation artificial intelligence projects (Gov.cn 2017). It steadily promoted major projects such as the space-terrestrial integrated information network and big data and launched the IoT and smart city initiatives, broadband communications, new types of networks and other key projects (The State Council 2015). China will accelerate the implementation of the Outline for Promoting National Integrated Circuit Industry Development and advance system innovation in the information industry. The core technology innovation in the information field will illustrate the new situation of catching up with the leaders at a faster speed, more shoulder-to-shoulder development and new leaders emerging.

22.3 Infrastructure for Digital Earth in China

The development of Digital Earth in China is inseparable from the support of network and information technology. The development of the entire infrastructure and related digital technologies is of great significance to the development of Digital Earth in China.

Currently, relevant new technologies, such as 5G, IPV6, cloud computing, big data and artificial intelligence, are continuously being applied in the infrastructure of Digital Earth in China. Related technologies including artificial intelligence, cloud computing, big data, and blockchain are also developing rapidly. China has introduced many new related policies, and many industrial alliances have been formed to add new impetus to Digital Earth in China. The infrastructure construction manifested as follows:

(1) ***Deployment of New-Generation Information Network Technology***. 5G network technology has made important breakthroughs in R&D, testing and verification (Fig. 22.1). In the implementation of the national major science and technology project “new-generation broadband wireless mobile communication network,” the design and R&D of a 3Gsps 12-bit ADC/DAC, PA, a wide-area hot-spot baseband chip and a low-delay baseband chip was completed, and the R&D of key technologies such as the 5G core network and ultradense networking based on SDN/NFV is being advanced. 5G R&D and testing work is advancing rapidly; the first batch of specifications for the third phase of testing has been released and the development of the global unified 5G standard is being promoted. The bearing and capacities of the radio and television networks have been improved. The two-way access strategy for radio and television and telecommunications services is being promoted throughout the country. The second stage of an experimental pilot of the cable, wireless and satellite integration network for radio and television is being advanced at a faster speed, and the experimental technology solution and establishment of three standards for the integration network in 11 provinces have been approved. The number of China’s IPTV users has reached 122 million. IPv6 is evolving comprehensively and being upgraded at a faster speed. The implementation of the Action Plan for Promoting

Fig. 22.1 5G network framework (from http://www.freep.cn/zhuangxiu_6/News_1937545.html)

Large-scale Deployment of Internet Protocol Version 6 (IPv6) accelerated the construction of next-generation internet with high speed, wide popularity, full coverage and intelligence.

(2) ***Innovative Construction of Cloud Computing Infrastructure***. The implementation of Opinions on Promoting Innovative Development of Cloud Computing and Cultivating a New Format of the Information Industry and the Three-Year Action Plan for Cloud Computing Development (2017–2019) in China has promoted the popularization of cloud computing applications, optimized the layout of cloud computing data centers, enhanced the usage rate and intensification level, and formed an industrial system with international competitiveness. Breakthroughs have been made in key technologies such as large-scale concurrent processing, massive data storage, and data center energy conservation. Cloud computing platforms with international competitiveness have emerged, such as Alicloud's Apsara platform, Baidu Brain and the WeChat open technology platform. In 2016, the proportion of large and ultralarge data centers increased to 25% from less than 8% in 2010. There are 295 enterprises with large data centers and cross-regional internet data services. The Internet of Things has been deeply integrated, and the pace of generic application has been sped up. The R&D and deployment of NB-IoT are being sped up, and China Telecom has built the world's first commercial NB-IoT network with the widest coverage and synchronous upgrading of the entire network of 310,000 base stations. The NB-IoT technology solution proposed by Huawei has been approved by 3GPP and become an international standard. The NB-IoT is being expanded to public facilities management, production and life at a faster speed to accelerate the intelligent transformation of power grids, railways, highways and other infrastructure.

(3) ***Localization of the GIS Platform***. During the development of Digital Earth in China, geographic information systems (GIS) have played a very important role in promoting Digital Earth in China. After 30 years of hard work, China's GIS

technology has made remarkable achievements. In the early stage of Digital Earth development, it was mainly based on two-dimensional visualization applications and lacked three-dimensional analysis capabilities. In response to the demand of Digital Earth in China, China has proposed and developed GIS technology that integrates two and three dimensions to gradually form the GIS software covering data models, scene modeling, spatial analysis and two- and three-dimensional software forms. With the development of data acquisition technology, Digital Earth in China has integrated traditional 3D modeling, oblique photography, laser-point clouds, BIM and other three-dimensional technologies based on two- and three-dimension integration technology to develop the new-generation three-dimensional GIS technology, which has realized three-dimensional modeling of multisource heterogeneous data, object-level 3D spatial analysis and visualization of nonvisual information, extending the research scope of Digital Earth in China from the Earth's surface to the entire space. Three-dimensional spatial data specifications have been formed to solve the sharing and interoperability problems inherent in such heterogeneous data in applications to bring real and convenient 3D experience to digital applications. Cloud GIS technology and cloud computing have greatly improved the data resources and computing resource capabilities of Digital Earth in China and expanded its range of applications. Cloud GIS technology has realized the interconnection and intercommunication of information and functions between cloud GIS (servers) and various terminal GIS (desktop GIS, mobile GIS, WebGIS), making applications and services ubiquitous. A client (such as WebGL) that is as thin as possible can also be used advantageously in cloud computing to reduce the client installation and maintenance costs in digital applications. As a result, the network-based intergovernmental and interdepartmental collaborative development of the "Digital Belt and Road" will be promoted.

As the "GIS core" for software platform construction in Digital Earth infrastructure, China's GIS basic software represented by SuperMap GIS has played a unique role. Through multisource heterogeneous data integration, it integrates, shares, analyzes, manages and mines data, and ultimately serves global change research, disaster reduction and prevention, new energy development, new urbanization, and agricultural food safety to aid in the development of Digital Earth in China.

(4) ***The Big Data Platform***. Big data has begun to significantly influence global production, circulation, distribution, and consumption patterns. It is changing humankind's production methods, lifestyles, mechanisms of economic operation, and country governance models. Big data occupies strategic high ground in the era of knowledge-driven economies, and it is a new strategic resource for all nations (Guo 2017).

In an initiative led by Guo Huadong, president of the Committee on Data for Science and Technology (CODATA) of the International Council for Science (ICSU), CODATA has worked with other international science organizations and initiatives to explore the value of big data in scientific research and to reinforce the crucial role of science in the development of big data. After the June 2014 "International Workshop on Big Data for International Scientific Programmes: Challenges and Opportunities" sponsored by CODATA in Beijing and cosponsored by the ICSU World Data System, Future Earth, Integrated Research on Disaster Risk, the Research Data Alliance, the Group on Earth Observations, the International Society for Digital Earth, and the Chinese Academy of Sciences Institute of Remote Sensing and Digital Earth, CODATA and others developed a joint statement of recommendations and actions [6]. This statement emphasized providing a better understanding of big data for scientific research, and strengthening international science for the benefit of society by developing research, policies, and frameworks related to big data. Since then, a series of meetings on big data for science has been organized or coorganized by Guo's research team. These have included the "Xiangshan Science Conference on Frontiers of Scientific Big Data," "The Academic Divisions of the Chinese Academy of Sciences Forum on Frontiers of Science and Technology for Big Earth Data from Space," and the "Exploratory Round Table Conference on Big Data in Natural Sciences, Humanities and Social Sciences." It is our opinion that scientific big data will play a key role in promoting scientific development (Guo 2017).

22.4 China's Experience in the Development of Digital Provinces and Cities

Digital cities refer to the use of spatial information to build a virtual platform that acquires and loads information such as that on natural resources, social resources, infrastructure, culture, and economics of provincial units or city units in the digital form to provide a wide range of services for governmental and social users to improve city management efficiency, save resources and promote the sustainable development of cities.

22.4.1 Digital Fujian

In 2000, when President Xi Jinping was in the position of governor of Fujian Province, China, he initiated the "Digital Fujian" project. He clarified the development connotation and development mode of "Digital Fujian" and proposed the development goal of being "digital, networked, visualized and intelligent." In 2001, the "Digital Fujian" Plan was launched, including one plan ("Digital Fujian" Tenth Five-Year Plan), three projects (Fujian Public Information Platform, Fujian Government Information Network Project and Spatial Information Research Center of Fujian) and one policy (Fujian information sharing policy). Fujian began to build three basic supportive platforms: a unified government affairs network, an information exchange system and an information security system to realize facilities sharing, platform sharing and data sharing, which established the overall framework of "Digital Fujian." Over the past 18 years, "Digital Fujian" has drawn up four five-year special plans using the top-level design as the guiding ideology for the overall coordination and planning of the information technology development of the whole province, to ensure that the construction of "Digital Fujian" moves forward in a phased, focused and orderly manner.

With the top-level design plan and long-term plans as guides, Fujian Province has advanced the construction of "Digital Fujian" in an orderly manner through the development goals, frameworks, mechanisms and development ideas that were determined in the initial years. The construction of "Digital Fujian" is close to people's livelihood, enterprises and society. The e-government practice of "Digital Fujian" comprises the joint development and sharing of data in all government systems, acceleration of the digital upgrading of tourism, transportation, taxation, medical treatment, education systems and other areas of people's livelihood, and reducing the "multiple leadership" in e-government. The new ideology makes "Digital Fujian" a new model that benefits the people. By 2020, the digital economy of Fujian will exceed RMB 400 billion with an annual growth rate of over 20% and a proportion of over 45% of the GDP, forming a development pattern with advanced digital infrastructure, efficient e-government collaboration, integrated and innovative digital economy and a secure, independent and controllable network and information, realizing the goal of being "digital, networking and intelligent." Fujian will actively promote the establishment of the Digital Earth Core Technology Industry Alliance, add to "Belt and Road" digital economy development funds and Digital Earth development funds, speed up the construction of a number of new smart city platform projects, strengthen organizational leadership, and optimize the development environment.

22.4.2 Digital Hong Kong and Digital Macao

The construction of Digital Earth has penetrated China's economy, society, and people's lives and has resulted in remarkable achievements in improving government management, promoting industrial development and serving people, especially the construction of Digital Hong Kong and Macao.

(1) ***Development History***: The government has been the main promoter of digital city construction and actively supports the digital development of cities. Since 1990, the Hong Kong government has spent 6 years establishing the first large land information system using geographic information systems (GIS) technology in Hong Kong and successfully applied it to land usage, cadastral maps and town plans. In 2009, the Hong Kong Transport Department launched a transport information system based on a central database, which provides four major services: a road traffic information service, Hong Kong eRouting, Hong Kong eTransport and an intelligent road network. In addition, the Hong Kong Lands Department is actively expanding smart city infrastructure and environmental detection applications based on mobile measuring vehicles.

In 2000, the government of the Macao Special Administrative Region (SAR) officially launched an environment geographic information system, which was jointly developed by the Cartography and Cadastre Bureau and Macao Environmental Protection Bureau (DSPA). The system draws a mathematical model to study the environmental conditions and perform evaluations through the comprehensive collection and analysis of existing and new environmental data in Macao, providing services for the urban environment quality evaluation, natural resources analysis, city planning, emergency warning systems and disaster assessment. In addition, to facilitate citizens' access to information on historical urban areas and cultural property reserves, the Macao Cartography and Cadastre Bureau launched the local Cadastral Information Network to include historical heritage and cultural conservation information, contributing to the protection of Macao's historical, cultural and architectural property.

(2) ***Preliminary Results***: At present, the construction of Digital Hong Kong and Macao has resulted in many achievements, covering disaster monitoring, urban construction, residents' lives, government management and other aspects.

On August 4, 2017, the Macao SAR signed the Framework Agreement on Strategic Cooperation in the Construction of a Smart City with the Alibaba Group. The government of Macao SAR will make full use of Alibaba's relevant leading technological capabilities, such as cloud computing and the application of big data, to promote the pace of the construction of a smart Macao, to widen the context of the SAR data, improve the modes of economic and social operation, and promote the development of the smart city. In the long term, Macao will be developed into a smart city that is "leading technology by digital development and serving people's livelihood with intelligence."

The construction of Digital Hong Kong and Macao show a good trend of "connecting every place and everything, handling everything on internet, and innovating every business." With the advances in technologies including cloud computing, big data, and the IoT, the deepening cooperation between the government and high-tech companies, the integrated development of different smart platforms, and the continuous improvement of the strategic guarantee system for integrated ground and air information technology, Digital Hong Kong and Macao will develop further and play a more important role in promoting urban economic development and improving the quality of life of urban residents.

22.5 Development of Digital Earth Applications in China

The wide application of Digital Earth technology has resulted in significant and far-reaching impacts on various economic and social areas in China. With the development of LiDAR, microwave and multispectral remote sensing technologies, great progress has been made in Digital Earth applications in China. The applications can be summarized in three aspects.

22.5.1 Digitalization: Drawing and Depicting China

To "Draw and Depict China with Digital Earth Technology" means to use digital technology to summarize and present the phenomena and laws that exist but are difficult to find using traditional administrative and technical means. Regardless of whether digital technology is used or not, these phenomena or laws exist objectively, but it is difficult to find or describe them without digital technology.

(1) ***Big Earth Data for Digital Earth***. "Big Earth data" is a fundamental aspect for Digital Earth. Big Earth data, including the huge datasets derived from satellite observations, ground sensor networks, and other sources, are characterized as being massive, multisource, heterogeneous, multitemporal, multiscale, high-dimensional, highly complex, nonstationary and unstructured. It provides support for data-intensive research in the Earth sciences (Guo 2017).

As an example, global change research demands the systematization of the Earth and comprehensive observations and has led to the rapid development of ground observation technology. Modern Earth science requires globally established, quasi-real time, all-weather Earth data acquisition capabilities and has developed an integrated space-air-ground observation system with high spatial, temporal, and spectral resolutions. Global change research focuses on global sustainable development and deals with key multidisciplinary challenges, including global change process monitoring, simulation analysis, and response strategies. These studies rely on big Earth data such as long-term, multispatiotemporal Earth observation data, accurate, continuous ground station observation data, and experimental data based on theoretical speculation and estimations. Therefore, big Earth data can provide a new approach to the development of global change research. As a tool in cross-disciplinary research, big Earth data has the potential to provide a virtual Earth that can be used in the Earth sciences and has close relations to information science, space science, technology, the humanities, and the social sciences. Generally, big Earth data include the main features of big data.

(2) ***Digital Agriculture***. "Digital agriculture" refers to intensive and information-based agricultural technologies supported by geoscience space and information technology. As an important symbol of agriculture in the 21st century, the development of "digital agriculture" and related technologies is an inevitable choice to support the development of modern agriculture in China.

One of the outstanding manifestations of the applications of information technology is the application of the Digital Earth platform in the field of digital agriculture, in breeding, crop growth, farmland management, and agricultural information (Meng et al. 2011). With the rapid development of Earth observation technology, research on and application of "digital agriculture" has been gradually deepened, providing more diversified information for digital agriculture and promoting the comprehensive development of agricultural information technology (Li 1992). In China, Digital Earth technology is widely applied in the acquisition of farmland plot information, agricultural measures, farmland environments and other information and has been successfully applied to monitor crop growth, soil moisture, crop water stress, crop nutrients, and crop disasters and in the estimation of the per unit yield of crops and agricultural irrigation guidance. Digital agriculture plays an important role in Chinese food security (Wu 2004).

22.5.2 Digitalization to Make China Different

"Digitalization to make China different" refers to a series of changes in the way that society operates and how people live through the extensive use of digital technology. "Digital Earth in China" has gradually led to revolutionary changes in people's daily behaviors and communication methods, allowing for people to enjoy the digital dividend.

(1) ***Disaster Monitoring and Prevention***. Digital disaster reduction technology has integrated the advantages of remote sensing, GIS, navigation systems, mobile terminals, and the internet and other technologies to comprehensively acquire and analyze disaster information. Compared with the traditional observation methods, the rapid, accurate and macro acquisition of information by digital disaster reduction technology using Earth observation technology, which is its core constituent technology, has played an irreplaceable role due to its all-weather, all-day, multiangle and highly efficient performance.

At present, digital disaster reduction research has abundant aerospace observation data sources, but there is an urgent need to develop the ability to quickly identify knowledge and obtain effective disaster information from massive data. With the advent of the era of big data, cutting-edge disaster reduction technology supported by big Earth data has brought new opportunities for the development of China's research on digital disaster reduction. It is expected to make breakthroughs in the bottleneck problem of open data for sharing. By integrating remote sensing satellite data, aviation monitoring data, navigation positioning data, ground survey data and social statistics data, integrated analysis of interdisciplinary and multitype disaster reduction data can be accomplished through the big Earth data platform to reduce the time cost of carrying out collaborative analyses of disasters based on multisource data and improve the ability to rapidly mine disaster information.

(2) ***Monitoring and Protection of Natural and Cultural Heritage***. Digital heritage refers to the applications of digital technology with spatial information technology as the core in the fields of cognition, protection and utilization of cultural and natural heritage. The applications of remote sensing, GIS, modern measurement technology and VR technology in the fields of heritage discovery, protection, display and utilization are the key endeavors. Entering the 21st century, digital heritage has entered a fast lane. Relevant national projects are being carried out one after another, such as the national project on exploring the origin of Chinese civilization and monitoring of the Chinese Grand Canal and Great Wall. In 2016, Guo Huadong established a "Protection and Development of Natural and Cultural Heritage Along the Belt and Road" project in the Digital Belt and Road (DBAR) research initiative. In 2017, a research team led by Bi Jiantao went deep into the Angkor Wat and Preah

Vihear temples in Cambodia to implement the monitoring and protection of natural and cultural heritage and realized the acquisition and modeling of centimeter-level 3D architectural cultural heritage data in a country along the Belt and Road for the first time. In 2018, a research team led by Wang Xinyuan found 10 archaeological sites of ancient Rome in Tunisia. The continuous implementation of these projects marks the beginning of a new development stage of digital heritage research.

(3) ***Applications in the Digital Mountain Field***. As a scientific subset and application example of Digital Earth, digital mountain research is the unification of spatial information methods and tools for mountain science research and integrated mountain management. It provides reliable basic data, analyzes solutions and simulates lab environments for mountain research through the integration of data, models, and analytical methods. Recently, a new phase of progress has begun in fields such as mountain cover mapping, digital terrain analysis and digital watershed construction. The development of the digital mountain observation and experiment platform needs to comprehensively consider the terrain gradient, vegetation gradient and multiscale nested observation methods to build a ground-air-space three-dimensional observation system with the help of UAV remote sensing platforms, to obtain multisource and multiscale surface observation data sets to support breakthroughs in mountain remote sensing theory and application research on digital mountain science.

(4) ***Research and Education***. Since the beginning of this century, China has established institutes, national and provincial key laboratories, and companies relevant to Digital Earth and Digital China. These include the Institute of Digital China, Peking University (IDC-PKU), founded in 2004, and the Beijing Key Laboratory of Environmental Remote Sensing and Digital City, founded in 2002. China has also hosted symposiums, summits, and workshops to discuss topics relevant to Digital Earth and Digital China, such as the Digital China Forum organized by PKU held annually from 2004 to 2018.

China has developed Digital Earth-related education activities for undergraduate students, graduate students and teenagers. Universities offer courses covering Digital Earth and Digital Cities, such as ‘Introduction of Digital Earth’ at Peking University (PKU) and ‘GIS and Digital Earth’ at Zhejiang University. Institutions and universities also offer large public science popularization activities for Digital Earth. For example, the Institute of Remote Sensing and Digital Earth (RADI) has ‘Poster Walls’ to show the development of Digital Earth technologies in China; the China Association for Science and Technology (CAST) and PKU host the annual ‘BeiDou Cup’ Youth Science Creation Competition to award achievements in the ‘BeiDou Navigation Satellite System (BDS) and Digital China’ field. Textbooks about Digital Earth have been published by professors from universities since the 1990s, and a variety of popular science books have been published since the beginning of the 2000s.

(5) ***Digital Geographical Names***. The public service project regarding geographical names includes four tasks: geographical name specification, geographical name marks, a geographical names plan and digital geographical names. The digital geographical names project comprises the informatization of geographical name services. The construction of geographical name information services can further

enhance the scientific and standardization level of geographical name management and achieve multidata collection. The rational use of these data and the development of various geographical name information services will transform such resources into enormous social and economic benefits. Digital geographical name technology makes full use of electronic maps, remote sensing images and other technical means in the field of Digital Earth and expands the use of the internet, big data and other technical methods to achieve the combination of geographical name information, map imagery, geographical name query and statistical analysis.

Relying on the geographical name database, telecommunications technology, the internet and other media will be used for a geographical name informatization service via a toponymic website, toponymic hotline, toponymic disc (electronic map), and a toponymic touch screen as the main contents to realize the sharing of geographical name information with all of society. The public can obtain accurate geographical name information quickly, conveniently and in a timely manner.

22.5.3 Digitalization to Drive and Promote China's Development

"Digital Earth to drive and promote China's development" means the essential improvement of production modes, production efficiency and product quality brought by the application of digital technology in the field of spatial information technology. In addition to the extensive application of digital technology in auxiliary aspects such as R&D, management, marketing, warehousing and logistics, an increasing number of technologies such as the IoT, artificial intelligence, industrial internet and industrial robots have been directly introduced into production to enable improvements in the production of enterprises and to provide a solid foundation to guarantee personalized customization and intelligent manufacturing. Currently, China is vigorously promoting "Made in China 2025" and "building a manufacturing power." This is a key direction of research and promotion of the ISDE Chinese National Committee to study how to strengthen the role of digital technology in the process.

(1) ***Digital New Technologies, New Industries, New Formats and New Models Are Constantly Emerging***. In 2017, China's digital economy reached RMB 27.2 trillion, showing a yearly growth of 20.3% and accounting for 32.9% of the GDP, and became an important engine to drive economic transformation and upgrading. The electronic information manufacturing industry, software and information services industry and communications industry continued to develop rapidly. In 2017, the information industry had a revenue of RMB 22.1 trillion, showing a yearly growth of 14.5%. In 2017, China's information consumption increased to RMB 4.5 trillion, a yearly growth of 15.4%, which was approximately twice the growth rate of final consumption during the same period. It accounted for 10% of final consumption and contributed more than 0.4% to GDP growth. The overall strength and global competitiveness of the network and information technology enterprises in China

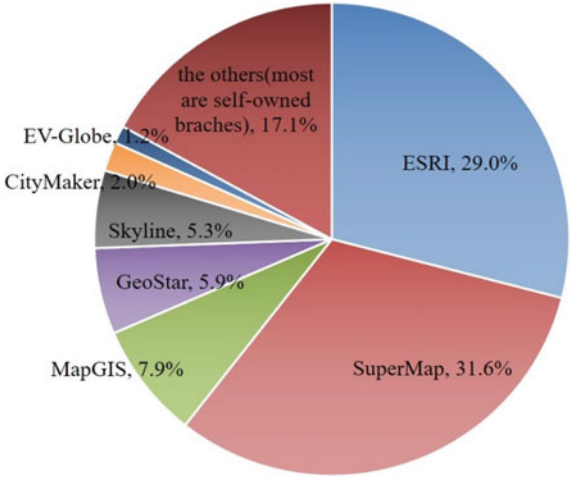

Fig. 22.2 GIS software market share in China (2015)

have been continuously improved (see Fig. 22.2), and seven internet enterprises rank among the top 20 in the world in terms of their market values.

(2) ***Digital Information Technology Promotes Changes in the Quality, Efficiency and Power of Economic Development***. The Guiding Opinions on Deepening the Integrated Development of the Manufacturing Industry and Internet and the Guiding Opinions on Deepening "Internet + the Advanced Manufacturing Industry and Developing Industrial Internet" have been implemented to promote the in-depth integrated development of the manufacturing industry and the internet. The implementation has been defined by software, driven by data, supported by platforms, added value to services and led by intelligence (Figs. 22.3 and 22.4). With the rapid development of industrial internet, a number of industrial applications for complex products such as high-speed trains and wind power have been developed and initially achieved commercialized applications. The pace of rural and agricultural information technology has been obviously sped up by fully implementing the project to deliver information into villages and households and offer services for the convenience of 233 million people. A number of demonstration templates for digital agriculture have been created to continuously improve intelligent agricultural production, business based on networks, and online services. "Internet + convenient transportation" has been promoted at a faster speed to develop intelligent transportation and facilitate passenger travel. A national transportation and logistics public information platform has been built and improved to promote the sharing of logistics information and promote cost reduction and efficiency improvements in logistics.

(3) ***E-government Has Been Advanced***. At the national level, the National General Plan for E-government was released to establish an overall coordination mechanism for national e-government, organize the implementation of national comprehensive e-government pilots, deepen the applications of e-government and explore the

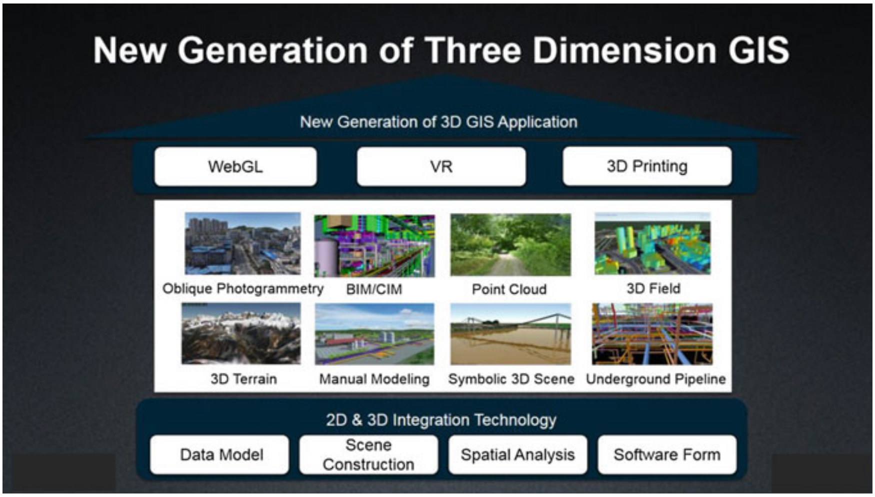

Fig. 22.3 The new generation of 3D GIS technology

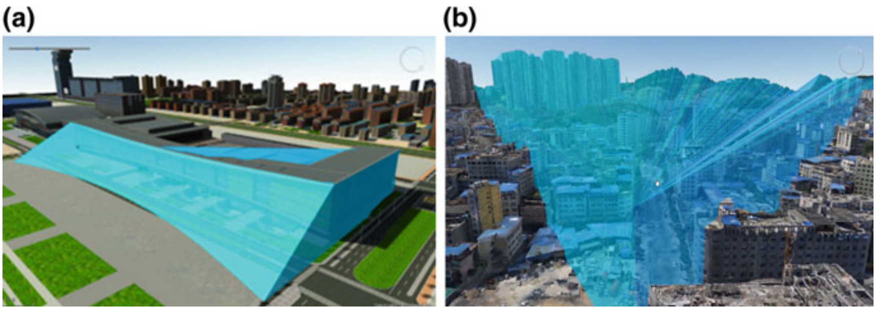

Fig. 22.4 Using a 3D entity model to describe abstract 3D objects: **a** 3D of shadow, **b** 3D of visibility

development of a comprehensive e-government pilot to promote the modernization of national governance systems and capabilities.

The government of China issued the Implementation Plan for the Integration and Sharing of Government Information Systems to accelerate the integration and sharing of government information systems, promote network communication, data communication and business communication, and continuously extend e-government services to the grassroots governments. E-government media have flourished. Party and government organizations and group organizations at all levels actively use Weibo, WeChat, other clients and new media to publish government affairs information, respond to social concerns, provide convenient services and promote collaborative governance, creating effective platforms for building an online and offline community and practicing the government's mass line. Public security organizations have accelerated the application of new technologies and continuously improved their ability and level of prevention and control, mass service, and social governance. The construction of the social credit system has achieved remarkable results. The national credit information sharing platform has been linked to 39 ministries and commissions and all provinces, autonomous regions and municipalities. The total amount of credit information collected has exceeded 6.5 billion items, and the system of joint punishment for dishonesty and joint incentives for honesty between departments has been improved.

(4) ***Information Services to Benefit the People and Add Convenience***. To develop the network and information technology businesses, it is necessary to implement people-centered development thinking. Regions and departments should regard information technology as an important means to safeguard and improve people's livelihood and should vigorously develop information services such as online education, telemedicine, network culture, "internet + public legal services" and "internet + public security" so that people can have a greater sense of gain in terms of sharing the results of internet development.

"Internet + education" expands the coverage of high-quality education resources. Significant progress has been made in the construction and application of the "three accesses and two platforms (network access for each school, resource access for each class and space access for each person, and the educational resource service platform and the educational management service platform)," the level of educational information technology has been significantly improved, and the promotion mechanism for the participation of all society has been continuously improved. Applications benefiting the people have been rapidly popularized. The interconnection of national transportation cards has been advanced rapidly. China has actively promoted the model of "internet + public security" and built the "internet + government service" platform for public security to improve the service efficiency and extend the service range. Many areas have expanded applications in other government public service areas including resident health, civil assistance, and financial subsidies, and initially established a mechanism for the coordination and sharing of pension services and community services.

(5) ***International Cooperation in the Digital Economy***. International cooperation in the digital economy has become a new highlight. China has promoted the launch of the G20 Digital Economy Development and Cooperation Initiative and the Initiative for International Cooperation in "Belt and Road" Digital Economy, actively promoted negotiations on nearly 20 e-commerce topics of free trade agreements such as regional comprehensive economic partnerships, deepened pragmatic cooperation in cyberspace, and promoted the joint construction and sharing of the Digital Silk Road. The system for serving enterprises that work overseas has been continuously improved. The channels for acquiring overseas enterprise information services have been expanded, and the release of early warning safety information has been strengthened. The "Belt and Road" big data service system has taken shape to actively provide effective information and services for relevant enterprises, organizations and individuals involved in construction of the "Belt and Road".

22.6 Summary

The goal of building Digital Earth in China is to provide crucial information technology and support resources for promoting China's economic, political, cultural, social and ecological civilization construction progress. The Chinese government has attached great importance to and strengthened the top-level design for long-term planning and specific implementation steps for Digital Earth in China. With the rapid development of basic theory and innovations in common key technology and information infrastructure in spatial information technology, Digital Earth in China has experienced explosive development, such as in digital agriculture, digital disaster reduction, and digital heritage. Digital Earth in China has been a model for the digital economy in some countries but not in other countries. This may be due to several reasons, but the social system and government organization are important aspects for the rapid development of Digital Earth in China. Although it has been successful, there are also many problems regarding the future development of Digital Earth in China, such as privacy, politics, possible access to government data by the public and data sharing. The Chinese government must work to overcome these issues and continue to focus on the development of Digital Earth in China

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Jiantao Bi is a Professor in Sanya Research Center of the institute of Remote Sensing and Digital Earth, CAS. He researches geographic information systems, data sharing and geographic information standards. He was the vice secretary-in-chief of ISDE Chinese National Committee.

Yongwei Liu is a professor in Remote Sensing at the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. His major focus is on the research, management and strategic planning of remote sensing technology. He has participated in the writing of "The Development Trend of Space Earth Observation", "The International Frontier of Earth Observation and Digital Earth", "Research on Hainan Commercial Space Development Strategy", etc.

Ainong Li is a professor and director of the Digital Mountain and Remote Sensing application, Institute of Mountain Hazards and Environment, CAS. His main research interests focus on mountain remote sensing and Digital Mountain. He is also the director of the Digital Mountain Committee, Chinese Committee of International Society of Digital Earth (CNISDE).

Min Chen is a Professor and the Vice Director of Key Lab of Virtual Geographic Environment (Ministry of Education of PRC), Nanjing Normal University, China. His research interests are geographic modeling and simulation, virtual geographic environment. He is the executive editor of Annals of GIS and an editor of Environmental Modelling & Software.

Ruixia Yang is an Associate Professor in Digital Natural and Cultural Heritage at the Institute of Remote Sensing and Digital Earth, CAS. Her research field focuses on digital environmental archaeology and geographical information technique for conservation of natural and cultural heritage.

Chapter 23
Digital Earth in Russia

Yuri M. Baturin, Valentina T. Dmitrieva, Eugene N. Eremchenko, Lyudmila V. Massel, Oleg A. Nikonov, Alexei A. Romanov, Vladimir S. Tikunov and Alena A. Zakharova

Abstract A brief overview of the history of Digital Earth in Russia, its current status and prospects for further development are proposed and discussed in this chapter. The anticipation of the concept of Digital Earth in Russian culture is demonstrated and explained. Conclusions about the specificity of the development of the concept of Digital Earth in Russia due to its geographical, historical and cultural characteristics are drawn, and development factors are revealed. The vital need for the concept in ensuring the effective governance and sustainable development of the country is emphasized. Theoretical and applied results achieved by the Russian Digital Earth community are presented. Special attention is paid to the outreach of the Digital Earth vision to state governance, business, society and education. The key importance of international cooperation for the successful implementation of Digital Earth in Russia is explained.

Keywords Digital Earth · Russia · Precursor · Sustainable development · Neogeography · Effective governance

Y. M. Baturin
S.I. Vavilov Institute for the History of Science and Technology, Moscow, Russia

V. T. Dmitrieva
Institute of Natural Sciences and Sports Technologies, Moscow City University, Moscow, Russia

E. N. Eremchenko (✉) · V. S. Tikunov
Geography Department, Lomonosov Moscow State University, Moscow, Russia
e-mail: eugene.eremchenko@gmail.com

L. V. Massel
Melentiev Energy Systems Institute, Irkutsk, Russia

O. A. Nikonov
'VNIIEM Corporation' JC, Moscow, Russia

A. A. Romanov
JSC «TsNIIMash», Moscow, Russia

A. A. Zakharova
Bryansk State Technical University, Bryansk, Russia

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23.1 Introduction

As a new geospatial principle and interdisciplinary research area, Digital Earth addresses the most fundamental problems of concern to all mankind—ensuring precise decision making, sustainable development, and efficient use of limited resources. These problems are particularly evident in large and diverse countries such as Russia. Two main factors determine the strong interest in the concept of Digital Earth in Russia. The first factor is the vastness. From a geospatial point of view, Russia is a big landmass with extremely unevenly distributed population, resources, and infrastructure. For more than four hundred years, Russia has been the biggest undivided country in the world, and national stability and sustainable development highly depend on the quality of governance. Therefore, sustainable managing of vast and diverse territories with the help of increasingly complicated hierarchical governing structures was recognized as a vital problem many centuries ago. Sustainable development of Russia depends highly on consistent and comprehensive geospatial data with a wide range of scales and the flawless integration of geospatial data of different scales and different origins into a single heterogeneous dataset. As a geospatial approach with radically new properties, Digital Earth is very attractive and promising, especially for Russia.

The second vital factor that creates a strong interest in the concept of Digital Earth in Russia is the predominance of space exploration in the national mentality. Russia has the longest history of space exploration in the world. Applied space research, especially the idea of holistic, non-mediated, direct representation of our planet using remote sensing data instead of maps has become very popular and commonplace for at least two generations of Russians since the beginning of the space age in the second half of the 1950s. Wide usage of satellite remote sensing for decision making, management and governance of all kinds and levels was very popular in the beginning of the twenty-first century, and thus Digital Earth as new scientific, technological and social initiative was met with great enthusiasm—Russian society was mentally prepared for a new scientific revolution.

In 2005, the Google Earth online service was started, following the geoportal Google Maps. This event marked the beginning of a great geospatial revolution in Russia. As a bright embodiment of the Digital Earth concept, Google Earth was almost instantly recognized in Russia, and new geospatial approach was widely appreciated with remarkable speed. New, highly demanded, colored high-resolution satellite images were recognized by Russian users as an invaluable resource for decision making. However, the implementation of Digital Earth in Russia was a rather long and controversial process. Understanding Digital Earth and the rapid expansion of detailed satellite data triggered a long process of adaptation of national legislation and management practices to the new technological reality. In the second half of the 2010s, the process of adopting Digital Earth reached its culmination: in 2017, the Russian government proclaimed Digital Earth as a new ideology of national space remote sensing. In addition, a critical review of national goals and space assets was initiated. The digital economy has been recognized as a new and ultimate goal for Russia's technological development. Under these circumstances, Digital Earth was gradually anticipated as a pivotal element of national command and control infrastructure due to its organic compatibility with digital economy. Currently, the synergy of both "digital" concepts is becoming an important factor in the development of national industry, national technologies and the nation itself.

23.2 Prehistory and Precursors of Digital Earth in Russia

The importance of Digital Earth for Russia and its visible scientific significance raised the question of its prerequisites in national history. There are indications that the essence of Digital Earth, as a new geospatial approach that was visibly different from other geospatial approaches, was anticipated in Russia many years and even centuries before the current geospatial revolution, and the concept of a universal, direct representation of Earth has repeatedly manifested in Russian culture.

23.2.1 Cultural Precursors of Digital Earth in Russia

The official history of Digital Earth started in the eve of the 20th century, when Vice President of the USA Al Gore introduced and described a new, promising type of geospatial information systems—so-called "Digital Earth"—in his book "Earth in the balance" (Gore 1992) and in a famous speech given at the California Science Center in Los Angeles on January 31, 1998 (Gore 1998). Digital Earth was described as a comprehensive, three-dimensional and multi-scaled model of Earth that could be used as an ultimate collector of spatially localized information. However, this core idea of Digital Earth was anticipated many times in different countries, including Russia. One of the most unbelievably accurate descriptions of an informational system that envisioned the future Digital Earth was made by the great Russian and Soviet writer Mikhail Bulgakov (1891–1940). In his mystical novel "Master and Margarita" (Bulgakov 1967), written between 1928 and 1940, he described a so-called 'Globe of Woland'—a magic globe that demonstrated and emphasized the ability to visualize all events in any place of the Earth immediately, interactively, completely and in full detail. The main features of the 'Globe of Woland' described in detail in the novel accurately and comprehensively anticipated the basic features of the Digital Earth approach—a three-dimensional, scale-independent, dynamic model of Earth. Moreover, Bulgakov envisioned avoiding mapping signs to improve the quality of perception, consciously anticipated and described in detail the basic principles of the future Digital Earth with unbelievable accuracy nearly 60 years before Digital Earth was manifested and interdisciplinary research was initiated.

Bulgakov's 'Globe of Woland' also had a predecessor. There is opinion (Sokolov 1988) that the idea of the magic Globe was borrowed from the novel 'War and Peace' (Tolstoy 1869) written by Russian writer Leo Tolstoy (1828–1910). The novel depicted an 'alive and vibration globe without any dimensions' (in original Russian text) that the hero saw in a dream. This kind of impossible object could be regarded as a metaphorical description of the idea of scale-independency. Notably, in the English translation of the novel, this paradoxical property of the Globe was reduced to a more imaginable form—an 'alive and vibration globe without fixed dimensions.'

Therefore, we assume that a representation of our planet as a scale-independent and projection-independent, sign-less, space-temporal replica of real Earth was anticipated, understood and popularized in Russia long before the establishment of Digital Earth as a scientific paradigm, technological and social initiative.

23.2.2 Technological Prerequisites of Digital Earth in Russia

With the beginning of the Space Era a new, holistic vision of our planet as a live Globe became widespread globally. The first image of Earth from outer space was produced in 1947 with the help of the US-launched German missile V-2 (NASA 2017). The first satellite was successfully launched from the Russian space center (cosmodrome) Baikonur in 1957. The American satellites Explorer-6, in 1959, and TIROS, in 1960, provided the first photographic and television images of Earth, respectively. In 1959, the Soviet automatic station Luna-3 captured the first image of the far side of the Moon. In 1961, Soviet cosmonaut Yuri Gagarin made the first manned space flight (Afanasiev et al. 2005; Baturin et al. 2008). During his day-long orbital mission flight (August 6–7, 1961), the second cosmonaut, Gherman Titov, took the first photographical images and movies of Earth from space manually.

A new vision of Earth became very popular, especially in Russia as it was an initial leader of the space race. The numerous benefits and hidden potential of remote sensing were quickly understood. This trend was amplified by the new concept of state governing with the help of digital computer networks, proposed during the same time by famous Soviet cybernetic and mathematician, academician Victor Glushkov (1923–1982), the chief designer of the first Soviet small ('personal' of some kind) computer for engineering purposes 'Mir-1' (1966). He proposed and popularized the idea of a so-called 'OGAS' (Universal State Automated System, or All-State Automated System)—a net-centric, internet-like architecture intended for collecting, storing and processing information on the state level to improve decision making. The project was proposed in the 1950s, became very popular in the 1960s–1970s, and gradually died out after the death of V. Glushkov in 1982 and as the country entered a deep crisis in the end of the 1980s. OGAS was not centered on geospatial data, but the clear necessity of spatial and temporal localizations of data in a universal, scale-independent framework induced interest in new approaches to handling geospatial data. The widely appreciated and supported concept of OGAS contributed to the future explosive growth of common interest in the Digital Earth concept in Russia (Fig. 23.1).

The fragmentation of the Soviet Union into 15 independent countries in 1991 and the severe, prolonged economic and political crisis significantly limited the scientific

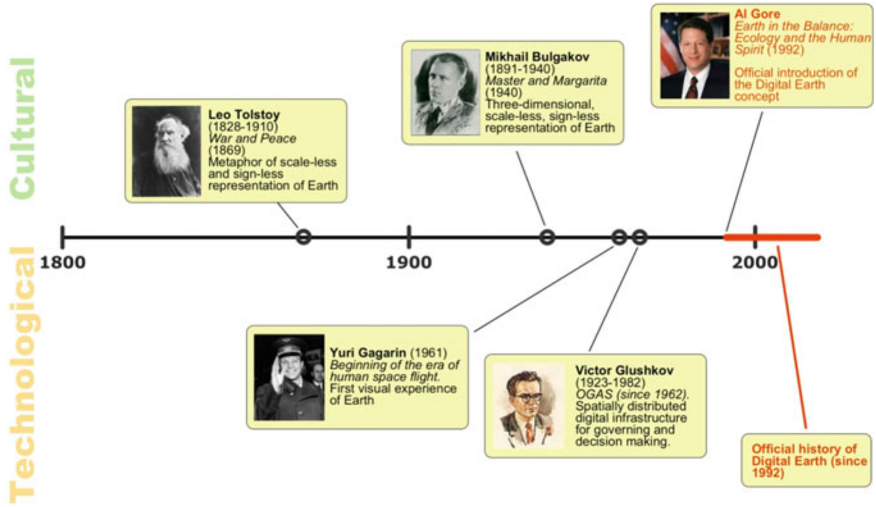

Fig. 23.1 Cultural and technological precursors of Digital Earth in Russia

potential of Russia and demands for innovations in the 1990s, and led to the shutdown of many promising projects. In the eve of the new millennium, the manifesting of Digital Earth in 1998 by Vice President of the USA Al Gore attracted the attention of the Russian scientific community. A real breakthrough came in the middle of the 2000s, following the start of the Google Earth online service in 2005, establishment of the International Society of Digital Earth (ISDE) in 2006, and proposition of the neogeography concept the same year.

23.3 Introducing Digital Earth in Russia

One of the first forerunners of Digital Earth in Russia was the virtual globe ArcGlobe—a software module and 3D viewing environment for the popular software ArcGIS (ESRI). ArcGlobe was introduced in the beginning of the 2000s and became popular as an effective new approach for integration of geospatial 3D data into the virtual globe. For the first time, ArcGlobe allowed for a user to immerse data into a rich geospatial context formed by global mosaic satellite images, and interact with it. However, the low spatial resolution of contextual geospatial data provided on DVD in the absence of online services and standalone applications as well as the relatively high cost prevented the wide usage of this interesting product. However, ArcGlobe ignited discussion about the future directions of GIS development and generated expectations for the emergence of a new type of geospatial product in the near future. The first products that incorporated the same approach to varying extents (e.g., NASA WorldWind, Microsoft Encarta, etc.) were introduced around same time, but were not widespread. For example, there are no mentions of NASA WorldWind in the articles registered in the Russian national scientific electronic library until 2005. The next big step toward understanding and assessing the new paradigm in Russia was made by Google.

The start of the Google Earth online service in the first half of 2005 provided an inspiring and thought-provoking effect and triggered the process of adopting the Digital Earth paradigm in Russia. Due to relatively good broadband access across the country and free access to Google Earth in its basic configuration, the high reliability, very rich contextual data and pressing demand for correct and unmediated geospatial data in the country resulted in amazingly rapid proliferation of the use of Google Earth in Russia. In 2007, the first open Russian model of a Russian city for Google Earth became accessible through the web site (Wolodtschenko et al. 2015). The model was based on a previous GIS-based model (Fig. 23.2a, b).

The model of Protvino was followed by others. They were increasingly used for urban and regional planning, education, and monitoring of social processes in urban environments (Fig. 23.3a, b).

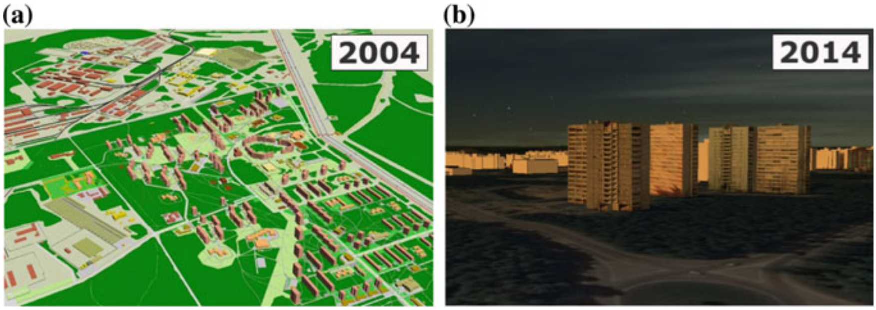

Fig. 23.2 **a, b** Left to right: evolution of the 3D model of the city of Protvino (Moscow region, Russia) during the adoption of the Digital Earth concept. **a** GIS-based 3D model of Protvino created in 2004, **b** realistic dawn view of Protvino generated using a photorealistic 3D model of Protvino based on the Digital Earth paradigm (2014)

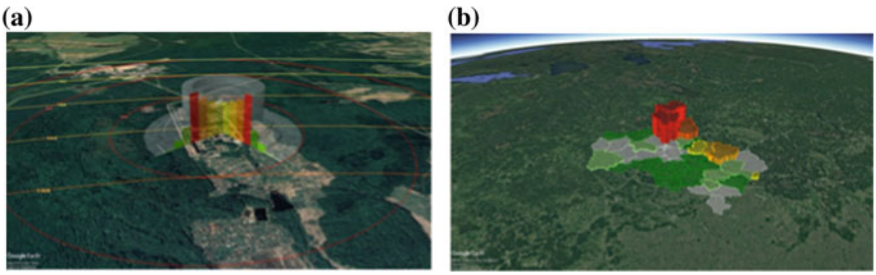

Fig. 23.3 **a, b** (From left to right) Visualizations of statistical and social data on urban (**a**) and regional (**b**) levels in the Digital Earth environment in Russia in 2005–2014

In 2008, the first software tools for Google Earth developed in Russia were proposed (Blogru.geoblogspot.com 2008). The scientific novelty of Google Earth and its advantages were obvious, leading to discussion about the nature of new approaches for working with geospatial data. In Russia, this discussion was induced by a comparative analysis of 'Geography' and 'Neogeography', initiated by A. Turner in his book 'Introduction into Neogeography' (Turner 2006). In Russia, neogeography was recognized and studied as a new scientific paradigm and quantum leap in cartography. Therefore, it was eventually identified with Digital Earth as an advanced geospatial approach, with Google Earth as its embodiment. Digital Earth was regarded as a significant innovation and promising achievement in a variety of geospatial products that emerged, especially after 2005. This vision stimulated the search for scientific, not solely technological, foundations of a new approach. In 2008, the first Russian intensional definition of neogeography, later adopted for the Digital Earth, was proposed (Eremchenko 2008). The fundamental interconnection between Digital Earth and the concept of situational awareness has also been identified and studied (Boyarchuk et al. 2010). The philosophical effects of the new geospatial paradigm were discussed in a comprehensive analysis based on the 'Noosphere' concept (Lepsky 2013). In 2008, a range of conferences dedicated to new approaches in cartography began to be held in Russia annually, and a growing number of scientific articles have been published each year.

In 2012, the book 'Virtual Geographic Environments' (Lin and Butty 2009) with the chapter 'Concept of "Digital Earth"' was published in Russia. The first scientific article with the term 'Digital Earth' (in Russian) in its title registered in the Russian official scientific database E-Library was published in 2013 (Lisitsky 2013). In 2015, a common vision of Digital Earth and neogeography was proposed (Eremchenko et al. 2015). In 2016, the first scientific event was held in Russia (Novosibirsk), organized by the ISDE as part of the annual Interexpo GEO-Siberia 2016 international conference (ISDE 2016).

The number of Digital Earth-related articles (Fig. 23.4) has grown annually. The growing interest in Digital Earth stimulated its transfer to different areas. The Digital Earth concept began to be perceived by a wide audience, especially among government officials. To some extent, 2017 was the watershed year.

At the 10th International Symposium on Digital Earth held in Sydney, Australia, in 2017, the Russian "Neogeography Group" was recognized as one of the founders of the Digital Silk Road Alliance (DSRA). The DSRA will build a cooperative network and a geospatial 'think tank' for the Silk Road countries and support the advancement of geo-spatial information and sustainable development through international cooperation within the Digital Earth paradigm (ISDE 2017).

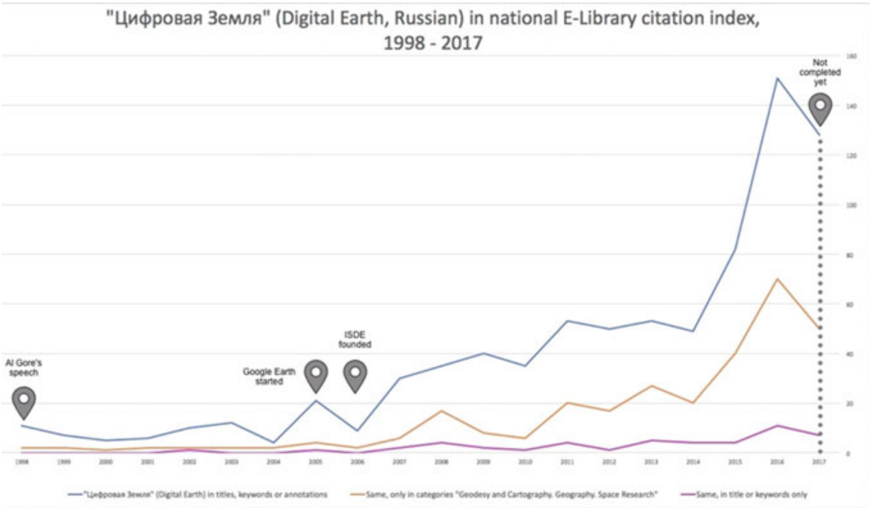

Fig. 23.4 Number of scientific papers and books about Digital Earth (in Russian), indexed in the Russian national scientific citation index E-Library from 1998 to 2017. Note that the term 'Digital Earth' was also widely used in hardware engineering to describe the ground potential of digital equipment

23.4 Establishing the Digital Earth Russia Community

The understanding, development and adoption of the Digital Earth vision in Russia were organized in an interdisciplinary manner from the beginning. A significant part of the efforts of the Russian Digital Earth community was dedicated to outreach and the projection of the Digital Earth vision into different disciplines, industries, and social groups to address vital problems of society. Conferences and meetings were organized in different Russian cities (Fig. 23.5) for different groups of participants.

Discussion of the Digital Earth concept occurred during the annual Neogeography conferences held in Moscow in 2008–2011, as well as at a long list of conferences organized and supported by famous Russian scientist and expert in scientific visualization, visual analytics, situational awareness and neogeography, Prof. Stanislav Klimenko (1941–2018). In 2009, 2014 and 2016, the Digital Earth Vision was presented and discussed at the Annual International Conferences "Information and Mathematical Technologies in Science and Governance" held in Irkutsk and Baikal (Siberia). In 2014, the Russian Digital Earth community helped organize a special session on the semiotics aspects of geospatial visualization, "Neogeo-Semiotic Synthesis", at the 12th World Congress of Semiotics in Sofia, Bulgaria (Semio2014.org 2014). Since 2016, the Digital Earth concept has been presented during the annual InterCarto/InterGIS conferences organized in different locations in Russia and abroad. From 2017, activity in the Russian Digital Earth community began to increase. For example, in 2017, the Digital Earth Vision was presented by

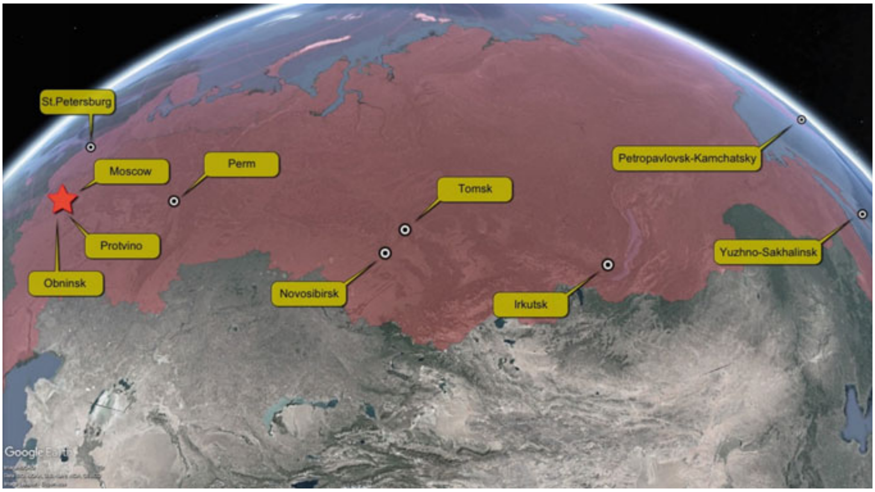

Fig. 23.5 Spatial distribution of Russian Digital Earth centers and the locations of the most significant scientific Digital Earth conferences and other events in Russia since 2008

Russian supporters at more than half a dozen scientific conferences in different fields: philosophy, visual analytics, governance, innovative economics, the Silk Road and Belt Initiative, geography and GIS, monitoring and security, scientific visualization and big data, aerospace and remote sensing, and cartography.

At some conferences, the Digital Earth sessions have become traditional (Neogeography.ru 2017, 2018). The Russian Digital Earth community has also focused on outreach as a vital way to proliferate Digital Earth expertise and provide a synergy effect in the scope of Silk Road infrastructure projects and a Digital Turn in the economy (Eremchenko et al. 2017).

The positive dynamics and fast recognition of the Russian Digital Earth community attracted the attention of colleagues abroad. At the 7th Digital Earth Summit held in Al-Jadida, Morocco in 2018, the council of the ISDE decided to organize the next (2020) 8th Digital Earth Summit in Russia. It will be held in Obninsk—a well-known scientific and university center with a history of being affordable. The selection of the relatively small (approximately one hundred thousand inhabitants) university town Obninsk with very diverse industry and science as the host of a Digital Earth Summit emphasizes the interdisciplinary and outreach goals of this forum and demonstrates the significance of Digital Earth in the Silk Road and Belt project because Obninsk is a Russian hub of the Silk Road.

Establishing a national corpus of relevant scientific journals is also a key factor for the successful development of disciplines, especially interdisciplinary ones. Scientific articles about different aspects of Digital Earth are published in various journals. In addition, the proceedings of the annual GraphiCon and InterCarto/InterGIS conferences, the annual almanac Geocontext, and other sources of information are relevant. To share the Digital Earth vision, internet portals, social networks, and media are actively used. Many reviews, news, and outreach-oriented discussion materials are published on the internet portal NeoGeography.ru. Notably, Digital Earth in Russia was developed mainly within the Russian linguistic context and terminology, therefore the constant coordination of discourse and results and harmonization of research with the international community is a significant issue.

Also in 2018, preparation for a Russian chapter of the ISDE was initiated (DERussia.ru 2018).

23.5 Exploration of Digital Earth in Russia

A key factor of success in technological development is a clear understanding of the nature of Digital Earth as a scientific paradigm and new approach for processing geospatial information. Since the introduction of the Google Earth geoservice in 2005, the discussion about Digital Earth in the Russian scientific community has focused on fundamental issues, primarily on the problem of developing a scientific definition of Digital Earth. Special attention was also paid to its paradoxical properties, primarily semiotic ones.

The following are the main directions of research of the Digital Earth phenomenon in Russia (Eremchenko 2017):

- development of an intensional definition of Digital Earth;
- proposal of a typology of geospatial visualization methods;
- discussion of the semiotic implications of Digital Earth, including introduction of the 'zero sign' concept;
- proposing and discussing the concept of georhetorics; and
- studying the concept of Digital Earth in the context of situational awareness, the digital economy, visual analytics, and smart city concepts.

Digital Earth is also used in Russia to observe social processes in the urban environment with unprecedented spatial and temporal resolutions.

23.6 Digital Earth: Russian Government Initiatives

In May 2017, less than two months after the 10th International Symposium on Digital Earth was held in Australia and two weeks after announcement of the Digital Earth Australia project, a similar Digital Earth-based concept of new space remote sensing policy was officially adopted by the Russian government (Kremlin.ru 2017). At the presidential meeting on developing the space sector held on May 22, 2017, the concept of Digital Earth was proposed and approved as a core idea of new national policy in space. The Russian Space Agency provided information about the "Digital Earth" project focused on stimulating development of the Russian economy in accordance with new "digital" trends and an innovative "digital economy". Digital Earth in Russia should become a central element of a highly effective national command and control system to ensure sustainable development in Russia. The main declared goals of the "Digital Earth" project are the creation and regular updating of a seamless raster coverage for the entire globe with 1 m accuracy (or better) and formation of a family of new geospatial services focused on the urgent demands of business, government, and society. Commercialization manifested as a fundamental approach to satellite remote sensing. One specificity of the Russian policy in the field of remote sensing is the desire to ensure independence and autonomy in space. In accordance with this policy, the country is developing all the elements of the infrastructure of the future Digital Earth.

Development of Digital Earth in Russia and its infrastructural elements was supported by regulatory documents such as "The concept of development of the Russian space system of remote sensing of the Earth for the period up to 2025", resolution of the Government of the Russian Federation No. 326 on 28 May, 2007, "On the procedure for obtaining, using and providing geospatial information", Bases of the state policy of the Russian Federation in the field of space activity for the period till 2030 and further prospect, approved by the President of the Russian Federation on April 19, 2013 № ПР-906, the state program of the Russian Federation "Space activities of Russia for 2013–2020" approved by the government of the Russian Federation on April 15, 2014 № 306, and others.

23.7 Infrastructure of Digital Earth in Russia

The concept of Digital Earth naturally integrates achievements in the fields of space exploration, advanced technologies, promising areas of fundamental scientific research, establishment of an appropriate infrastructure backbone, and social, industrial and governmental demands. The need to revise the existing principles of obtaining, accumulation, processing and use of geospatial data in accordance with the internal logic of scientific and technological development was realized in Russia in the first decade of the twenty-first century.

In Russia, this state-of-the-art system consists of number of components and national assets such as a remote sensing satellite constellation, global navigational satellite system (GLONASS) and a unique project of a common geographically distributed information system of remote sensing (ETRIS DZZ).

23.7.1 Remote Sensing Constellation

Satellite remote sensing capabilities are fundamental to a Digital Earth-based information system. Russia has long and bright history of remote sensing, though the present constellation and its potential are rather modest. At the beginning of 2019, it consisted of the high-resolution (better than 1 m) satellites of the "Resurs" family and moderate resolution (2.5 m) satellites of the “Kanopus-B” family, the meteorological satellites “Meteor-M” and “Electro-L”, as well as hydro-meteorological and experimental satellites. Increasing the number of satellites and the capacity of the national constellation of remote sensing satellites is considered a major national task. A plan to increase the number of national remote sensing satellites from 8 (2017) to 20 by 2025 was revealed (Roscosmos.ru 2017). Highly reliable “Kanopus-B” satellites work in the common constellation with the identical Belorussian satellite BKA. As of May 2019, there were 7 satellites in the common “Kanopus-B” constellation (6 Russian satellites and 1 Belorussian satellite).

23.7.2 National Global Navigation Satellite System

Global Navigational Satellite System (GLONASS) is a key national space resource. A core element of GLONASS is a space segment that consists of 24 satellites that are evenly distributed on 3 orbital planes (8 satellites in each plane). Like GPS, GLONASS provided two free worldwide navigational signals (L1 and L2). Development of GLONASS was initiated in 1976. The deployment of the first experimental satellites of the “Uragan” family began in 1982. The system began limited operation in 1993, deployment of the full GLONASS constellation (24 satellites) was successfully completed in 1995, and full-scale operation of the system began. However, the system degraded due to a lack of resources and incoherent national space policy.

Rehabilitation of GLONASS was stimulated by a federal special purpose program initiated in 2002. Through this program, the orbital segment of the system was eventually recovered, and in 2009 GLONASS was redeployed and returned to full-scale operation as a second global navigational satellite system for the world. Now, the orbital segment of the system is based on “Glonass-M” satellites. GLONASS development is regulated by RF Government Ordinance No. 189 “Supporting, developing and using of GLONASS for 2012–2020” dated March 3, 2012. Development of a new “Glonass-K2” satellite with improved specifications, deployment of navigational satellites with new types of orbits, and creation of a wide-area augmentation system are planned.

In conjunction with another navigational systems like GPS, BeiDou and GALILEO, GLONASS is actively used for creating new digital infrastructure in Russia. One prominent example is the ERA-GLONASS system intended to generate rapid information about car incidents. Since January 1, 2017, all new cars in Russia and other countries of the Eurasian Custom Union must be equipped with ERA-GLONASS car modules. A similar system, eCall, was developed in the EU and will be technologically compatible with ERA-GLONASS.

23.7.3 The International Global Aerospace System (IGMAS)

Historically, the first predecessor of the modern Digital Earth Russia system can be considered, was the IGMAS (International Global Aerospace System) project proposed in 2009 (Menshikov 2009). IGMAS was proposed as a "special space system", or system-of-systems, comprising space, aerial and ground segments and intended for "real-time monitoring of asteroid and comet hazard… continuous incoming of real-time forecast monitoring information on the occurrence of natural and manmade disasters on a global scale, as well as timely detection of asteroid and comet hazard and availability of such information to a wide range of consumers" (Kuzmenko et al. 2010). The IGMAS project remained unrealized but contributed to the idea of creating a unified global information system that met Digital Earth requirements.

23.7.4 The ETRIS-DZZ System

The "Digital Earth Russia" project that has been developed by the Russian Space Agency since 2017 includes a new state-of-the-art ground segment system as a key element—a 'common geographically distributed information system of remote sensing' (ETRIS DZZ). The new system, developed by the "Russian Space Systems" holding, was successfully tested and recommended for operation in 2016 (RussianSpaceSystems.ru 2016). ETRIS DZZ consists of 13 centers distributed throughout Russia and abroad, including in the Arctic and Antarctic. Compared with the existing single-point reception, the deployment of a system with a multi-point reception organization will significantly improve the efficiency of the use of existing and planned Russian remote sensing satellites due to the timely discharge of accumulated information from satellite memory on most orbital turns.

23.7.5 The SPHERE Project

The ambitious SPHERE project was announced by the president of Russia on June 7, 2018. The project envisages the deployment of an extensive (approximately 640 satellites) LEO constellation aimed at solving three main tasks: communication and internet access, remote sensing, navigation and geopositioning. There are three stages of deployment of the system: 2022, 2024, and 2028 (Kremlin.ru 2018). The specifications of the future SPHERE system and information about the satellites is not accessible yet.

23.7.6 Services and Applications

Remarkable visualization of Earth with the help of state-of-the-art computer systems is a prominent aspect of the Digital Earth paradigm. Historically, the Russian scientific community has focused on the study of Digital Earth as a scientific paradigm based on existing practical realizations (NASA WorldWind; Google Earth, ERDAS Titan, etc.). In addition, the range of palliative, 2D geoportals such as Google Maps was developed in Russia—Maps.Yandex.ru, Kosmosnimki.ru, etc. However, the limited capabilities of map-based geoportals are obvious and the demand for a real Digital Earth-like solution persists.

In 2010, the ‘Geoportal of Roscosmos’ (https://gptl.ru) was presented; it was promoted as an innovative, updated daily global coverage made using satellite images. Low-resolution images are free of charge and accessible for any user, higher-resolution images can be purchased. The cost of developing the ‘Geoportal of Roscosmos’ was estimated at approximately $300,000. Nevertheless, the need to create a fully featured Digital Earth was obvious due to the practical needs of the vast country.

The first national geospatial product that met the requirements of the Digital Earth paradigm was the NeoGlobus software, developed in VNIIEM Corporation, a leading aerospace enterprise specializes in producing satellites, including the remote sensing satellite families “Meteor” and “Kanopus-B”. In 2010, NeoGlobus was presented at the seventh international industrial forum “GeoForm+2010” as an ‘innovative environment for integration of geospatial data’ based on a global seamless mosaic of satellite images (VNIIEM 2010). NeoGlobus was proposed and implemented as an environment for long-term planning and tasking for Russian remote sensing satellites of the “Kanopus-B” family, and therefore its market niche was limited.

23.8 Digital Earth Russia: Private Business Initiatives

Russian private business was also involved in Digital Earth R&D. One of the most successful Russian Digital Earth services that was implemented at the same time and is increasingly being used in various fields is Sputnik GIS, developed by Russian privately owned company Geoscan Group.

A predecessor of the Sputnik GIS project was started in June 2009 as a 3D globe based on NASA WorldWind SDK, intended for spatial data visualization. Later, Sputnik GIS developed by Geoscan emerged. The history of development is interesting because it is well-suited for the specific demands of the national Russian market.

Sputnik GIS is based on the Digital Earth paradigm but has a substantially and gradually expanded functionality compared with most widespread solutions such as Google Earth. From the beginning, Sputnik GIS was oriented for use by emergency services for UAV monitoring. The first versions had few features:

- Visualizing UAV flight trajectories;
- Visualizing SRTM as a 3D surface on the globe; and

- Visualizing UAV-borne data (orthophotos).

The next step in the evolution of Sputnik was creating a Ground Control Station (GCS, Geoscan Planer) for the Geoscan UAV. The Geoscan GCS used a fully 3D environment and had the ability to plan flight with respect to the local terrain, modelled using the SRTM or other sources.

The third big step in Sputnik GIS evolution was releasing support for the Agisoft PhotoScan *.tls format. This feature made Sputnik GIS a unique software solution for 3D modelling, visualization and analysis of cities. Along with *.tls format support, basic measurements tools such as ruler, corner ruler and area were released. At the same time, Geoscan finished the project of creating a Tomsk city 3D model (Fig. 23.6). It was a rather ambitious project, because Tomsk is a big Siberian city with a population of more than half a million. In addition, Tomsk is well-known for its very rich and unique urban heritage, especially wooden architecture, which is very difficult to model in 3D. Nevertheless, the project was completed in a short term with exceptional, unprecedented quality. Since 2014, the Tomsk city administration has used Sputnik GIS intensively and successfully. Later, similar models were created for other big Russian cities: Khabarovsk, Vladivostok, Kazan, Tula, Veliky Novgorod (Sputnik.Geoscan.aero 2018). Moreover, the practical possibility of creating high-precision photo-visual 3D models of cities and entire regions has been demonstrated. For example, a 3D model of the Tula region in central Russia (an area of more than 25 thousand square kilometers, with a population of approximately 1.5 million inhabitants) was successfully created.

Geoscan also developed and released new versions of Sputnik GIS with a number of features including change detection, volume calculation, section generation,

Fig. 23.6 View of a photorealistic detail of a 3D model of the city of Tomsk, created and visualized in Sputnik GIS

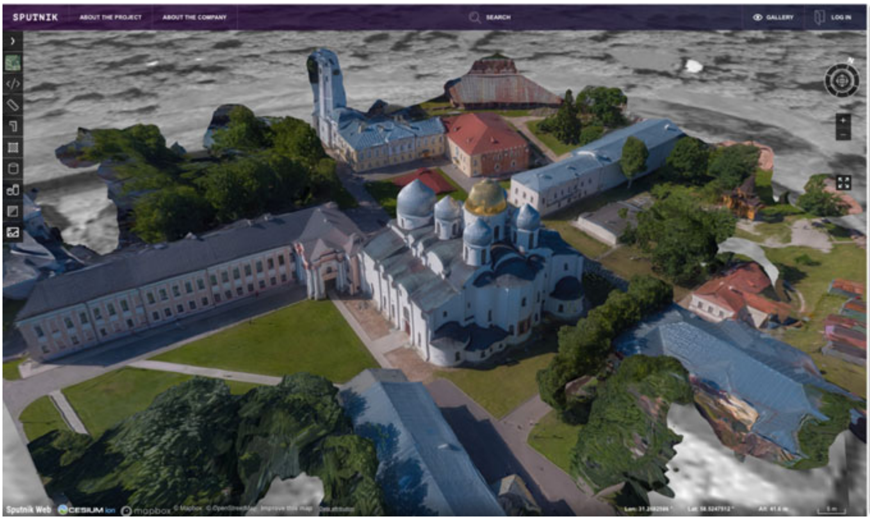

Fig. 23.7 Precise 3D model of historical Sofia Cathedral in Novgorod, Russia, created and visualized in Sputnik WEB GIS

contour generation, slope maps, creation and visualization of the NDVI, thermal maps and more. With the idea of involving UAV technologies in different industries, Geoscan developed the Sputnik GIS product family:

- Sputnik GIS—for surveyors and urban planners;
- Sputnik Agro—for agricultural companies and individual farmers;
- Sputnik PTL—for energy companies; and
- Sputnik WEB—a web implementation of Sputnik GIS with cloud photogrammetry features (Fig. 23.7).

Sputnik GIS has a long (nearly 10 years) history of development and is a mature, versatile, functional, multipurpose Russian Digital Earth service, oriented toward the specific needs of national and international (Arza-García et al. 2019) customers and developed dynamically. Due to the user-oriented approach, significant upgrading capabilities and full integration with state-of-the-art UAVs, Sputnik GIS became an effective replacement for Google Earth as a nationwide Digital Earth platform.

23.9 Conclusions

The Digital Earth paradigm has been actively investigated in Russia since 2005 and was anticipated many decades before. This anticipation originated from the vital necessity of a global, scale-independent, three-dimensional, unified, unmediated representation of geospatial context. Digital Earth is natural geospatial approach for all cultures and nations, especially for Russia.

Russian studies of Digital Earth were mainly focused on its fundamental issues. A range of applications and online services, inspired by Google Earth, was created in Russia and actively used, especially in state governance and emergency services. The culminating point of the process of adopting the Digital Earth Vision was its manifestation as a core ideology of national space remote sensing in 2017. The process of harmonizing national activities with the International Society for Digital Earth through the establishment of the Russian Chapter of the ISDE has been finalized.

Some fundamental issues and effects of the Digital Earth paradigm, unveiled by the Russian Digital Earth community, are fruitful and could impact a wide range of disciplines. The process of harmonizing geospatial data within the new framework of the 'Silk Road and Belt' and technological development of new generation of geospatial services should also be fruitful. The future of Digital Earth in Russia looks promising, bright and full of scientific and technological achievements.

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Yuri M. Baturin is a corresponding member of the Russian Academy of Sciences, professor of M.V. Lomonosov Moscow State University. He is the head of Chair of Computer Law and informational security. He develops legal and psychological problems of digitalization. He dealt with virtual models for the history of science and technology, as well as the legal status of 3D documents.

Valentina T. Dmitrieva is a Professor of the Department of geography and tourism of the Moscow City University. Research interests: laws of development of hydrological and climatic systems, ecological and geographical education, information technology in the educational process.

Eugene N. Eremchenko is a Head of Russian Neogeography group, researcher of M.V. Lomonosov Moscow State University, secretary of the commission GI for Sustainability and councilor of the ISDE. Research interests: Digital Earth and geospatial basics, neogeography and GIS, remote sensing, 3D-modelling, visual analytics, sustainability, situational awareness, decision making, outreach of geospatial technologies.

Lyudmila V. Massel is a chief researcher, Head of Information Technologies Laboratory in Melentiev Energy Systems Institute SB RAS, professor of Automated Systems Department of the Cybernetic Institute in the Irkutsk National Research Technical University, author of more than 200 articles in the field of intelligent technologies, semantic modeling, situational management, cyber security, the design of information systems and technologies, the development of intelligent decision support systems in the energy sector.

Oleg A. Nikonov is the Head of R&D division of JSC 'VNIIEM Corporation' JC, participated in the development of remote sensing space systems "Kanopus-B" and "Meteor". His area of interest: remote sensing, satellites systems, Digital Earth, neogeography, situational awareness.

Alexei A. Romanov is a Doctor of Science (Engineering), professor, member of International Academy of Astronautics (IAA), Councilor of General Director of JSC «TsNIIMash». Research interests of Dr. Romanov: space information systems, remote sensing of the ocean and atmosphere, system analysis and design, digital enterprise, navigation and information systems, small spacecrafts. He is the author of over 200 publications, holds 7 patents and authored 12 scientific books.

Vladimir S. Tikunov is Professor, Head of the Integrated Mapping Laboratory, Geography Faculty of M.V. Lomonosov Moscow State University, and Director of the Center of the World Data System for Geography. He published over 500 scientific works, including 21 monographs, texbooks, and manuals in 28 countries of the world and in 14 languages. He has led a number of Russian and international projects. He was Vice-President and, currently, is Chairman of the commission of the International Cartographic Association.

Alena A. Zakharova is a Deputy Vice-Rector and Professor in Computer Science at Bryansk State Technical University. Her research interests include geoinformatics, 3D modeling of oil and gas deposits, intelligent and cognitive data analysis and visualization. She is a full member of the International Informatization Academy and a member of program committees of a number of conferences on computer science.

Part IV
Digital Earth Education and Ethics

Chapter 24
Digital Earth Education

Cuizhen Wang, Camelia M. Kantor, Jerry T. Mitchell and Todd S. Bacastow

Abstract Digital Earth (DE) education provides students with geospatial knowledge and skills to locate, measure, and solve geographic problems on Earth's surface. The rapid development of geospatial technology has promoted a new vision of DE to embrace data infrastructure, social networks, citizen science, and human processes on Earth. The high demand for a geospatial workforce also calls for an ever-changing, diverse form of learning experiences. Limited efforts, however, have been made regarding DE education to adapt to this changing landscape, with most interventions falling short of expectations. This chapter gives an overview of current teaching and learning structures with DE technologies. Successes and obstacles for K-12 education are explored first, followed by classroom technologies and experiential learning and outreach exercises such as academic certificates and internships in higher education. Taking the geospatial intelligence model from the U.S. Geospatial Intelligence Foundation (USGIF) as an example, recent advancements in DE education for professional careers are described via its geospatial competencies, hierarchical frameworks, and credentials. In alignment with the principles of DE development, future DE education calls for an integrated learning framework of open data, real-world context, and virtual reality for better preparedness of our students in the geospatial world.

Keywords K-12 · Higher education · Internships · Geospatial competency · Credentials

C. Wang (✉) · J. T. Mitchell
Department of Geography, University of South Carolina, Columbia, SC, USA
e-mail: Cwang@mailbox.sc.edu

C. M. Kantor
Academic Affairs, United States Geospatial Intelligence Foundation, Herndon, VA, USA

T. S. Bacastow
Department of Geography, Pennsylvania State University, University Park, PA, USA

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24.1 Introduction

The vision of Digital Earth (DE), initially presented by former U. S. Vice-President Al Gore in 1998 (Gore 1999), has been to build a multi-resolution, three-dimensional representation of the planet in a system that allows users to navigate through space and time and to support decision-makers, scientists, and educators (Grossner et al. 2008; Goodchild et al. 2012). With recent technological advances, the system is now much closer to reality by utilizing vast amounts of geographic information. In the Big Data era, new visions for DE are emerging to take into account the developments in web-enabled sensors and opportunities provided by social networks and citizen-contributed information. Advances in information technology, data infrastructures and Earth observations, and the scientific and societal drivers for the next-generation of DE have been highlighted in recent literature (e.g., Craglia et al. 2012; Goodchild et al. 2012; Guo et al. 2017).

Little of the DE development focus, however, has been cast on education. The descriptor of user(s) is generically defined or refers to, at best, a few professional organizations. Nowhere in this particular vision of users does the *learner* appear even though education has caught the attention of DE proponents in the past (Kerski 2008; Donert 2015). The focus of this chapter is on the *learner* and the education/training structures that support teaching and learning with DE technologies. K-12 successes and obstacles are identified first, followed by higher education, professional credentialing opportunities, and finally the future of DE education and professional development.

24.2 Digital Earth for K-12

A variety of geospatial technologies are currently used in K-12 classrooms, and how to best do so has been pondered for some time (Fitzpatrick 1993; Nellis 1994). A keyword analysis of the *Journal of Geography*—a journal primarily dedicated to teaching and learning in geography—found first-time article keyword entries for remote sensing in 1990, computers in 1991, global positioning systems in 1993, geographic information systems in 1993, and Google Earth in 2007, indicating a steady progression of interest in these tools for education (Mitchell et al. 2015). More attention has been placed on educational uses of Geographic Information Systems (GIS) generally (Kerski 2008; Kerski et al. 2013), but concern for remote sensing (Kirman 1997), Google Earth (Patterson 2007; Zhu et al. 2016), and other virtual globe representations (Schultz et al. 2008) also is evident.

Classroom use of GIS began to appear in the 1990s (Kerski et al. 2013) and scores of research articles related to its educational use have appeared since in journals such as *International Research in Geographical and Environmental Education*, *Journal of Geography*, and *Cartography and Geographic Information Science*, among others. There are far too many sample articles to acknowledge in this short overview, but topics have included GIS and elementary school map skills (Shin 2006), bridging GIS teaching and learning between high school and college (AP GIS&T Study Group 2018), and GIS teacher training (Hohnle et al. 2016; Hammond et al. 2018). This interest was driven in large part by the ability to harness GIS for problem-based learning and the study of real-world phenomena and concerns (Milson and Kerski 2012).

Several examples illustrate this last point. In the United States, Mitchell et al. (2008) worked with middle school students to map hurricane storm surge and a chemical spill in relation to vulnerable populations such as children and the elderly; young people in 4-H clubs created trail maps and plotted locations for industrial development (Baumann 2011); and The Geospatial Semester offered secondary students the opportunity to learn about geospatial technologies and increase their spatial vocabularies by working on local problems such as siting a solar farm (Kolvoord et al. 2019). Elsewhere, students have used the technology to design a high-speed railway loop (France), map invasive flora (Canada), and identify locations for street lights to enhance public safety (Japan) (Kerski et al. 2013).

Whether and how GIS is used in instruction varies globally. The various structures that govern education and curriculum-making are important drivers in this regard. In countries where GIS has been made a part of the national curriculum, the spread of GIS in education has been faster (Kerski et al. 2013; Rød et al. 2010; Lam et al. 2009). These countries include China, Finland, India, Norway, South Africa, Taiwan, Turkey, and the United Kingdom. Note that, save for the Americas, these locations span the globe.

These achievements aside, most advocates would be quick to admit, however, that the promise of geospatial technology use in the K-12 classroom has fallen far short of expectations (Collins and Mitchell 2019). Some of the original obstacles plaguing greater use of geospatial tools by K-12 students remain depending on location; these include the inaccessibility of computers such as in South Africa (Breetzke et al. 2011) and Turkey (Demirci 2011) and not having a teacher and/or an educational context whereby tool use is well-taught and encouraged (Mitchell et al. 2018). As previously noted, educational standards also vary considerably internationally, meaning curricular integration of the technology can be equally variable. Improvements have included a decrease in software and hardware costs and a much greater availability of data—especially local data—for use in class projects. A focus on the student necessitates an emphasis on their teachers as well. Three important aspects apply, here. First, before a teacher embraces DE technologies they should also understand *geography* as a discipline for the unique contribution a spatial perspective brings (Bednarz and Ludwig 1997; Bednarz and van de Schee 2006). Too many teachers hold a narrow and information-oriented view of geography that is limiting for instruction (Bourke and Lidstone 2015). Second, a teacher must perceive DE technologies as useful and able to create learning opportunities not afforded by other methods (Lay et al. 2013). Finally, after fostering this positive mindset, DE teacher professional development (PD) must include several key components.

In order for teacher's DE PD to be successful, to have a "stickiness" (in other words, staying power and continued classroom use), the learning experience must be of sufficient duration. Too often geospatial training workshops are short in duration with little ongoing support (Baker et al. 2015). Successful teacher implementation requires long-term support instead of one-time PD. For example, Walshe (2017) showed that pre-service geography teachers with "*gradual yet repeated exposure to GIS with increasing complexity across the [school] year*" better developed their practice. Professional learning communities also sustain DE use. A strong cohort of learning peers can result in teachers from different disciplinary areas assisting and working with each other (Mitchell et al. 2018). Encouragement by school administration is crucial. Devoting new resources and allowing teachers to try something out of the norm: these are DE features where administrative support is necessary (Hong and Melville 2018). The best DE PD brings together diverse subject matter expertise and connects the learning to the existing curriculum to elevate the relevance of the tools to existing instruction (Hong 2014). Finally, extensive feedback and coaching, from improving classroom delivery to growing teacher confidence in using some of the more powerful features of DE tools when teaching their students, is a necessary support. Importantly, these findings are supported by work with educators across many countries, including Germany (Hohnle et al. 2016), the United States (Mitchell et al. 2018), the United Kingdom (Walshe 2017), and Hong Kong, China (Lam et al. 2009), suggesting that common teacher-training approaches in DE could be useful. A well-trained teacher corps that is mindful of how DE can be deployed in pedagogically appropriate ways (Mishra and Koehler 2006) can lead to a student population ready to connect DE technology with a problem-focused approach to learning.

24.3 Digital Earth for Higher Education

In a geospatial world, "geo" is fundamental in preparing students with geographical knowledge and skills to locate, measure, and quantify geographic phenomena (Medina and Hepner 2017). In DE higher education, students are expected to build on a firm math, science, and geography foundation with specialized courses in surveying, cartography, photogrammetry, remote sensing, and geographic information systems. The civil and governmental sectors of our society also are placing an ever-increasing reliance on the ability to build, query, analyze and communicate geospatial information to support a myriad of world issues.

24.3.1 Instructional Technologies

Pedagogical approaches for DE have developed rapidly, accompanying transformational changes such as crowdsourcing, cloud computing, and artificial intelligence (AI) that impact geospatial technologies. At many universities, introductory level GIScience courses are now taught online. Joyce et al. (2014) presented a remote sensing computer-aided learning (RSCAL) program released in 2013 in Australia, which utilized interactive online tools to facilitate students' active learning in classrooms. As a freely available online tool, the program interacts with a range of visualization, animation, and audio to enhance learning of the fundamentals of remote sensing. Torres et al. (2017) utilized WebGIS tools to enhance personalized learning in landscape education, in which students learn the landscape as a diversity of spatial elements and a complex system of physical and human factors. Many schools also are making significant efforts to infuse their GIS curriculum with a variety of commercially available or open-source technologies such as QGIS (QGIS Development Team 2018) and geospatial course materials developed by Boundless, a geospatial technology firm.

Since the debut of geobrowsers such as Google Earth in May 2005 (Fig. 24.1), these new geospatial tools make spatial data easily available worldwide and mark an evolutionary point for the DE community (Foresman 2008; Bearman et al. 2016). An increasing number of courses have adopted geobrowsers and virtual globes for classroom use. A compilation of similar geobrowsers and virtual globes released by a variety of private and public sectors all over the world is shown in Table 24.1. These user-friendly digital platforms are visually appealing to students and present a useful device for faculty to create a virtual Earth environment for interactive learning and enhanced student spatial thinking. By interacting with the real and digital Earth and within collaborative environments, students not only use and analyse data,

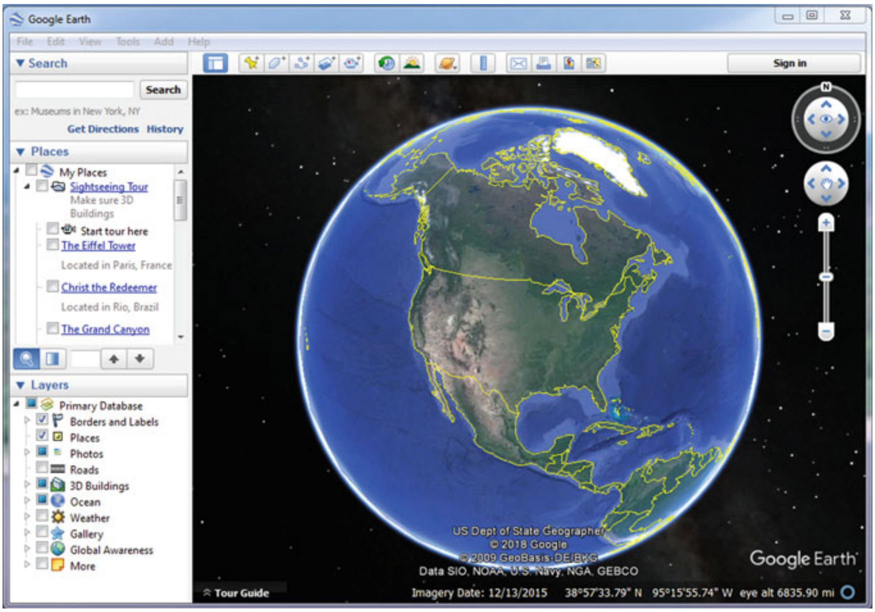

Fig. 24.1 The interface of Google Earth (Earth version 7.3.2, DigitalGlobe, Inc.)

Table 24.1 A list of geobrowsers and virtual globe platforms worldwide

Name	Source	Website
Google Earth	Digital Globe, USA	https://www.google.com/earth/
OpenStreetMap	OpenStreetMap Project, USA	https://www.openstreetmap.org
WorldWind	NASA[a], USA	https://Worldwind.arc.nasa.gov
Censium	Analytical Graphics, USA	https://cesium.com/ion
GBDX	DigitalGlobe, USA	https://platform.digitalglobe.com/gbdx
Bing Maps	Microsoft, USA	https://www.bing.com/maps
ArcGIS Explorer	ESRI, USA	www.esri.com/software/arcgis/exploer
SkylineGlobe	Skyline Software Systems, USA	http://skylineglobe.com
Open Data Cube	Digital Earth Australia, Australia	https://www.ga.gov.au/dea/odc
Géoportail	DGME[b], France	https://www.geoportail.gouv.fr/
Digital Earth Science Platform	Chinese Academy of Sciences, China	http://english.radi.cas.cn/ (to be released in late 2019)

[a]NASA: National Aeronautics and Space Administration
[b]DGME: French General Directorate for State Modernisation

but contribute to its collection, processing, and integration with other freely available platforms. DE is becoming an educational tool and a medium to facilitate our improved understanding of both natural and human processes on Earth (Annoni et al. 2011; Patterson 2007). Geo-media, for example, is a recently emerging concept that links geoinformation, online mapping, mobile APPs and volunteered geographic information for multimedia representation in classroom usage (Donert 2015).

Rapidly evolving geospatial platforms, open-source programs, and citizens-as-sensors (Goodchild 2007) allow for a higher level of spatial data adaptation in classrooms. These widely available geoportals, however, have their own limitations in DE pedagogy. On the one hand, they put pressure on educators to continually update their curriculum. Gaps between classroom learning and workplace frontiers are often observed when educators cannot stay abreast of all new changes in the market. On the other hand, some argue that while students can easily access spatial data using these tools, the level of spatial literacy they gain can be reduced and their critical spatial thinking skills can be endangered (Bearman et al. 2016). Most recently, numerous geo-“hackathons” have been conducted around the globe where geo-enthusiasts capture geo-tagged information or data using a variety of tools (GPS, WPS, RFID, etc.) which is then analyzed using GIS. The hackathon concept is intended to encourage digital innovation with existing assets and resources (Briscoe and Mulligan 2015).

While hackathons provide opportunities for collaboration and field work and allow students to learn and manipulate the tools, limited timing and focused technologies may have students entirely miss the geographic context and its principles.

24.3.2 Academic Curricula

As presented by the United Nations Educational, Scientific and Cultural Organization (UNESCO), education fulfils its valuable role of providing foundational knowledge and skills, engaging critical thinking, and building students positive attitudes to become active participants in a world characterized by diversity and pluralism (UNESCO 2018). Within a "credentialism" concept framework built in the 1970s, academic credentials continue to be the basic requirement for any professional occupation. However, both industry and academic professionals have concerns over the ability of academia being able to keep up with rapid industry changes. Graduating students also worry that the skills and abilities gained are not job-market oriented. Efforts currently are being made by academia, industry and government departments tasked with education and training to search for the right mix of competencies from across industries rather than from discipline-specific degrees.

As a consequence, DE concepts are offered in a multi-disciplinary education infrastructure by departments that are more cross-disciplinary in nature. Educating a student as a qualified geospatial analyst requires coursework in image interpretation, geographic information systems, open-source information, geospatially referenced data representation, management, and analytical skills. In the United States, more than 50% of GIScience courses are offered in geography and environmental science departments (ASPRS 2004); offerings also appear in other academic departments such as forestry, oceanography, engineering, or even public health and political science. The applied context of DE is positioned at multiple spatial scales and is interconnected among these disciplines. In a survey of 163 GIScience education programs at U.S. institutions in 2007–2008, Kawabata et al. (2010) reported that, while geography departments were the major provider of GIScience curricula, 40% of the GIScience degrees or certificates in these institutions involved multiple disciplines and nearly 20% interacted with more than three.

Unfortunately, there is no standardized DE pedagogy. The DE curriculum has complied with the systematic body of knowledge in GIScience for the collegiate teaching community. Since the early 1990s, the National Center for Geographic Information and Analysis (NCGIA) has recommended a core curriculum for GIS (Goodchild and Kemp 1992) and remote sensing (Estes et al. 1993; Foresman and Serpi 1999). Current GIScience curriculum has three primary concentrations:

- Cartography/surveying,
- Photogrammetry/remote sensing, and
- Geographic information systems/spatial analysis.

Crossing academic boundaries, DE curriculum also is undertaken by industry geospatial players in collaboration with or independently from academia. Students now have much better access to hardware, software, course materials and data via memorandum of understanding (MOUs), grants, challenges and scholarships, and partnerships between individuals, industry, and schools. For example, Esri offers GIS access to K-12 schools throughout the world, and the United States Geospatial Intelligence Foundation (USGIF) has established agreements with Digital Globe Foundation, Boundless, and Hexagon Geospatial to offer free software, data support and high-resolution imagery for classroom usage. However, the formula for seamlessly transitioning across different DE concepts is still lacking. While those out of academia focus more on technical and industry specific skills, universities continue to hold the primary role in forming a well-rounded learner who graduates with both a liberal arts background and technical, software agnostic knowledge.

The motivation to develop DE pedagogy and curriculum originates in a variety of disciplines and is driven by various stakeholders. With increasing computing power, the focus of DE has been moving toward the automation of tasks and dynamic visualization of historic or real-time data. Making sense of data has led to a shift of geospatial analysis from maps to models (spatiotemporal analytical methods; statistical, numerical, mathematical models) running on high performance computing. These are now developed and used to understand complex adaptive systems found in the natural or built environments as well as in health, political, social or economic systems on Earth (Galvani et al. 2016). With advances in computer-processing and broadband internet, geobrowsing has brought DE to the fingertips of people worldwide (Craglia et al. 2012). All these technological advances lead to changes in the workforce and in the nature of how organizations operate and interact with each other. This in turn requires re-imagining geospatial education in an excessively digital world as a customized and customizable package that takes into account rapid shifts in technology (Kantor 2018).

But DE is more than GIScience and technological development. Critical spatial thinking is a key aspect in geography as a discipline (Whyatt et al. 2011). Goodchild (2012) proposed that DE represents the full integration of geospatial technologies into the human activities of our daily life. In this sense, two learning objectives should be amended to the skill-based GIScience curriculum above:

- Critical spatial thinking, and
- Problem solving.

Thinking spatially enables better interpretation of a digital world to reach a solution: space (where); representation (what); reasoning (why); and analytics (how). Uttal and Cohen (2012) explored the relationship between spatial thinking and students' performance and attainment in science, technology, engineering and mathematics (STEM) disciplines. Similarly, it is integral to everyday life and fundamental to DE education. Without critical spatial thinking, students often ignore the context setting of spatial problems when using GIS and remote sensing software (Bearman et al. 2016). They may know very well how to run the models, but they also could have a difficult time understanding the extracted geo-information and therefore lack the ability to truly answer the complex spatial problems facing our world today. Unfortunately, many universities still organize their GIScience courses based on the transmission of knowledge rather than on questioning and problem solving (Cachinho 2006). With skills-based lectures and lab settings, the involvement of student's critical thinking in current GIScience curricula has been limited. As outlined in Bearman et al. (2016), DE educators can teach students to understand spatial issues in three aspects: spatial data, spatial processing, and spatial outputs and communication. This systematic set of training eventually links to a positive attitude of problem solving.

The challenge of developing DE curricula within such a rapidly changing technological environment has created the need to develop curriculum frameworks made of standards, guidelines, and building blocks that can be shared and transferred across educational providers, namely universities or private or government training agencies tasked with workforce development (Malhotra et al. 2018). Reasonably, DE education is restructuring from a skills-based to a competency-oriented model to meet the rapid evolution of societal and workforce needs (Schulze et al. 2013). Reflecting a variety of competencies, a number of geographic information science and technology (GIS&T) bodies of knowledge (BoK) have been identified to guide GIScience curricular development. For example, the University Consortium for Geographic Information Science Body of Knowledge (UCGIS BoK) has been adopted by the American of Association Geographers as a set of standards of GIScience learning (DiBiase et al. 2006). DE education could follow a similar curriculum framework from essentials to advanced functions. Its breadth of knowledge equips students with geospatial and problem-solving skills to assist human activities in our society (Kantor 2018).

Even with these frameworks, challenges still remain in preparing qualified personnel for both today and tomorrow. To leverage them, external activities for experiential learning such as internships have become common in academic and professional development. These activities are crucial in shaping a student's career pathway and their implementation should start as early as high school.

24.3.3 Experiential Learning: Academic Certificates and Internships

While academic degrees are still recognized as valuable for geospatial careers, the complexity of the digital world, the fast-paced workforce environment, and continuous technology innovation have all led to a focus on competencies. Good course performance toward academic degrees, however, may not directly fulfil specific workforce needs, especially in the Big Data era with rapid technological change (Kantor et al. 2018). By the time the technologies are taught, there is little time left for critical thinking, problem solving, and integration. Academic certificates and internships are then adapted to prepare students for their geospatial careers. By interacting with targeted communities, experiential learning activities enhance community engagement and foster critical spatial thinking of students in exploring cultural and political issues (Sinha et al. 2017). This, then, meets the ultimate goal of problem solving in DE development.

Academic certificates

Academic certificate programs are usually a series of courses provided by an educational institution. The certificate is granted as a proof that the coursework is taken and completed in a satisfactory manner. GIScience certificates, for example, have been offered as a suite of courses (12–21 credit hours) at numerous universities. The course sequence matches the learning outcomes of the geospatial curriculum framework.

The USGIF Geospatial Intelligence Certificate Program is an excellent example of academic certificates in the scope of DE. Currently there are seventeen USGIF accredited institutions in the United States and Europe offering a geospatial intelligence certificate or degree. Their course curricula bridge classroom learning and professional training and offer future decision-makers actionable insights about Earth and its people for business, humanitarian, security, and defense-related decisions. In general, current geospatial intelligence certificate/degree programs address three overarching educational objectives:

- to provide traditional students with a broad base of the knowledge, skills, and abilities requisite to work in the geospatial industry at an analyst level or higher;
- to offer a means of educating the non-traditional workforce by balancing work-related training provided in formal collegiate education; and
- to leverage education, training, and work experiences to obtain industry recognized credentials (certification and licensure).

Aside from technical and discipline-specific applied courses, all students seeking the geospatial intelligence certificate or degree also are required to complete a capstone project/experience. As an example, the following outlines the capstone requirements at Delta State University (Mississippi, USA), the first institution to offer an undergraduate geospatial intelligence degree:

- Applied projects: The program of work must demonstrate the use of geospatial technologies to improve workflow efficiencies, consequence analysis, new applications or methods, or improve return on investment.
- Applied geography: The program of work associated with an applied geography project must focus on improving the understanding of a geographic region through the use of geospatial technologies.
- Geospatial education: The program of work must demonstrate a need for the creation of educational materials pertaining to a common challenge encountered when using geospatial technologies.

Academic certificate programs have been in effect in various countries. A good example of international efforts is UNIGIS Distance Learning, a worldwide network of universities from nine countries and regions including Austria, Portugal, Spain, Hungary, Poland, Netherlands, United Kingdom, Latin America, and the United

States (https://unigis.net/). Initiated in 1990, UNIGIS offers professional diplomas, postgraduate certificates, and master's degree programs in six languages within its global network of fifteen Study Centers. All of these programs are in the fields of GIS, Geoinformatics, geospatial intelligence, and geospatial leadership.

Internship Programs

Traditional learning theories in academic curricula educate students for critical thinking, but often lack hands-on training to prepare them for authentic career work. To fill in this gap, many institutions have established internship programs to build a flexible learning environment for students to meet the rapidly evolving geospatial landscape. For example, the University of South Carolina (South Carolina, USA) offers an internship course—GEOG 595 (Internships in Geography)—as an experiential study for geography majors and minors. Through a semester-long internship contract with community partners, this 3- to 6-credit course prepares students for the workplace and give students an opportunity to explore career options and to put their skills into practice. For students in DE education, their internships engage with private and public partners in the geospatial community to support personalized learning. To establish a common ground for the program, it is crucial to build a community network across competencies that share mutual interests in geospatial analysis. The network comprises geospatial agencies and industries at local, state, regional, and national levels to support interns with activities that vary in terms of skill requirements and learning objectives.

The internship programs utilize a personalized curriculum and education metric. The evaluation of an intern's learning is job-specific. Given the diversity of internship activities for different interns, the learning outcomes cannot be quantified using traditional assessment schemes such as quizzes, homework, and exams. Kantor et al. (2018) propose discipline-based education research (DBER) in geospatial intelligence to better educate students to think about and understand their location-based tasks and to reflect back with improved outputs (Colom et al. 2010). The DBER strategy can be embedded in the internship courses. With job tasks and learning outcomes outlined in each internship contract, the intern perceives, understands, and embraces the critical connections between geospatial competencies and the degree-offering discipline. In this way, the curriculum is specifically designed to fit different student learning styles (Dolan et al. 2017).

The personalized curriculum adaptively helps an intern gain human intelligence on problem solving by observing, measuring, assessing and reporting the problems, and improving the individual abilities needed to cope with challenging situations. Human intelligence points to the fundamental difference between humans and machines when programming has reached its limits and run out of data (Hawkins and Blakeslee 2005). This type of adaptive learning (Posner 2017) is fundamental in DE curriculum development, but has been a major drawback in traditional unified curricula in classrooms.

Aside from the regular, full-time students in experiential learning, there is a growing student population formed of adult learners seeking to complete their degrees or to earn academic certificates. Many of these students return to school with work experience within the field and are looking to gain recognized credentials that would help them advance their careers. Among various skills programs, one good example is the Postgraduate Training Program operated by the Center for Spatial Data Infrastructures and Land Administration (CSDILA) at the University of Melbourne (Melbourne, Australia). The Center attracts world class postgraduates to gain specialized supervisory expertise in spatial data infrastructure. These students are motivated and informed (with experience), expect to apply newly gained knowledge and skills the next day, and thus create a different type of pressure on collegiate curricula. "Experience" is now expressed in various forms, carries a multitude of names (i.e. internship, apprenticeship, experiential learning, field-based training, and working knowledge), and has become part of the collegiate educational journey.

24.4 Digital Earth Education to Professional Careers

The rapid development of geospatial technology enables considerable employment growth in the geospatial technology industry as well as DE-related service employment sectors and fields. Geospatial technology has been identified as one of the three (along with nanotechnology and biotechnology) most important emerging and evolving fields with the highest number of new jobs (Gewin 2004). The U.S. Department of Labor reported an annual growth of 35% in the geospatial workforce (USDOL 2005). Upon a worldwide study by Oxera (commissioned by Google), the global geospatial services sector generated $150–270 billion per year (NSDI 2013). Various efforts, from academia to workforce, have been made to maximally prepare students for the ever-evolving geospatial world. For example, the Spatial Industry Business Association (SIBA), an association in Australia and New Zealand, has established an educational initiative, Geospatialscience, to build an interactive network that bridges school-age students with DE-related careers in the geospatial industry.

This section presents an example of DE education to professional careers in the field of geospatial intelligence, which has developed competencies to better complement DE by illustrating its real-world application. The geospatial intelligence model can serve as a catalyst for making the DE vision a reality via tools, expertise, and techniques, and integrate them into a new interconnected platform. Geospatial intelligence can bring these tools and perspectives forward to help extract actionable information from vast amounts of geographic data. Closely related to this chapter's topic, geospatial intelligence already has a framework for teaching and learning that could leverage DE education.

24.4.1 Geospatial Competency-Based Models

As early as 1999, Lucia and Lepsinger (1999) offered this definition of a competency: "… *a cluster of related knowledge, skills, and attitudes that affects a major part of one's job (a role or responsibility), that correlates with performance on the job, that* *can be measured against well-accepted standards, and that can be improved* via *training and development*." This definition leads to a formula where competencies (C) are proper subsets of well-accepted industry standards (IS), training (T), and performance on the job (PJ):

$$C \subset IS + T + PJ \tag{24.1}$$

This is a formula for training, but competencies also are becoming a major focus in education. Competency-based education provides the foundational knowledge, skills, and, most importantly, attitudes towards a profession. The purpose of "education" is to ensure the attainment of these specified knowledge, skills, and "attitudes" (Banathy 1968). Attitudes in particular are very volatile competencies and depend on external influences and self-motivation. They also are very difficult to assess and thus improve. In education, the previous formula would look different as it would need to incorporate these attitudes as essential in teaching students why to use the system and how to improve it (at the graduate level), not just how to build and operate it (technical training). Thus, the education formula is where competencies (C) are proper subsets of well-accepted (industry) standards (IS), education (E), and apprenticeship (A):

$$C \subset IS + E + A \tag{24.2}$$

Both education and apprenticeship help build not only knowledge and skills, but also attitudes designed and assessed according to industry standards. With changing demographics in student populations (e.g., an increase in adult learners), as well as changes in the modes of delivering educational and training content, attitudes are becoming an important competency to consider in both education and training.

24.4.2 Geospatial Frameworks

Looking back at the geospatial credentials market, despite all the societal advances in technology and connectivity, the 1999 view on competency-based training remains unchanged while education continues to grow more interconnected with industry standards. The major shifts in both have been witnessed by industry standards and attitudes which in turn have impacted knowledge and skills or abilities expected from the workforce. In building the geospatial workforce, several organizations have been using collaborative and cross-industry efforts to identify job specific competencies that are then followed by developing geospatial frameworks for competency-based collegiate (4 year and vocational) and training offerings.

Two prominent frameworks are the Geospatial Technology Competency Model (GTCM) designed by the National Geospatial Technology Center of Excellence (GeoTech Center) and the Geospatial Intelligence Essential Body of Knowledge (EBK) designed by USGIF. Both competency-based models have been developed with help from subject matter experts (SMEs) from across industry, government, and academia. The results should reflect the competencies needed by today's geospatial professionals and guide both educational and training curriculum development.

The GTCM was submitted to the U. S. Department of Labor (USDOL) in August 2018 and a working version was released in September 2018 (GeoTech Center 2018). The GTCM has become an important resource for defining the geospatial industry and a valuable tool for educators within the domain of geospatial technology. The University of Southern Mississippi's Geospatial Workforce Development Center conducted an initial effort in the early 2000s to define skills and competencies, an effort that led to the first draft of the GTCM. Work continued under the direction of the Geographic Information and Technology Association (GITA), the American of Association Geographers (AAG), and the Wharton School of Business at the University of Pennsylvania (DiBiase et al. 2006) but it remained a draft. In early 2009 the GeoTech Center became involved in the effort to complete the GTCM. A broad-based panel of geospatial experts were convened and suggested including two industry-related technical competencies: industry-wide and industry-specific, in the model. Public comments were sought, and comments were addressed with a final GTCM draft submitted to the U. S. Department of Labor's Employment and Training Administration's (DOLETA) Geospatial Technology Competency Model. The draft was approved by DOLETA in 2010. The industry has continued to evolve and grow and the GeoTech Center has undertaken the work to update the 2010 version of the GTCM. Partnering with DOLETA, the GeoTech Center updated the GTCM in 2014. The USDOL prefers that competency models are updated every four (4) years (GeoTech Center 2018). The 2018 GTCM update focuses on Tiers 1–5 as defined below:

- Industry-Related Technical Competencies:

  Tier 5—Industry-Specific Technical Competencies
  Tier 4—Industry-Wide Technical Competencies

- Foundational Competencies

  Tier 3—Workplace Competencies
  Tier 2—Academic Competencies
  Tier 1—Personal Effectiveness

USGIF produced the Geospatial Intelligence EBK by conducting a cross-industry job analysis to identify the knowledge, skills, and abilities critical to the geospatial intelligence workforce in consultation with psychometric consultants and the geospatial intelligence community. Qualified Subject Matter Experts (SMEs) from government, industry, and academia participated in each phase of the job/practice analysis to ensure an accurate reflection of geospatial intelligence practices. The Geospatial Intelligence EBK was revised in 2018 and published in 2019 with major additions and improvements. The GEOINT EBK describes geospatial intelligence competency and practice in terms of key job tasks and essential knowledge, skills, and abilities required for a professional to be successful. These are organized into four competency areas as described below.

- Competency I: GIS & Analysis Tools describes the knowledge necessary to ensure the various elements and approaches of GIS and analysis are properly understood in order to successfully capture, store, manage, and visualize data that is linked directly to a location.
- Competency II: Remote Sensing & Imagery Analysis describes the knowledge necessary to generate products and/or presentations of any natural or human-made feature or related object of activity through satellites, airborne platforms, unmanned aerial vehicles, terrestrially based sensors, or other similar means. This competency area contains the knowledge necessary to synthesize technical, geographic, and intelligence information derived through the interpretation or analysis of imagery and collateral materials as well as the processes, uses, interpretations, and manipulations of imagery for dissemination.
- Competency III: Geospatial Data Management describes the knowledge required to acquire, manage, retrieve, and disseminate data to facilitate integration, analysis, and synthesis of geospatial information.
- Competency IV: Data Visualization describes the use of cartographic and visualization principles to generate products that represent information about the physical environment that can be easily understood by decision-makers.

The Geospatial Intelligence EBK also includes cross-functional knowledge areas. These are necessary when there are widely accepted knowledge, skills, and abilities that transcend specific core competencies or where competencies are found across the full scope of practice. Cross-functional geospatial intelligence knowledge, skills, and abilities generally reflect:

- Qualitative "soft skills" used in geospatial intelligence,
- Unique aspects of the universal geospatial intelligence tradecraft applicable to the majority of practitioners and,
- Common geospatial intelligence knowledge and practices that, if followed, will improve the performance of a practitioner (USGIF 2018).

The Geospatial Intelligence EBK was initially developed for working professionals, not geared towards an academic curriculum. With the growth in the number of academic institutions offering geospatial intelligence credentials (certificates and, more recently, degrees), the EBK needed to be restructured for its broader audience. To make it more "academic friendly", USGIF has invested in recent updates of the Geospatial Intelligence EBK to include learning objectives at four different experience levels and designed with regards to Bloom's Taxonomy levels and psychometrics. Faculty will now be able to devise and maintain a master course map with formative and summative learning objectives as well as improve teaching and learning assessments. Assessment data, captured by faculty, will be used to evaluate student success with respect to each competency at the end of each semester. The academic certificates are expected to provide a basal measure of competency across the full spectrum of the Geospatial Intelligence EBK topics aimed at an "Essentials" exam (already piloted during Spring of 2019) level that will allow students who pass the exam to enter the professional world and gain an entry-level certification.

A geospatial intelligence degree is expected to provide the knowledge and skills required at the Certified GEOINT Professional (CGP) exam level. Institutionally designed frameworks for assessing student mastery is expected to be incorporated into their existent learning management systems (i.e. Blackboard, Moodle, Canvas) and the resulting data will be used to guide self-improvement. Student success rates with credentialing exams taken post-graduation and job placement also could serve as a secondary means of assessing program effectiveness. The 2018–2019 revision and updating of the Geospatial Intelligence EBK started from a “matrix” tool that was developed for each competency in the current EBK, followed by the identification of Emerging Geospatial Intelligence Competencies. Each matrix includes competency specific topic areas in the left column, as well as questions pertaining to each proficiency level (i.e., Prerequisites, Foundation, Application, Mastery/UGP) in the subsequent columns. The questions read as:

- Question 1: What do you need to know to be ready to learn about the Topic Area at a fundamental level?
- Question 2: What do you need to learn about the Topic Area at the fundamental level?
- Question 3: What do you need to know to apply the Topic Area?
- Question 4: What do you need to know to advance fundamental knowledge in the Topic Area?

The SMEs were then assigned a specific matrix to author, and added content indicating the knowledge and skills necessary to adequately address each topic area at the specified proficiency levels. Then, learning objectives for each matrix subtopic (i.e., knowledge and skills) were generated by the SMEs (Table 24.2).

Therefore, the new EBK features the following:

- Vetted learning objectives for each subtopic identified during the “deep dive” process.
- A numbering scheme for the EBK to facilitate easy communication and identification of learning objectives.
- A progression of subtopic knowledge necessary to grow and advance within a given competency.

The new EBK format is significantly more academic curriculum friendly and helps guide the pathway into geospatial intelligence learning starting from high school, moving into college, and then into the professional workforce. In addition, the newly updated Geospatial Intelligence EBK has identified and recognized the importance of a number of emerging areas, namely: Data Science, Use of varied datasets, Machine Learning, Virtual reality, Neural networks/AI, small Unmanned Aerial Systems (sUAS), Automation, and Critical thinking. Therefore, geospatial intelligence has both human and technical scopes. People are essentially trained to utilize various technical tools to understand human geospatial behaviour.

Today, the geospatial intelligence academic programs initially built upon the GTCM are shifting their curriculum towards the Geospatial Intelligence EBK to better reflect the program’s growth, maturity, and establishment as a standalone

Table 24.2 An example competency area (prerequisites) of remote sensing and imagery

Matrix subtopic	Learning objective(s)
Basic computer literacy	Execute basic computer tasks including typing, use of commercial software products, navigating file systems, reading and writing computer files, internet navigation, downloading and uploading files
Basic digital image processing	Summarize the steps taken to perform basic digital image processing Explain why digital image processing is performed
Remote sensing software package	List the common remote sensing software packages and their uses
Basic remote sensing process and components	Outline the basic remote sensing processes List the components that coincide with each remote sensing process
High school physics	Integrate high school physics principles (e.g., the electromagnetic spectrum, principles of light and optics, statics and kinetics etc.) with other areas of study (e.g., math, other science)
High school math (algebra, geometry, trigonometry, and statistics)	Explain how advanced math principles (e.g., algebra, trigonometry, geometry, and statistics) apply to other fields, such as science

geospatial discipline. Efforts are being made and there is a strong ongoing partnership between the GeoTech Center and USGIF to leverage the use and fusing of both frameworks for the benefit of the greater geospatial community. These frameworks are being updated so that all the programs of study can maintain currency and relevance to the discipline. To provide a balance of theory, technical skills development, and ethical reflection, the presentation of knowledge required to achieve professional competency would be sequential and interlocking. Programs of study should aim to first orient students to fundamentals before embarking on specialization, whereas specialization should serve as a means of broadening knowledge rather than limiting practice.

In addition to the GTCM and Geospatial Intelligence EBK, the National Science Foundation also has supported various projects aimed at the development of job/occupation specific Developing a Curriculum (DACUM) frameworks (e.g., GeoTech Center produced a DACUM for GIS & Remote Sensing, Northland Community College DACUM for the sUAS maintenance technician, etc.). These newly updated competency models demonstrate a movement towards making them more “education friendly” via the introduction of learning objectives and outcomes as well as a separation into levels of expertise based on Bloom’s Taxonomy. This again demonstrates the need for a continuum between education and training in building career pathways.

24.4.3 Geospatial Credentials: Certificate Versus Certification

Despite significant efforts towards establishing, maintaining, and updating the competency models in the geospatial community, the geospatial credentialing market use of the terms certificate and certification is confusing. There is ambiguity over the terms as well as the credit value between course-based academic certificates offered by numerous universities and those certificates and certification obtained after attending an hour, a half-day, a full-day, or several days/weeks/months of training in person or online.

The Cambridge Dictionary defines certification as "*a proof or document providing that someone is qualified for a particular job, or that something is of good quality*". It then goes further to imply that, for example, more adult workers are going back to school for a certification to improve their job opportunities. Based on the current credentialing market, the rule of thumb is that certifications are geared towards to-be-certified professionals; that individuals are at least at the journeyman level with a balanced combination of educational credentials and hands-on, practical work experience; and that the credential needs to be maintained through Continuing Education of Professional Development Units. One exception is Esri's Technical certification that does not require maintenance because it is largely focused on Esri's software as opposed to the software agnostic certifications offered by the aforementioned professional organizations.

In comparison, an academic certificate does not require maintenance once students complete the required courses. Therefore, certifications and certificates can be divided into three different major categories, all functioning under a larger "credentials" umbrella (Fig. 24.2).

The American Society for Photogrammetry and Remote Sensing (ASPRS), the GIS Certification Institute (GISCI), the National Geospatial Intelligence Agency (NGA) GEOINT Professional Certification (GPC), and the USGIF Certified

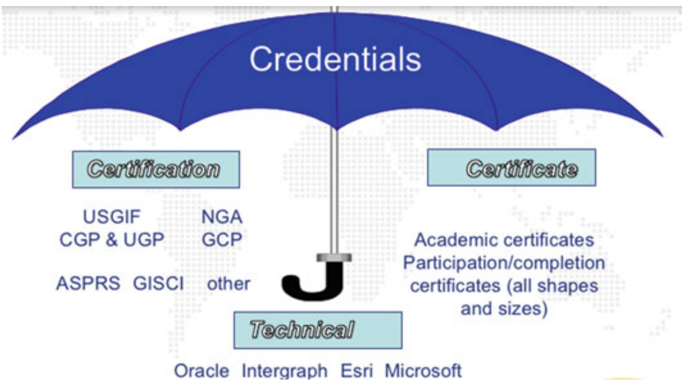

Fig. 24.2 Geospatial credentials

GEOINT Professional (CGP) and Universal GEOINT Professional (UGP) are major players in the professional geospatial certification arena (Fig. 24.2). These groups are making significant efforts to maintain software agnostic credentials. These credentials can be earned by documenting relevant educational achievements, professional experience, contributions to the profession, and by affirming a commitment to ethical practices.

In brief, ASPRS is a scientific association serving thousands of professional members around the world with the mission "to advance knowledge and improve understanding of mapping sciences to promote the responsible applications of photogrammetry, remote sensing, geographic information systems (GIS) and supporting technologies" (ASPRS 2004). ASPRS offers ten certifications (Table 24.3) geared towards photogrammetrists, mapping scientists, and technologists. GISCI is a non-profit organization that provides the GIS community with a certification program leading to GISP® (Certified GIS Professional). NGA offers the government a focused GEOINT Professional Certification (GPC) program as part of a broader Under Secretary of Defense for Intelligence (USD(I)) initiative to further professionalize the Department of Defense Intelligence Enterprise (DIE) workforce (NGA 2018).

USGIF is a more recent addition to the professional certification community, but the only one to offer a sequence of geospatial intelligence credentials that range from rigorously evaluated academic curricula via USGIF accreditation of certificates and degrees to the offering of an Essentials (entry-level) exam and professional certifications. The USGIF accredited programs offer certificates that require at least 18 (undergraduate) or 12 (graduate) credits of coursework, including a capstone project resulting from research, internship, or apprenticeship work. The value of these certificates is considered superior to that of other "certificate" credentials given the depth and breadth of required curricula. With the spring 2019 planned introduction of its Essentials exam and its ongoing K-12 curricula development efforts, USGIF intends to bridge the gap between high school prerequisites, collegiate credentials, and professional certifications in a continuum of building blocks based on the Geospatial Intelligence EBK (USGIF 2018).

The Open Geospatial Consortium (OGC) "*provides a consensus process that communities of interest use to solve problems related to the creation, communication and use of spatial information*" through the OGC Standards Program and, lately, its own certification and training (Open Geospatial Consortium 2018). OGC's standards are used by its community of interest which includes those in aviation (air travel safety and operational efficiency), built environment and 3D (open standards to support productivity across the supply chains of the building design, physical infrastructure, capital project and facilities management industries), energy and utilities, emergency response and disaster management, business intelligence, and defense and intelligence. In academia, OGC provides a fertile environment in which university geomatics, computer science, geography, and geoscience departments can modernize and advance their curricula.

Table 24.3 Examples of professional certifications

Specification	Professional certifications	Technical certifications
GIS (and Spatial Analysis)	ASPRS (Photogrammetrist, Mapping Scientist-Remote Sensing, Mapping Scientist-GIS/LIS, Lidar, UAS)	ASPRS (Photogrammetric Technologist, Remote Sensing Technologist, GIS/LIS Technologist, Lidar Technologist, UAS Technologist)
Geospatial Technology	URISA/GIS Certification Institute-Certified GIS Professional (GISP)	ESRI Technical Certification
Geospatial Science	NGA-GEOINT Professional Certification (GPC)	ORACLE Spatial Essentials
Geospatial Intelligence	USGS—Digital Aerial Certification	Microsoft technical certifications
Remote Sensing	USGIF Certified GEOINT Profes-sional—GIS & Analysis Tools (CGP-G), Remote Sensing & Imagery Analysis (CGP-R), Geospatial Data Management (CGP-D) and Universal GEOINT Professional (UGP) designation	
UAV, UAS (Unmanned Aircraft Systems Maintenance Technician	Federal Aviation Administration (FAA)—Unmanned Aircraft Systems certification	
Web (CSW), Geopackage, Geography Markup Language, KML, Sensor Observation Service, Simple Feature Access, Web Coverage, Web Feature and Web Map Service	Open Geospatial Consortium (OGC)	
Other	Mississippi Enterprise for Technology (MsET)- SPACE and STARS Certifications	

As evidenced in this section, there have been significant advances in the geospatial educational and professional communities. Most organizations agree that competencies are best learned by following updated frameworks that are in line with industry standards as well as through experiential educational practices which include practicum, cooperative learning, internships, and that have no cost limitations. The geospatial intelligence community has achieved significant partnerships and shared credentialing but is still working to achieve full collaboration. A shared understanding of the end value is needed to reduce the uncertainty of value and disruption in academia.

24.4.4 Geospatial Intelligence Bridging Academic and Professional Connections

The rapidly evolving geospatial intelligence field demands that academic education and professional training complement each other. The community educates students in critical spatial thinking and the conceptual use of technology to solve unstructured problems, while training focuses on increased performance in described circumstances (Kantor et al. 2018). The critical balance of academic education and practical skills training, which is necessitated throughout a geospatial intelligence professional's career, is illustrated by the age-old adages of individuals "*being educated but poorly trained*" or "*well-trained and poorly educated*" (Burrus 2016).

The core of geospatial intelligence includes providing geospatial insights to decisionmakers about human needs and potentially addressing the impact of false geospatial information that arises in a competitive environment. As a meta-discipline, it entails a view of professional know-how unbounded by typical academic and organizational limits and barriers. This is to say, geospatial intelligence is not simply a collaboration of fields, but rather a fundamental merging of disciplines in theoretical and practical ways. This implies that for one to legitimately be an expert in geospatial intelligence and DE, the individual must have know-how in many traditional domains including the technical, the human, and the problem's domain.

Geospatial intelligence also is polymorphic which explains the discipline's definitional challenge. This elusive explanation is similar to that described in the Indian parable of the blind men trying unsuccessfully to identify an elephant by touching just one of its different parts. As the poet Godfrey Saxe (1816–1997) wrote, "…, *each was partly in the right, they all were in the wrong*" (Saxe 1963).

Geospatial intelligence is a sub-discipline of geography being offered in forms of certificates and academic degrees at universities in the United States and Europe and is also cross-disciplinary in nature. It is still evolving. Moving beyond defense-related issues, the field now is leading the integration of concepts and practices in oil and gas, health, business, precision agriculture, and emergency response to name a few. It benefits engineers who build and improve weather satellites, scientists who gather measurements of atmospheric, terrestrial, and oceanic conditions, database managers, Big Data analysts, business analysts who conduct cost and marketing analyses, political scientists involved in national and international conflict resolution, law enforcement in their efforts to not only reduce but mitigate crime, and even farmers seeking the best options to increase their yields.

While some are still hesitant to embrace geospatial intelligence because of its historic association with the U. S. intelligence community, there is growing understanding that geospatial intelligence, like DE, brings a unified geospatial approach to addressing the human and environmental challenges of today and tomorrow. It has been practiced by many nations although often different terminology is used. Research on the United Kingdom and Russia highlights the lesson that success in geospatial intelligence is the combination of the utilitarian aspects of technology mixed with a sophisticated understanding of the mental maps of our self, our partners, and our rivals (Bacastow 2019). Geospatial intelligence's evolution offers a model of how DE could leverage education and training to advance the perspective where politics and culture are resistant. Geospatial intelligence's experience offers DE an example of how a cohesive curriculum can advance and help to define value.

24.5 The Future of Digital Earth Education

Based upon a decade of dialogue hosted by the ISDE, three Pivotal Principles have been identified to guide DE development in the 21st Century: open data, real-world context, and informed visualization for decision support (Desha et al. 2017). These principles call for higher accessibility and a broader, interdisciplinary context of Big Earth Data and advanced analytical visualization skills for sustainable governance and decision making. This is necessary for building an overarching framework for future DE education from K-12 to professional careers.

24.5.1 DE Future in K-12

DE technologies show great promise and growth potential in K-12 education, however, a number of impediments remain. Some obstacles are technical while others are institutional. As technology penetrates classrooms more readily as infrastructure and hardware costs decrease (more so in developed rather than less developed countries), it is the latter problem—institutional—that requires greater intervention. Focusing on improving pre-service teacher training programs to include more geography and DE technologies can encourage greater use and application. This will need to be followed with intensive feedback and coaching with established teachers. Research has shown that these concerns appear across the globe (Germany, Hong Kong, United States, United Kingdom, elsewhere); time and monetary resources will need to be put in place to effect substantive change. A second necessity will be to include DE technologies within academic standards. These agreed upon learning objectives drive curriculum, and if DE is specifically included then usage will rise. A number of countries have successfully done so already, but these are countries with centralized national curricula. Countries with decentralized education systems will likely remain fragmented in their K-12 DE development. In sum, K-12 DE use currently remains scattershot and spatially variable. Although exciting projects appear in a few special cases, large-scale implementation has been elusive, and DE's K-12 potential remains untapped.

24.5.2 Micro-credentials

Credentials, in the form known by us today, may be very different in the future. Customization may include different time frames and delivery formats, as well as learning content that is narrower and focused on specific technologies and competencies, and delivered via transportable and transparent credentials and by traditional (universities) and/or less traditional (industry) institutions. Ultimately, all credentials should serve a larger purpose—that of building a networked human society ready to tackle the environmental, social, and economic challenges that lie ahead.

To address the rapid changes in technology and workforce competency needs, the future seems to favor a combination of credentials, from the micro-credentials enhanced by digital badges to degrees and certificates. More recent on the credentialing market, a micro-credential is a digital currency that recognizes competency in a specific task, knowledge, or skill and that the individual can use and share across various outlets (e.g., LinkedIn, Facebook) to enhance their marketability and give them a competitive edge (e.g. it can be combined with digital badges). Created as self-paced, shorter modules, micro-credentials can be more easily designed to mirror changing market trends. Also, they can be more affordable and easily digested by potential students, especially by the adult learners. Micro-credential requirements vary significantly from credential to credential since anyone can grant them and there are no official requirements.

Typically, micro-credentials are shorter than other credential options like college degrees or certificate programs; however, that is not always the case since the requirements are usually determined by the credential-granting institution. Because of the lack of consensus in terms of format and definition of what micro-credentials should entail, the reputation of the institution offering them still plays a major role in one's decision to pursue these credentials.

If carefully designed and implemented, they represent creative ways to bridge the gap between traditional higher education and 21st century technology and beyond. However, while designed for a specific purpose, micro-credentials should be thought of and planned in sequences and represent milestones in one's educational pathway (e.g. used toward a certificate and/or degree) and professional development. The existent geospatial models should be used as frameworks in the design of DE credentials to reflect annual changes and create a common language across the geospatial community.

24.5.3 Challenges and Opportunities for DE Education and Professional Development

Today, it is not surprising that DE-related credentials support the acquisition, understanding, management, analysis, visualization and (to some extent) ethics of data. According to Grossner and Clarke (2007), the term DE has come to represent a global technological initiative, but also "an intellectual movement." While the human aspects of DE were articulated by Foresman (2008), the current DE focus is still on the technical issues of the problem without much regard to its human aspects. The vision of DE should not be solely about space and spatial relations but also about place, culture and identity, spanning the entire physical and virtual space (Craglia et al. 2012). This new vision is still only slowly being adopted and there is uncertainty related to the needed competencies required in the preparation of future DE specialists. The future of DE should be planned on several important pillars:

- Education: provides a liberal arts background, methodologies, and depth as well as breadth of thinking. The human is ultimately where knowledge work is done and those insights are produced in geospatial intelligence. It is dependent on the geospatial analyst's meta-knowledge.
- Training/Professional development: built on education and expanding the knowledge base for increased performance. The training and professional development should focus on the human-machine team where there is a focused effort to develop information about relationships among disparate objects and events.

DE education and professional development can be implemented in several subsets as below:

- Competencies: industry-based but also focused on improving attitudes towards the discipline and the understanding of its larger, community implications.
- Technology: seen as a needed but also ubiquitous tool where abilities improve with experience and require flexibility to adjust to rapid changes;
- Leadership: the capacity to have a balanced combination of education and training/professional development to gain a holistic understanding of the problem beyond technology, combined with vision, a positive attitude, and strategic thinking.
- Research: the capacity to have a higher level of education and training/professional development coupled with imagination, creativity and positive attitudes to further contribute to the advancement of geospatial theory and knowledge as well as new improved technologies and innovative ideas.
- Education research: discipline-based education research (DBER) focused on better understanding the science of teaching and learning within and across geospatial disciplines and with sufficient resources to contribute to improved pedagogy and andragogy.

These subsets can fit under both education and training/professional development in various forms and shapes. While there is a classic continuum of education moving into training/professional development, the future movement may not be linear, but circular in nature. Certificates, certifications, and micro-credentials can be customized to fit individual pathways at different times in one's career. High levels of flexibility, creativity, positive attitudes, and time-relevant education research and implementation will be vital in a society rapidly embracing the Digital Earth. We have been deeply transformed by a (geo)digital revolution, reaching a moment where technology is becoming a commodity more so than a skill. The future will (hopefully) bring us back to what makes us intelligent creatures on Earth, ones capable of innovation, creativity, imagination, and ethical conduct.

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Cuizhen Wang is a Professor of Geography at the University of South Carolina, USA, with primary research in bio-environmental remote sensing and Big Earth Data. She is a USGIF Subject Matter Expert in Remote Sensing and Image Analysis, a member of the DBAR Coastal Work Group and the Director of the ICoE on Big Earth Data for Coasts.

Camelia M. Kantor is a VP of Academic Affairs at the United States Geospatial Intelligence Foundation. With 17 years of educational experience, she leads academic institutions of higher education via the Collegiate Accreditation, serves as a Subject Matter Expert, manages professional certification efforts, and serves as a geospatial spokesperson.

Jerry T. Mitchell is a Research Professor of Geography at the University of South Carolina, USA. He has been the Editor of the Journal of Geography since 2010 and will serve as the President of the National Council for Geographic Education in 2020.

Todd S. Bacastow is a Teaching Professor in Department of Geography at the Pennsylvania State University, USA. His primary focus is teaching analysts serving with the intelligence and business communities, maintaining an active research program on improving the training and education of the geospatial analyst. He authored the Massive Open Online Course (MOOC) that was delivered to over 25,000 students in 190 countries.

Chapter 25
Digital Earth Ethics

Yola Georgiadou, Ourania Kounadi and Rolf A. de By

Abstract Digital Earth scholars have recently argued for a code of ethics to protect individuals' location privacy and human dignity. In this chapter, we contribute to the debate in two ways. First, we focus on (geo)privacy because information about an individual's location is substantially different from other personal information. The compound word (geo)privacy suggests that location can be inferred from people's interests, activities, and sociodemographics, not only from traditional geographic coordinates. (Geo)privacy is a claim of individuals to determine for themselves when, how, and to what extent location information about them is communicated to others. Second, we take an interdisciplinary perspective. We draw from (geo)computing to describe the transformation of volunteered, observed, and inferred information and suggest privacy-preserving measures. We also draw from organization studies to dissect privacy into ideal types of social relationships and privacy-preserving strategies. We take the point of view of Alice, an individual 'data subject' encountered in data protection legislation, and suggest ways to account for privacy as a sociocultural phenomenon in the future. Although most of the discussion refers to the EU and the US, we provide a brief overview of data protection legislation on the African continent and in China as well as various global and regional ethics guidelines that are of very recent vintage.

Keywords Ethics · Geoprivacy · Spatial data · Inference attacks · Privacy-preserving measures

25.1 Introduction

The previous chapters of the Manual of Digital Earth describe remarkable progress to date. Key technologies envisioned by Vice President Gore in 1998 are now in place for the first-generation and next-generation Digital Earth (DE). Similar progress in DE ethics is not yet evident despite the early ethical stirrings in the geographic community. As early as 1990, at a roundtable on *Ethical Problems in Cartography*,

Y. Georgiadou (✉) · O. Kounadi · R. A. de By
Geo-Information Science and Earth Observation, University Twente, Enschede, The Netherlands
e-mail: p.y.georgiadou@utwente.nl

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Brian Harley wondered whether cartography was out of step with other disciplines. He suggested that the real ethical priority is for a map to be a socially responsible representation of the world: *"Can there be an ethically informed cartography and what should be its agenda? [S]hould we be concerned with transcendental values that go to the heart of social justice in the world at large?"* (Harley 1991, p. 9). In this chapter, we update Harley's vocabulary for the current era of datafication of everyday life (Cukier and Mayer-Schoenberger 2013) and explore the *Ethics of Where* instead of the ethics of cartography. This leads us to recent debates on data justice—fairness in the way people and their resources are made visible, represented and treated as a result of their digital data production (Taylor 2017).

In 2012, DE scholars observed that any effort to develop a next-generation Digital Earth will require a principle of privacy protection that minimally guarantees control over any individual's locational privacy and the ability to turn it on or off at will. They noted, *"there is also room for a Digital Earth code of ethics that could set standards for behavior in a complex, collaborative enterprise [...] necessary to tackle the growing issues of privacy and ethics that are associated with access to fine-resolution geographic information"* (Goodchild et al. 2012, pp. 11092–3). In 2014, some of the authors of the previous paper reiterated the call for privacy and reaffirmed the need for a code of DE Ethics. They argued that *"technological advancements have to be accompanied by the development of a DE code of ethics that ensures privacy, security, and confidentiality in a world where everybody can be connected to everybody else and everything all the time. Without solving this critical dilemma and allowing people to decide whether or not they want to be connected and how much of their thoughts and emotions they want to share, the dream of a wonderful virtual future may well turn into DE nightmare"* (Ehlers et al. 2014, p. 13). They boldly suggested that Digital Earth should follow the Kantian ethics of personal autonomy and human dignity in composing its code.

An obvious source of inspiration and lessons for such a code are the practices of the Association for Computing Machinery (ACM), which represents and regulates the behavior of a global computing community of approximately 100,000 members. In 2018, the ACM updated its Code of Ethics and Professional Conduct to address the significant advances in computing technology and the growing pervasiveness of computing in all aspects of society (ACM Code Task Force 2018). The responsibility to respect privacy, one of the seven general ethical principles in the ACM Code of Ethics, applies to computing professionals in a profound way. The ACM urges computing scholars and professionals to become conversant in the various definitions and forms of privacy and understand the rights and responsibilities associated with the collection and use of personal information. The ACM appeals to all computing professionals, including current and aspiring practitioners, instructors, students, influencers, and anyone who uses computing technology in an impactful way. Given that big computing companies have a significant impact on society, we should explore how their views on privacy have diverged over time from the current ACM ideal and how they contest privacy as a concept. Some consider privacy irrelevant. As early as 1999, Scott McNealy, the founder and CEO of Sun Microsystems, declared *"you have zero privacy … get over it,"* a statement some in the privacy industry took as tantamount to a declaration of war (Sprenger 1999). Others consider it an evolving social norm. In 2010, Mark Zuckerberg claimed that *"people have really gotten comfortable not only sharing more information and different kinds, but more openly and with more people," he said. "The [privacy] social norm is just something that has evolved over time"* (Johnson 2010). Others such as Apple CEO Tim Cook note that *"the poor privacy practices of some tech companies, the ills of social media and the erosion of trust in [Cook's] own industry threaten to undermine "technology's awesome potential" to address challenges such as disease and climate change"* (Romm 2018).

Privacy is a contested concept for good reasons. First, the etymology—the history of linguistic forms—reveals how privacy changed meaning from derogatory to laudatory. The ancient Greek word ἰδιώτης (pronounced idiōtēs) originally meant a private man, an ignoramus, as opposed to δημόσιος (pronounced dēmosios; meaning 'of the people'), a person of public distinction (Liddell and Scott 1940). Currently, the stem of idiōtēs forms the word idiot and dēmos is one of the two stems of democracy. The word private in Latin meant 'deprived' of public office–privacy designated a (negative) state of deprivation. For instance, a private in the army is a person with no rank or distinction and very little privacy (Glanville 2018). Second, privacy is contested because it can be portrayed in various competing ways—as a positive or negative right (Floridi 2014); as an instrument for Kantian ethics—human dignity and personal autonomy; and as an instrument for Aristotelean virtue ethics—personal development and human flourishing (van der Sloot 2014). The watershed US Supreme Court case, *Kyllo v. United States*, reported in Mulligan et al. (2016) and reproduced in the box below, is an example of how a seemingly simple case of home privacy violation was contested by the defendant, the federal government and the Supreme Court in 2001. The five to four decision of the Supreme Court eventually upheld the Fourth Amendment—the right of an individual to retreat into his own home and be free from unreasonable governmental intrusion, in this case, free from the intrusion of a thermal imaging device deployed by a federal agent to scan the outside of Kyllo's home (US Supreme Court 2001).

Kyllo v. United States involved an investigation of a marijuana cultivation and distribution operation in which a federal agent used a thermal imaging device to scan the outside of Kyllo's home. The resulting thermal image was used to obtain a warrant to search the house. Kyllo moved to suppress the evidence recovered from the search of his home, arguing that the use of the thermal imaging device to scan it was an invasion of his reasonable expectation of privacy. In a five to four decision, the Supreme Court held that 'obtaining by sense-enhancing technology any information regarding the interior of the home that could not otherwise have been obtained without physical "intrusion into a constitutionally protected area", constitutes a search—at least where (as here) the technology in question is not in general public use'.

The Kyllo case was contested at every level. The parties disagreed over the object of privacy under contention. The government argued that Kyllo had no expectation of privacy in 'the heat emitted from the home', while Kyllo argued that what privacy protected was the 'private activities' occurring within the home. The five justices who made up the majority determined that the case was about the 'use of technology to pry into our homes', the related matter of the sanctity of 'private lives', and the need to draw a not only 'firm but also bright' line to protect the sanctity of the home and the activities occurring within it. During oral argument, the justices drew attention to evidence provided to the appellate court revealing that a thermal image reading could 'show[ed] individuals moving . . . inside the building' to emphasize that what was at risk was not data, but 'what's going on in the house'.

The dissenting justices drew a distinction between 'through-the-wall surveillance that gives the observer or listener direct access to information' and 'inferences from information in the public domain' explaining that inferences drawn from 'gathered data exposed on the outside of petitioner's home' did not intrude on privacy. Justice Stevens's writing for the dissent explained, 'it would be quite absurd to characterize [the police's] thought processes'—the inference they drew from the data that seeped through the walls—as 'searches'. The majority justified its decision to prohibit the use of thermal imagers absent a warrant in order to protect the privacy of in-home activities on the basis that 'at the very core' of the Fourth Amendment 'stands the right of a man to retreat into his own home and there be free from unreasonable governmental intrusion'. The ruling was justified by the need to limit the Government's access to individuals' private lives.

Currently, the dissenting judges' claim that inferences drawn from thermal imagery of Kyllo's home were not an intrusion of his privacy but only the *'police's thought processes'* and the government's assertion that *'the heat emitted from the home'* is not private seem normal. In the Netherlands, heat detection from police helicopters is not considered systematic government observation (Hennepadvocaat 2019) and thus constitutes legal proof. Our location and movement, tweets, emails, photos and videos, purchases, our every click, misspelled word, and page view—are routinely observed by government and big tech via mobile phones, surveillance cameras, drones, satellites, street views, and corporate and government databases to draw inferences that can control, predict and monetize our behavior. Siegel (2013) notes that an individual's data can be purchased for approximately half a cent, but the average user's value to the Internet advertising ecosystem is estimated at $1,200 per year. Wall Street values tech giants, not because of the services they provide but for the data they collect from individuals and its worth to advertisers (Halpern 2013). Ironically, these data may be emitted by millions of automated accounts, each sold by obscure companies many times over, or celebrities, businesses or anyone desiring to exert influence online, according to a New York Times investigation (Confessore et al. 2018).

These facts have not escaped the public's attention. The Snowden revelations (Greenwald and MacAskill 2013) and the Cambridge Analytica scandal (The Guardian 2018) were probably the biggest contributors to citizens' changing perceptions of privacy, though not in the way Zuckerberg predicted in 2010. People care now more about privacy, and liberal governments responded accordingly. A 2018 survey by The Atlantic found that in the USA, *"overall, 78.8 percent of people said they were "very" or "somewhat" concerned about the privacy of their information on social media, and 82.2 percent said they self-censor on social media"* (Beck 2018). In 2018, legislation was passed in Vermont to regulate data brokers and California gave its residents the right to be informed about the kinds of personal information companies have collected about them, as well as the right to request that their personal information be deleted. Colorado-based companies will be required to, among other things, dispose of certain kinds of personally identifying information. The different types of information prone to compromise individual privacy are explained in detail in Sect. 25.2. Overall, two thirds of Americans are now eager to see stricter privacy laws (Halpern 2018). On May 25, 2018 the General Data Protection Regulation (GDPR) came in force to protect individuals in the 28 member countries of the European Union, even if their data is processed elsewhere. The GDPR applies to publishers, banks, universities, most Fortune 500 companies, ad-tech companies and the Silicon Valley tech giants. With the GDPR, *"companies must be clear and concise about their collection and use of personal data like full name, home address, location data, IP address, or the identifier that tracks web and app use on smartphones. Companies have to spell out why the data is being collected and whether it will be used to create profiles of people's actions and habits. Moreover, consumers will gain the right to access data companies store about them, the right to correct inaccurate information, and the right to limit the use of decisions made by algorithms"* (Tiku 2018).

Ethical issues arising in studies of our planet, as a system involving natural, man-made and hybrid processes, are enmeshed with scientific or industrial practices. Professional codes of ethics safeguard the public good by requiring honesty, trust and fairness, and the avoidance of harm. Respect for privacy and other people's work addresses concerns of intrusion and intellectual property. Studies involving geospatial information may be riddled with ethical ambiguity because professional responsibility requires acknowledging that the proposed methods may not travel well to other geographies. In short, location is burdened with contextual specifics. If such specifics are not parameterized, the earth sciences are vulnerable to the reproducibility crisis (Baker 2016). Ethics in Digital Earth methods are thus fundamentally important to study, and we expect open science approaches (Vicente-Saez and Martinez-Fuentes 2018) to mature in coming years and allow improvement of their methodical robustness.

In this chapter, we contribute to the *Ethics of Where* in two ways. First, we focus on information privacy, and location privacy, or (geo)privacy. This is necessary because information about an individual's location is substantially different from other kinds of personal information. The reasons for this include the ease of capturing an individual's location, the improvement of a service when the user shares their location with a service provider, and the potential to infer sensitive information about social, economic or political behavior from location history (Keßler and McKenzie 2018). Data inferred from an individual's location are socially constructed. If a society considers a given mode of personal behavior—e.g., political opinion, sexual orientation, religious or philosophical beliefs, trade union membership—to be socially legitimate, then these data are deemed personal and worthy of protection. We define privacy as a positive right concerning *"the claim of individuals to determine for themselves when, how, and to what extent location information about them is communicated to others"* because control of location information is the central issue in location privacy (Duckham and Kulik 2006, p. 36). Second, we complement other studies that describe the current state of the art and formulate challenges (Keßler and McKenzie 2018; Zook et al. 2017) or describe different scenarios concerning the development of geoprivacy (Wegener and Masser 1996) and revisit them (Masser and Wegener 2016) by taking an interdisciplinary perspective. We draw from the field of (geo)computing to describe the transformation of volunteered, observed, and inferred information (Sect. 25.2) and suggest privacy-preserving measures (Sect. 25.4). We draw from organization studies to dissect privacy into some ideal types of social relationships and strategies (Sect. 25.3), and draw from cultural theory to suggest future research (Sect. 25.5). The final section provides a brief overview of data protection legislation on the African continent and in China as well as various global and regional ethics guidelines.

We use the compound word (geo)privacy to suggest that, although control of location information is the central issue, location can be inferred from people's interests, activities, and sociodemographics, not only from 'traditional' location information, e.g., geographic coordinates (Keßler and McKenzie 2018). Further, we emphasize the distinction between privacy as a negative right (freedom from interference) and privacy as a positive right (freedom to control). This is because old, predigital technologies—such as the instantaneous photographs and newspaper tabloids in Brandeis and Warren's time—restricted individuals to claiming privacy as a negative right only, as freedom from interference or '*the right to be left alone*' (Warren and Brandeis 1890). New digital technologies can reduce or significantly enhance privacy as a positive right, i.e., the freedom to control (Floridi 2014), often in combination with social and/or organizational and/or legal measures/strategies (Mulligan et al. 2016).

25.2 Transforming Volunteered and Observed Data to Inferred Data

We distinguish three types of personal data: volunteered, observed and inferred data. These new types replace the old, 'personal, nonpersonal' data distinction, which has outlived its usefulness in the era of datafication. We define the three data types as suggested by the World Economic Forum (2011, p. 7): "*Volunteered data are created and explicitly shared by individuals, e.g. social network profiles. Observed data are captured by recording the actions of individuals, e.g. location data when using cell phones. Inferred data are data about individuals based on analysis of volunteered or observed information, e.g. credit scores.*" These three types involve both spatial and nonspatial data. We define spatial data as data that includes explicit coordinates interpretable in an open, well-known system. Examples are map coordinates, postal codes and street addresses. We do not think of mobile cell tower numbers as spatial data because special insight into the coding mechanism is required to understand their location.

To explain how volunteered and/or observed spatial data can be transformed into inferred data, we describe spatial data types with private or confidential components and provide examples of possible inference attacks on them. In principle, the subjects of these data types can be humans, organizations, groups of people, animals, nonliving physical objects such as buildings, or other confidential information with location attributes. Here, we focus on individual humans as data subjects. Hence, we drop the term 'confidentiality' and focus on 'privacy' because data classified as confidential (e.g., health records) is also private at an individual level. Similarly, inferences or inference attacks refer to private data that can be derived for each individual included in a spatial dataset.

We define a key identifier as an attribute that can be exploited with minimal effort to identify a subject. According to the Health Insurance Portability and Accountability Act (HIPAA) Privacy Rule, some common key identifiers are a person's name, telephone number, fax number, street address, electronic mail address, social security number, vehicle license plate, device identifier, biometric identifier, facial image, Internet protocol (IP) address, and web universal resource locator (URL) (U.S. Government Publishing Office 2009). Other potential key identifiers are account names on Internet platforms (e.g., in social media applications) and coordinate pairs of private information (e.g., location of households). In some cases, a key identifier links private information to a single individual only for a subset of the data. For example, in a dataset with locations of households, a small percentage corresponds to single-family houses (or detached houses) with only one occupant. The key identifier is a direct identifier for this subset. In other cases, a key identifier links private information to a small group of people closely related to the subject. This group may be family members who become emotionally traumatized if their private information is released or may be other house occupants that are incorrectly identified as the subjects. In addition, we define a quasi-identifier as an attribute that pinpoints a subject uniquely or almost uniquely, when combined with at least one other quasi-identifier attribute. A unique identifier (UID) is an attribute that allows for uniquely identifying single subjects. In some cases, a UID can be a key identifier (e.g., social security number, which identifies a subject), in others, its value may not be subject-specific, for instance, if it identifies a drug brand or a pharmaceutical factory process number, which cannot be used to disclose private information. Finally, a private attribute is any attribute that is not a key identifier, a quasi-identifier, or a UID, and contains other information about the subject from which inferences regarding privacy can be drawn.

The above data typology focuses on the usefulness of spatial or non-spatial data in inferences that affect privacy. Below, we discuss a second data typology that characterizes the roles of spatial and temporal attributes.

The simplest spatial data type is *'discrete location data'* (abbreviated *Dd*); it is a collection of one or more key spatial identifiers. The disclosure of this data type implies disclosure of subjects linked to the private information or to a small circle of possible subjects for each key identifier. Examples of *Dd* are the locations of domestic violence events and addresses of cancer patients. In both these cases, subjects can be identified as a person living at the disclosed location. As with all the data types discussed here, we assume that the data holder can interpret the data because they are aware of the contextual information that defines the search (e.g., "this is a collection of addresses of cancer patients").

A second data type is *'discrete location data with covariates,'* hereafter referred to as *Dd* + . The "+" symbol extends the notion of *Dd* by including additional attributes. The additional attributes are one or more quasi-identifiers. Quasi-identifiers are demographic, social, or economic attributes. A private attribute may or may not be present. An example of *Dd* + is a crime dataset of locations of offences (key identifier), the age of the victim (quasi-identifier), the ethnicity of the victim (quasi-identifier), and the type of the offence (private attribute). The location of offence is a key identifier, at least for that subset of the data collection where the type of offence occurs predominantly in residential addresses.

An inference attack on *Dd* and *Dd* + data types aims to identify (or re-engineer) the location of some subject(s). The data may not be disclosed but presented as a printed or a digital map. Such media can be geoprocessed to re-engineer the locations with considerable accuracy (Brownstein et al. 2006; Leitner et al. 2007). Multiple anonymized copies of the data can be disclosed, accompanied by specifications of the anonymization technique, for instance, for scientific transparency and reproducibility. This can provide hints to the attacker and, depending on the strength of the technique, locations can be re-engineered with the Gaussian blurring algorithm (Cassa et al. 2008).

A third data type is *'space-time data,'* hereafter referred to as *STd.* Data of this type contains location and timestamps for one or more subjects, which can be distinguished with a UID. Each location represents or approximates where a subject was at a particular time. Typical examples are call data records (CDR) and data used in location-based services (LBS). Unless the identity of the subject is known (e.g., when UIDs are real names), there is no key identifier or quasi-identifier. Nevertheless, the subjects' spatiotemporal whereabouts can be analyzed to draw a plethora of inferences such as their home address, work address, time spent away from work, and places visited during weekends (Alrayes and Abdelmoty 2014).

Gambs et al. (2010) analyzed GPS mobility traces of 90 taxi trails in San Francisco, US. They attempted to infer the home location of the drivers using a heuristic approach of the first and last recorded locations during working days. However, they did not have validation data to assess the accuracy of their approach. De Montjoye et al. (2013) focused on the uniqueness of spatiotemporal trajectories and analyzed mobility data from mobile phone interactions (calls and messengers) for approximately 1.5 million people. They found that four random locations are enough to uniquely characterize 95% of mobile users for a sample in which the location of a user is specified hourly, with a spatial resolution equal to that determined by the carrier's antennas.

The fourth and last data type is the *'space-time-attribute'* data, hereafter referred to as *STd* + . As with *Dd* + , the "+" symbol denotes an extended version of *STd*, which includes additional attributes that can be quasi-identifiers or private attributes. An example of *STd* + is the georeferenced data of a Twitter user. Twitter data contains spatial and temporal information as well as the short message text posted by the user. Inferences can be made similar to those for *STd*. Additionally, the textual or otherwise semantic information may reveal private matters about the sender such as interests, beliefs, and attitudes. For instance, Preoţiuc-Pietro and Cohn (2013) exploited the primary venue type in Foursquare check-ins (i.e., professional and other, travel and transport, residence, food, nightlife spots, university, outdoors, arts and entertainment, and shop and service) to cluster users by behavioral patterns and estimate their next activity based on the history of past venue visits. In another real-word but small-scale study, LBS network data of university volunteers was analyzed based on location similarity. Inferences were made to predict the users' demographics such as education level and gender (Li et al. 2018).

Participatory sensing data are data collected by volunteers, mainly for research, using mobile sensors such as biometric bracelets, smartwatches or smartphones. They include data from mobile devices such as sensors carried by 'humans as sensor operators,' sensors carried by 'humans as objective sensors,' and devices carried by 'humans as subjective sensors' (Kounadi and Resch 2018). Participatory sensing data are the *STd* + type. For example, participants in a participatory research campaign may use mobile apps that track their space-time information and report their level of stress (i.e., sensitive information) throughout their activity spaces (Zeile et al. 2011). In participatory sensing data, private attributes are observed or volunteered geoinformation whereas private attributes are also inferred geoinformation in LBS network data. Thus, due to the error of the inference process, the disclosure risk of LBS network data may be lower than that of participatory sensing data.

The four types of spatial data are illustrated in Fig. 25.1, where:

- $S_{1\ldots k}$ is the spatial attribute such as the coordinates, postal codes, or street addresses;
- $T_{1\ldots n}$ is the temporal attribute such as hour, date, or month; and
- $A_{1\ldots m}$ are quasi-identifiers and/or private attributes.

All spatial data types include a spatial attribute. Two of the data types contain a temporal attribute (*STd* and *STd* +) and two contain additional attributes (*Dd* + and *ST* +).

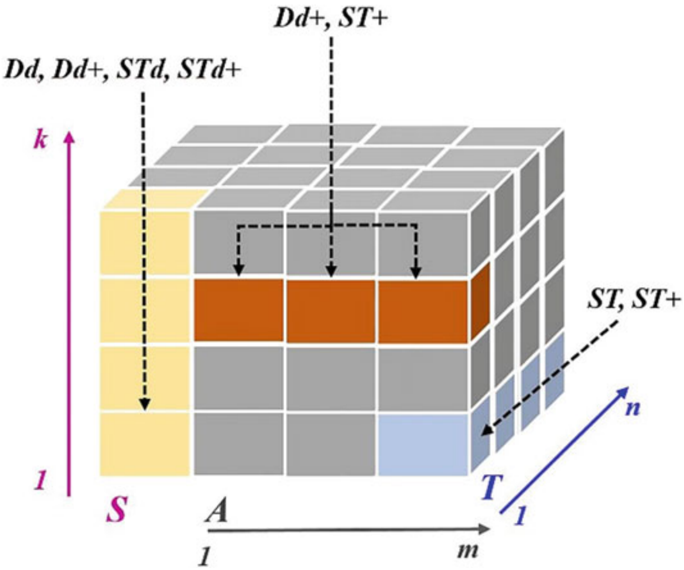

Fig. 25.1 Four spatial data types, Dd, Dd+, ST, ST+, and the types of attributes they contain (S, T, A)

25.3 A Typology for (Geo)Privacy

Privacy is always relational. It does not make sense for a lonely man on a desert island. At its simplest, privacy relates two parties—a human to a human, a human to a group of humans, a human to a private corporation or a human to a government institution. These relations can be arranged in a typology of (geo)privacy (Table 25.1). This grouping is a gross simplification of reality. For instance, LBS involve no less than thirteen human, machine and software parties—the mobile device, the hardware manufacturer, the operating system, the operating system manufacturer, the mobile application, the mobile application developer, the core application, the third-party software, the third-party software developer, the LBS, the LBS provider, the network operator and government (Herrmann 2016). Further, government institutions and private corporations often cooperate. The National Security Agency obtained direct access to the systems of Google, Facebook, Apple and other US Internet giants as part of the Prism program, which allows for officials to collect material including search history, the content of emails, file transfers and live chats (Greenwald and MacAskill 2013). Nevertheless, the four ideal types of relations help create a rough grid into which finer resolution grids may be inserted in future iterations.

At the heart of the typology is Alice. We may imagine her as a member of ACM who must comply with the ACM Code of Ethics or as a member of a (geo)computing department at a European university, which must comply with the GDPR. Alice values (geo)privacy as a positive right, a right that obliges action by individuals, groups,

Table 25.1 A typology of (geo)privacy relations

		Goal incongruity	
		Low(er)	*High(er)*
(Alice's) Ability to control human behavior, machine behavior, outputs	*Low(er)*	Cell (4) Alice—Government institution **Privacy strategy**: Compliance; lodge complaint to DPA in case of violation of the GDPR; anti-surveillance resistance	Cell (3) Alice—Private corporation **Privacy strategy**: Control behavior of corporation (via GDPR); lodge complaint to DPA in case of violation of the GDPR
	High(er)	Cell (1) Alice—Bob **Privacy strategy**: Right and duty of partial display	Cell (2) Alice–(Bob–Carol–Dan-etc.) **Privacy strategy**: Geoprivacy by design

or institutions to determine for themselves when, how, and to what extent information about them is communicated to others (Westin 1967). To transfer from Westin's times to the information age, Alice values privacy as the positive right of individuals, groups, or institutions *"to control the life cycle (especially the generation, access, recording, and usage) of their information and determine when, how, and to what extent their information is processed by others"* (Floridi 2014, p. 114). The relationality of privacy highlights the possibility that the privacy goals of two binary parties can be incongruous and results in the horizontal dimension of the typology in Table 25.1. Incongruity can be low or high. The vertical dimension refers to Alice's ability to control the transformation process of her volunteered, observed or inferred information or that of her research subjects. Her ability is high when she can control the entire transformation process—the behavior of humans (incl. herself) and machines and outputs. It is low when she can control some or none of these (Ouchi 1979; Ciborra 1985). Alice's ability (low or high) to control the transformation process results in the vertical dimension in Table 25.1.

In Cell (1), two humans (Alice and Bob) are interacting face-to-face in a private or public space. This is the archetypal human-to-human interaction. Both Alice and Bob are conscious of being observed by each other and other humans and have similar privacy goals—to uphold a tacit social code, the *'right and duty of partial display.'* The sociologist Erving Goffman (1957) described how all humans reveal personal information selectively to uphold this code while constructing their public personae. Hence, the low incongruity between Alice's and Bob's goals to protect their privacy—both strive to uphold this tacit social code, to protect (or curate) their public personae, and modulate it gradually over time, as the relation expands or shrinks. As Fried (1968) explains, Alice may not mind that Bob knows a general fact about her but may feel her privacy is invaded if he knows the details. For instance, Bob may comfortably know that Alice is sick, but it would violate her privacy if he knew the nature of the illness. If Bob is a good friend, he may know what particular illness Alice is suffering from but it would violate her privacy if he were actually to witness her suffering. Both control their behavior and the knowledge they share (outputs) about each other and may choose to modulate them over time. Goffman's theory applies in settings where participants can see one another face-to-face and has implications for technology-mediated interactions, e.g., in email security (Agre and Rotenberg 1997). When emailing each other, Alice and Bob may choose from a continuum of strategies to safeguard their privacy depending on context. They may refrain from emailing, they may email each other but self-censor, they may delegate privacy protection to mail encryption and firewalls, or they can work socially and organizationally to ensure that members of their community understand and police norms about privacy (Bowker et al. 2010).

Cell (2) describes the interaction of a human, e.g., Alice, the research leader of a participatory sensing campaign, with a group of campaign participants (Bob, Carol, Dan, Eric, etc.).

The goal incongruity between Alice and the group may be high if the group members are not aware of possible breaches to their privacy and their implications. As campaign leader, Alice has a high ability to control outputs and the behaviors of group members and machines and takes a series of privacy-preserving measures for the entire group before, during and after the campaign, a strategy Kounadi and Resch (2018) call *'geoprivacy by design.'* Kounadi and Resch (2018) propose detailed privacy-preserving measures in four categories, namely, 6 measures prior to the start of a research survey, 4 measures for ensuring secure and safe settings, 9 measures for processing and analysis of collected data, and 24 measures for safe disclosure of datasets and research deliverables. Table 25.2 provides illustrative examples in each category. Interestingly, measures to control human behavior include two subtypes:

Table 25.2 Examples of measures that control the transformation process

	Measures controlling human/machine behavior and outputs
Prior to start of campaign	human behavior (participation agreement, informed consent, institutional approval); outputs (defined criteria of access to restricted data)
Security and safe settings	human behavior (assigned privacy manager, trained data collectors); machine behavior (ensuring secure sensing devices, ensuring a secure IT system)
Processing and analysis	outputs (deletion of data from sensing devices, removal of identifiers from data set)
Safe disclosure	outputs (reduction of spatial and temporal precision, consideration of alternatives to point maps) human behavior (providing contact information, using disclaimers, avoiding the release of multiple versions of anonymized data, avoiding the disclosure of anonymization metadata, planning a mandatory licensing agreement, authenticating data requestors)

outreach measures, e.g., participation agreements, and measures of self-restraint, e.g., the use of disclaimers, avoiding release.

Cell (3) describes the interaction of Alice with a private corporation, as a user of a location-based service, of which Google Maps is the most popular and commonly used. Alice *volunteers* her location to the LBS to get directions to a desired destination (Herrmann 2016). In this case, the goal incongruity between Google and Alice is high, as evident from comparing Alice's commitment to (geo)privacy with that of Google's former executive chair Eric Schmidt. *"If you have something that you don't want anyone to know, maybe you shouldn't be doing it in the first place"* (Newman 2009). Alice's ability to control how her location information is used by LBS to infer other information about her is low. As an EU citizen, she can rely on the GDPR to (partly) control the behavior of the LBS provider. Another strategy is lodging a complaint to her national Data Protection Authority (DPA). DPAs are independent public authorities in each EU state that supervise application of the GDPR and handle complaints lodged concerning violations of GDPR. If the private corporation where Alice works systematically monitors its employees, including their workstations and Internet activity, a Data Protection Impact Assessment (DPIA) may be required.

Cell (4) describes the interaction of Alice with government institutions. Alice trusts that her government will respect her right to information privacy (thus the goal incongruity is low) but may be in the dark regarding the transformation process unless a whistleblower leaks a secret surveillance program (e.g., Greenwald and MacAskill 2013) or the abuse of private data (The Guardian 2018). Further, if the public organization where Alice works engages in processing that is likely to result in a high risk to the rights and freedoms of individuals, Alice may lodge a complaint to the DPA and request a DPIA. Such processing may include the systematic and extensive evaluation of personal aspects of an individual, including profiling, the processing of sensitive data on a large scale, or the systematic monitoring of public areas on a large scale.

Another strategy for Alice is collective, e.g., participating in popular resistance to unpopular government action. When the government of the Federal Republic of Germany announced a national census on 27th April 1983, German citizens protested so strongly that a dismayed German government had to comply with the Federal Constitutional Court's order to stop the process and take into account several restrictions imposed by the Court in future censuses. Asking the public for personal information in 1983, the fiftieth anniversary of the National Socialists' ascent to power, was apparently bad timing, to say the least (Der Spiegel 1983). When the census was finally conducted in 1987, thousands of citizens boycotted (overt resistance) or sabotaged (covert resistance) what they perceived as Orwellian state surveillance (Der Spiegel 1987).

Notably, these remarkable events took place in an era where the government was the only legitimate collector of data at such a massive, nationwide scale and at a great cost (approx. one billion German marks). Currently, state and corporate surveillance are deeply entangled. In response, technologically savvy digital rights activists have been influential in several venues, including the Internet Engineering Task Force (IETF) and the Internet Corporation for Assigned Names and Numbers

(ICANN), through the Noncommercial User Constituency (NCUC) caucus. However, their efforts have largely remained within a community of technical experts ('tech justice') with little integration with 'social justice' activists (Dencik et al. 2016).

25.4 Measures to Preserve Geoprivacy

In Sect. 25.2, we characterized various data types that deserve specific scrutiny when privacy is concerned. This characterization was motivated by the perspective of a variety of attackers' strategies (either theoretically possible or practically realized) to identify private information on a subject. Below, we describe geoprivacy-preserving measures to counter such attacks. Section 25.3 highlighted the relationality of privacy and described the four fundamental relations that are critical to understanding privacy as a societal phenomenon. In real life, the social graph is not bipartite and humans cannot be bluntly labeled as either 'attacked' or 'attacker'. Relations are often transitive and privacy-relevant information may travel along longer paths, which implies that intermediate agents may have dual, possibly frictional, roles. One rather regulated, yet much-discussed case, is that of patients whose hospital visits are covered by health insurance companies. Geoprivacy may be related to the living or working conditions of the patient. The patient's typical direct relation with the insurance company does not make this case less trivial. A second example that played out recently in the Netherlands was that of a citizen with a tax dispute, and the national museum foundation that had issued an annual pass to that person (van Lieshout 2018). The tax office accessed the person's museum visit details to prove that he actually lived in the Netherlands, and not abroad, as he claimed.

To identify core geoprivacy measures, we must define the landscape of variables and the values they take, and explore their interrelationships. Six *fundamental variables* are discussed below, along with their values, and are summarized in Table 25.3. The first variable is the 'attacked', who is any subject in a dataset that may be harmed from potential inferences. The attacked is an individual such as Alice—i.e., aware of privacy risks and subscribing to the ACM code of Ethics—or someone who is unaware of privacy risks and relevant legislation and regulations. The second variable is the *'attacker'*, who could use the data for a malevolent purpose. The attacker may be a government institution, corporation, researcher, or other individual. The third variable is the *'data type'*, any of the four types discussed in Sect. 25.2 (i.e., *Dd*, *Dd*+, *STd*, or *STd* +). The fourth variable is the *'purpose of attack'*, which may assume two values: (a) private attribute(s) of the attacked are identified (attribute(s) is unknown but the attacked is known) and (b) the attacked who has certain private attribute(s) is identified (attacked is unknown but the attribute(s) is known). In attacks of the first category, the attacker knows that the attacked's details are contained in a dataset and the attacker aims to draw inferences on the attacked. In those of the second category, the attacker knows the private information and aims to infer the identity of the attacked.

Table 25.3 Fundamental geoprivacy variables and their associated values

Variable	Values
Attacked	1. Any individual
Attacker	2. Government/Institution 3. Corporation 4. Researcher 5. Any individual
Spatial data types	1. Discrete location data (*Dd*) 2. Discrete location data with covariates (*Dd*+) 3. Space-time data (*STd*) 4. Space-time-attribute data (*STd*+)
Purpose of attack	1. Identify private attribute(s) of the attacked 2. Identify the attacked who has certain private attribute(s)
Attacker's strategy	1. Key-identifier exploitation 2. Combine to uniqueness 3. Re-engineering locations 4. Analyzing locations 5. Homogeneity attack 6. Background attack 7. Composition attack
Privacy-preserving measures	1. Pseudoanonymity 2. K-anonymity 3. Spatial *k*-anonymity 4. *l*-diversity 5. Differential privacy

We have used terminology from Sects. 25.2 and 25.3 to define four of the six fundamental variables. Two more variables in the geoprivacy landscape are discussed next. The fifth is the *'attacker's strategy'* (also referred to as "*inference attacks*") that can take seven forms: (a) key-identifier exploitation, (b) combine to uniqueness, (c) re-engineering locations, (d) analyzing locations, (e) homogeneity attack, (f) background attack, and (g) composition attack.

The simplest type of inference is *key-identifier exploitation*. It requires the presence of key identifiers in the dataset. The accuracy of such inferences range from low to high depending on the relationship type that the data represents (i.e., one-to-many or one-to-one). For example, a location representing a block of flats links it to many households (and even more people) whereas an address in a single-family residential area only links the location to a small number of family members. Other key identifiers represent a strict one-to-one relationship (e.g., a fingerprint or iris scan). Datasets collected by a governmental institution are more likely to contain such key identifiers, while subjects such as Alice have little control over the inferences that the institution can draw about them.

Individuals may be identified if the data comprise a combination of quasi-identifiers in the dataset that allows for the unique identification of subjects (i.e., *combine to uniqueness*). Unlike pseudonyms, quasi-identifiers are real attributes such as sex and age, which can be further processed or linked to external data to disclose the subject's identity. Such disclosure may occur if hospitals share their medical records with governmental institutions such as a country's census bureau (Cell (4) relation). A hypothetical *Dd* + contains attributes such as the date of visit, age, gender, occupation, municipality of residence, and final diagnosis. A data analyst from the census bureau can identify a unique combination of quasi-identifiers in which there is a visitor diagnosed with a given disease who is male, lives in a known municipality, and has a known professional occupation. The combination of such facts in a certain municipality may lead to unique subject identification with a simple Internet search. However, only a fraction of the subjects may be identified in this way.

As explained in Sect. 25.2, in examples regarding *Dd* and *Dd* +, *re-engineering of locations* is performed using geoprocessing and spatial analysis techniques. When these locations represent private information, re-engineering of location implies identification of the attacked. For example, a researcher publishes a map of the distribution of pregnant teenagers in a study area as dots on a map (a Cell (2) relation). The map is georeferenced to a known coordinate system, and the dots are digitized as circles. Then, the centroid of each circle can be extracted as a single location. Geocoding can be used to reveal the addresses of the studied teenagers.

The analysis of locations of individuals may yield various inferences including the location of their home, which is a key identifier for a data subject. When key identifiers are inferred or re-engineered, the risk of identification is typically lower than when the key identifier is available in the dataset because of possible errors and inaccuracy in the inferencing processes. For example, an LBS stores the time and location of all user service requests (a Cell (3) relation). An attacker who has access to data on service requests may wish to infer the home locations of the users. First, the attacker excludes all service requests during working hours and weekends and splits the dataset by user. The remaining datasets represent sets of possible home locations for each user—requests sent at night and during weekdays, where people are more likely to be at home. The following analysis may be repeated for each user separately: (a) apply spatial clustering and identify the cluster with the highest density and (b) extract the point with the smallest accumulated distance to all other points (i.e., a point set centroid) within the highest density cluster. The extracted point is inferred as the home location of the user.

Anonymized data may disclose information if they yield homogeneous groups of subjects regarding their private attributes. This strategy is referred to as a *homogeneity attack* and requires that a dataset (either in its current form or after processing) includes a private attribute of categorical or ratio scale. For example, a researcher collects Twitter data during a three-month period (a Cell 2 relation). The home location of subjects is estimated using spatial analysis and the subjects' political preference (i.e., a categorical private attribute) is inferred using natural language processing and machine learning techniques. The researcher publishes the dataset in anonymized form, aggregating the home locations to zip code, including the political preference, and excluding all Twitter-relevant information (e.g., account names). An attacker knows a subject who uses Twitter frequently and where this person lives. However, all records associated with the zip code of the subject display a single political preference. Thus, that subject's political preference is disclosed due to a lack of diversity in the private attribute.

A *background attack* is possible when an attacker has knowledge (in the form of background information) on the distribution of a private attribute. For instance, mobile operators collect call data records that contain the location, time and a user identifier for each call (a random UID distinguishes users) (a Cell (3) relation). The operator can apply spatiotemporal analytics to infer the most visited venue during weekends for each subject. Anonymized copies of the data may be shared with another corporation for advertising purposes. The operator may have aggregated subject home locations by zip code (the home location is already known to the operator because of contract information), and may include visited venues during weekends in addition to other information. An attacker from the corporation knows that a subject is in the dataset and may know their home address. In the records of the zip code of the known person, it is possible that four different restaurants are revealed as frequently visited. The attacker knows that due to the subject's religion, three out of the four restaurants are unlikely. Thus, private information about the user is disclosed using background information.

The term *composition attack* refers to a privacy breach that occurs when exploiting independent anonymized datasets from different sources that involve overlapping subject populations (Ganta et al. 2008). A composition attack may build on the attacker's knowledge about a subject or the distribution of the private attribute and relies on the existence of further sources of auxiliary information. For example, in the mobile operator case, a subject may visit only two restaurants due to their eating habits. The data may have been anonymized to include the zip code and the most visited venues during weekends. Because the attacker also possesses Foursquare check-in data and knows that the subject is a frequent Foursquare user, they can search the venue results within the subject's zip code. There may be six distinct venues in the second dataset but only one appears in both datasets for the same zip code, and so the most visited venue by the attacked during weekends is disclosed.

The sixth variable is the *'privacy-preserving measures'* that mitigate an attack strategy by controlling the final digital outputs (Table 25.3). Data holders with full control of the transformation process may apply various privacy-preserving measures. Alice, as a sophisticated attacked, should consider the attacker's strategies and the privacy-preserving measures and intervene in her outputs by controlling, blurring, or censoring her digital behavior. The degree to which this is possible depends on her ability to control the transformation process (see Table 25.1). Next, we discuss five measures at her disposal, namely, (a) pseudonymity, (b) k-anonymity, (c) spatial k-anonymity, (d) l-diversity, and (e) differential privacy.

Pseudonymity is the use of pseudonyms as identifiers (or as key identifiers) (Pfitzmann and Köhntopp 2001). Unlinked pseudonyms are fake identities associated with data subjects. A pseudonym can be used to permit a subject's distinguishability, such as a UID as a random number. If distinguishability is not needed, given the use forms of the data, all key identifiers should be removed. However, if we consider that the attacker can apply strategies beyond *key identifier exploitation*, such as *combine to uniqueness,* pseudonymity mitigates but does not eliminate disclosure risk. *Combine* *to uniqueness* can be prevented with *k-anonymity*, which ensures that any subject is a member of a group of size *k* with the same values of the quasi-identifiers (Samarati and Sweeney 1998). Thus, a *key-identifier exploitation* attack is mitigated by a *k* level of anonymity. The larger the *k*, the more difficult it is to identify a subject.

A similar measure to *k*-anonymity is *spatial k-anonymity*, in which a location cannot be distinguished among *k-1* other locations. This can mitigate the risk from analyzing locations, and its application varies depending on the data type. For example, to prevent re-engineering from a *Dd*, every location should be an approximation of *k* locations (such as residential addresses) within an area. In this case, randomly displacing residential addresses based on some uniform distribution is preferable over a normal distribution because the latter may provide hints to potential attackers (see Sect. 25.2). To prevent the inference of home locations from an *STd*, each subject's location should ambiguously map information to at least *k* other subjects for every moment in time. This approach can be done by decreasing the spatial resolution.

Machanavajjhala et al. (2006) showed that *k*-anonymity mitigates but does not prevent identification due to homogeneity and background attacks. The authors proposed the *l-diversity* privacy measure, which requires a *k*-anonymous dataset to have at least *l* 'well-represented' values for the *private* attributes in each equivalence class. The characteristic *l* is the minimum number of times a value of a private attribute appears in a dataset. The last measure is *differential privacy*, which guarantees that any disclosure from the data does not change significantly due to the absence or presence of a subject in the database (Dwork 2006). *Differential privacy* returns answers to aggregate queries and, according to Ganta et al. (2008), certain variations of the measure may satisfy conditions to prevent *composition attacks*.

25.5 Toward a Sociocultural Understanding of Privacy

In the previous sections, we explored the *Ethics of Where* from the point of view of Alice, an individual complying with the ACM Code of Ethics and/or the rules of a GDPR-compliant European university. Alice's technological sophistication enables her to control (part of) the transformation process (from volunteered/observed to inferred information) and preserve her privacy from attackers (Table 25.3), as well as the privacy of her research subjects (Table 25.2). Her knowledge of GDPR legislation reassures her that the behavior of corporations and government institutions is controlled by law and enforced by sanctions. GDPR instruments (e.g., DPIA) enable her to lodge complaints to preserve her privacy as a private or public sector employee. She may tackle perceived privacy breaches of the data protection legislation by alerting her representative in the legislature, by joining a collective movement of peaceful protest or by bringing a case of privacy violation to a court of law, as in *Kyllo v. United States*.

In the future, we should tackle privacy at the sociocultural level, starting from a basic premise in social theory, as Alice's (privacy) preferences and commitments are shaped by and shape the culture of her community and society (Georgiadou et al.

2019). Her individual preferences and the culture—i.e., the shared beliefs, attitudes, way of life, or world view—of the community or society in which she is socialized are deeply enmeshed and mutually reinforcing, and there is no way to determine the dependent and independent variables. This means that we should consider privacy a social construction to account for the substantial differences in social organization in countries around the world, each with different preferred ways of social organizing and different attitudes to privacy. We may distinguish four ideal types of social organizing—individualist, hierarchist, egalitarian, or fatalistic (Douglas and Wildavsky 1983). Each type is supported by (and supports) a 'cultural bias': a compatible pattern of perceiving, justifying, and reasoning about nature, human nature, justice, risk, blame, and privacy. These ideal types do not exist in unadulterated form, but can help us identify which hybrids may be most effective in which institutional settings, and how these hybrids change over time.

Individualists tend to frame information privacy as a product that can be exchanged in the marketplace for a fair price. An excellent recent example of this approach is the advocacy of the GenerationLibre think tank (Laurent 2018) to extend the private property paradigm to personal data. GenerationLibre aspires to change the way the digital ecosystem works by giving user-producers: *"(1) The possibility for e-citizens to negotiate and conclude contracts with the platforms (possibly* via *intermediaries) regarding the use of their personal data, so that they can decide for themselves which use they wish to make of them; (2) The ability to monetise these data (or not) according to the terms of the contract (which could include licensing, leasing,* etc.*); (3)The ability, conversely, to pay the price of the service provided by the platforms without giving away our data (the price of privacy?)"* (p. 7).

Hierarchists may be willing to surrender some of their privacy to a legal/rational authority (e.g., government) they trust in exchange for another public good they value, e.g., security or economic growth. The Chairperson of the German Social Democratic Party (SPD), Andrea Nahles (2018), framed the problem: *"Empires like Google and Amazon cannot be beaten from below. No start-up can compete with their data power and cash. If you are lucky, one of the big Internet whales will swallow your company. If you are unlucky, your ideas will be copied."* Her solution is a Data-for-all law: *"The dividends of the digital economy must benefit the whole society. An important step in this direction: we [the state] must set limits to the internet giants if they violate the principles of our social market economy. [...] A new data-for-all law could offer decisive leverage: As soon as an Internet Company achieves a market share above a fixed threshold for a certain time period, it will be required to share a representative, anonymized part of their data sets with the public. With this data other companies or start-ups can develop their own ideas and bring their own products to the market place. In this setting the data are not "owned" exclusively by e.g. Google, but belong to the general public."* However, as Morozov (2018) argues, Nahles' agenda *"needs to overcome a great obstacle: citizens' failing trust in the state as a vehicle of advancing their interests,"* especially in a country such as Germany with a long history of data privacy activism.

Morozov (2018) argues for an egalitarian approach to privacy as constitutive of who we are and as radical citizen empowerment. *"We should not balk at proposing* *ambitious political reforms to go along with their new data ownership regime. These must openly acknowledge that the most meaningful scale at which a radical change in democratic political culture can occur today is not the nation state, as some on the left and the right are prone to believe, but, rather the city. The city is a symbol of outward-looking cosmopolitanism–a potent answer to the homogeneity and insularity of the nation state. Today it is the only place where the idea of exerting meaningful democratic control over one's life, however trivial the problem, is still viable."* Similarly, the Oxford-based *Digital Rights to the City* group proposes a deeper meaning to the right to information that amounts to the declaration that *"we will no longer let our information be produced and managed for us [presumably by the state or corporations], we will produce and manage our information ourselves"* (Shaw and Graham 2017). Fatalists are those persuaded by the abovementioned slogans *"you have zero privacy…get over it"* or *"if you have something that you don't want anyone to know, maybe you shouldn't be doing it in the first place."* However, as Snowden said, *"arguing that you don't care about the right to privacy because you have nothing to hide is no different than saying you don't care about free speech because you have nothing to say"* (Reddit 2015).

25.6 Toward Digital Earth Ethics: The Ethics of Where

In the previous sections, we mentioned privacy arrangements in the legal systems of two polities—the United States and the European Union—a serious limitation in a chapter on Digital Earth Ethics that encompasses the entire planet. However, it is possible to see how privacy is dealt with differently in these two cases. The word privacy is not mentioned in the US Constitution except indirectly in the Fourth Amendment, which protects the right of people to be secure in their persons, houses, papers, and effects against unreasonable searches and seizures. In contrast, in the European Union, privacy is a human right according to Article 8 of the European Convention on Human Rights: a *"right to respect for private and family life, home and correspondence."* This is largely due to the events around World War II, where personal information was often used to target individuals and groups and facilitate genocide. In 2018, we witnessed a serious shake-up of the treatment of privacy, data protection, and cybersecurity by legal systems around the world. The EU's GDPR, put in place in 2018, is a landmark development for privacy and how we perceive it. In this transitional period, a number of countries seem to follow a similar pathway as the GDPR: for instance, Canada, Japan, and India are looking at comparable extraterritorial privacy regimes. A common denominator between them is privacy as a constitutional right. Similar legislative developments are manifesting in China and the African continent.

In China, the Cybersecurity Law, the most important Internet legislation to be passed in the country thus far, came into effect on June 1, 2017. The law is intended to align China with global best practices for cybersecurity. Network operators must store select data within China and Chinese authorities may conduct spot-checks on a company's network operations. *"The Cybersecurity Law provides citizens with an unprecedented amount of protection to ensure their data privacy. The law defines "personal information" as information that can be used on its own or in conjunction with other information to determine the identity of a natural person, including but not limited to a person's name, birthday, identity card number, biological identification information, address, and telephone number. In other words, once such information is de-identified, it will no longer be subject to the requirement for personal information in the Cybersecurity Law"* (Lee 2018, p. 87). Other countries such as Korea and Singapore are less decided and may be consciously delaying their legislative moves until the scene becomes clearer.

In the African continent, approximately 40% of the countries have enacted data protection legislation that abides the OECD standards (1st generation), the EU DPD 1995 standards (2nd generation), or even features GDPR elements (3rd generation). The latter refers to Mauritius, one of Africa's dynamic but small economies, which updated its 2004 law in 2017 with a new Data Protection Act 2017 featuring elements of the GDPR. In June 2014, the African Union (AU) adopted the Convention on Cyber Security and Personal Data Protection, known as the Malabo Convention, the first treaty outside the EU to regulate the protection of personal data at a continental level. The Convention aims to establish regional and national legal frameworks for cybersecurity, electronic transactions and personal data protection, but its actual impact will depend on ratifications, which had not occurred by early 2016. In 2018, the AU created data protection guidelines that are broadly aligned with the GDPR for its Member States, with contributions from regional and global privacy experts including industry privacy specialists, academics and civil society groups (Georgiadou et al. 2019). On a global scale, there is a substantial imbalance in sensitive data flows, with mostly American Internet tech companies sourcing data globally. This imbalance is the substrate for a continuation of developments in technology, the legal scenery and contractual arrangements that we do not expect to be settled soon. Unfortunately, privacy and data protection as global goods intersect with cybersecurity and counterterrorism, which gives little hope for transparency and focus on solutions. Nevertheless, we should follow these developments closely (Raul 2018).

In addition to legislative efforts, global and regional institutions are busy developing ethical principles and guidelines. The *UNESCO Declaration of Ethical Principles in relation to Climate Change* addresses the responsibility to overcome the challenges and reinforces ethics at the center of the discussion on climate change. Member states have mandated UNESCO with promoting ethical science: science that shares the benefits of progress for all, protects the planet from ecological collapse and creates a solid basis for peaceful cooperation. The *Global Ethics Observatory (GEObs)*, a system of databases with worldwide coverage in bioethics and environmental ethics, science ethics, and technology ethics, helps researchers identify Who's Who in Ethics, Ethics Institutions, Ethics Teaching Programs, Ethics-Related Legislation and Guidelines, Codes of Conduct and Resources in Ethics. Other global actors in the responsible data movement, e.g., UN Global Pulse (2017), Red Cross/Red Crescent 510 (2018) and UNOCHA (2019), also develop data ethics guidelines as a cornerstone of their groundwork.

At the European Union level, the *High-Level Expert Group on Artificial Intelligence (AI HLEG)* proposed the first draft AI ethics guidelines to the European Commission in December 2018. These cover issues such as fairness, safety, transparency, the future of work, democracy and the impacts of application of the Charter of Fundamental Rights, including privacy and personal data protection, dignity, consumer protection and nondiscrimination. The *European Group on Ethics in Science and New Technologies (EGE)* provides the Commission with high-quality, independent advice on ethical aspects of science and new technologies in relation to EU legislation or policies. The EGE is an independent advisory body founded in 1991 and is tasked with integrating ethics at the international level, at the interinstitutional level with the European Parliament and the Council, and within the Commission itself. The *European Union Agency for Fundamental Rights (FRA)* is the EU's center of fundamental rights expertise. It helps ensure that the fundamental rights of people living in the EU are protected. Fundamental rights set minimum standards to ensure that a person is treated with dignity. The Agency seeks to instill a fundamental rights culture across the EU by collecting pertinent and timely data and information, by sharing evidence-based insights and advice with policy- and decision-makers, by raising rights awareness and promoting fundamental rights through cutting-edge communications, and by engaging with a wide array of diverse stakeholders from local and international levels.

However, requiring global and regional guidelines and principles to conceptualize ethics and privacy across diverse cultural and political contexts and to substitute for lacking or existing weakly enforced legislation (Taylor 2017) may further deplete local institutional capacity and harm citizens. The question of how to improve digital data flows between local and global institutions while maximizing the use of innovative geospatial technologies and protecting citizens' rights as well as local institutions is particularly relevant in view of the increasing use of artificial geospatial intelligence, mobile technology and social media to extract information about individuals and communities.

Finally, legal and social strategies and privacy-preserving technological measures should form the backbone of university curricula for students and working professionals. The advent of the GDPR in 2018 created a sudden educational demand for university courses, of which the massive open online course (MOOC) *'Privacy by Design and GDPR'*, designed by computer scientists at Karlstad University in Sweden, is a recent EU-focused example (Fischer-Hübner et al. 2018). The educational challenge is to gradually expand the content of such courses for a global audience of students from countries with emergent privacy and data protection legal frameworks, different understandings of privacy and different social organization as well as different levels of technological sophistication in countering privacy attacks, because *The Ethics of Where* should eventually be everywhere.

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Yola Georgiadou is Professor in Geo-information for Governance at the ITC Faculty, University of Twente, The Netherlands. Yola studies how social actors structure policy problems characterized by intense disagreement on values and uncertain spatial knowledge. Her methods are qualitative. Her normative orientation is “working with the grain” of local institutions.

Ourania Kounadi is an Assistant Professor in GIScience at the ITC Faculty, University of Twente. Her research interests include location privacy, spatial confidentiality, and spatial crime analysis. Regarding location privacy, she has conducted literature reviews, methodological and empirical studies. Currently, she is examining application tools to allow safe collection and dissemination of geographic information.

Rolf A. de By is an Associate Professor in Geospatial Information Processing at the ITC Faculty, University of Twente. His research interests are in the domain of applying advanced information systems that make use of earth observation and other geospatial data sources to important societal problems, especially those occurring in developing nations.

Chapter 26
Digital Earth Challenges and Future Trends

John van Genderen, Michael F. Goodchild, Huadong Guo, Chaowei Yang, Stefano Nativi, Lizhe Wang and Cuizhen Wang

Abstract The previous 25 chapters introduced relevant technologies, applications, and other topics related to Digital Earth. Respective challenges and future research were also proposed by various authors. In this concluding chapter, we briefly review Digital Earth past and present, followed by a set of challenges and future trends, speculating on how Digital Earth may evolve over the coming years. Such challenges and trends are discussed in the context of science drivers, technological advances, application adoption, and relevant virtual—physical community building.

Keywords Geoscience · Big Data · Sustainable development · Climate change

26.1 Introduction

As mentioned in the introductory chapter, the concept of Digital Earth was first coined in Al Gore's book entitled "*Earth in the Balance*" (Gore 1992), and was further developed in a speech written for delivery by Gore at the opening of the

J. van Genderen (✉)
Department of Earth Observation Science, University Twente, Enschede, The Netherlands
e-mail: genderen@alumni.itc.nl

M. F. Goodchild
Department of Geography, University of California, Santa Barbara, CA, USA

H. Guo
Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China

C. Yang
NSF Spatiotemporal Innovation Center and Department of Geography and GeoInformation Science, George Mason University, Fairfax, VA, USA

S. Nativi
Joint Research Centre, European Commission, Ispra, VA, Italy

L. Wang
School of Computer Science, China University of Geosciences, Wuhan, China

C. Wang
Department of Geography, University of South Carolina, Columbia, SC, USA

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California Science Center in 1998 (Gore 1998). And then the First International Symposium on Digital Earth was held in Beijing in 1999 (ISDE 1999). Since then, the symposium has been held every two years, and the International Society of Digital Earth (ISDE) registered in Beijing in 2006. With the establishment of the Society, rapid progress was made. The Society launched the *International Journal of Digital Earth* (IJDE) in 2008, and this journal was accepted by the Science Citation Index after only 18 months of existence. Started as a quarterly journal, it is now published twelve times a year, with almost 100 scientific papers being published per year. The *Big Earth Data* open-access journal was also established in 2017 to further advance the data aspect of Digital Earth. Now the Society organizes, besides its flagship event of the biannual symposium, a series of summits, which focus on a narrower set of topics and issues. The Society has now established several national and regional chapters and a national committee around the world, and more will no doubt follow over the coming years. Moreover, ISDE has become a Participating Organization Member of the Group on Earth Observations (GEO) and an Affiliated Member of the International Science Council (ISC) since 2009 and 2017, respectively. Also ISDE has been accepted as a new member of the United Nations Committee of Experts on Global Geospatial Information Management—Geospatial Societies (UN-GGIM GS) in August 2019.

By analyzing the Google and Web of Science (SCI-E) academic indexing systems, we found that: a) Google Scholar has indexed ~20,000 publications since 1992 on "Digital Earth" with a steady annual increase, and b) a more restrictive search of the Web of Science using "Digital Earth" as the topic and as all fields returned values of 553 (left of Fig. 26.1) and 6669 (right of Fig. 26.1), respectively (as of May 26, 2019). Publication numbers jumped during 2008−2010 when IJDE was officially launched and when it received the first SCI-E impact factor. The diversity of research

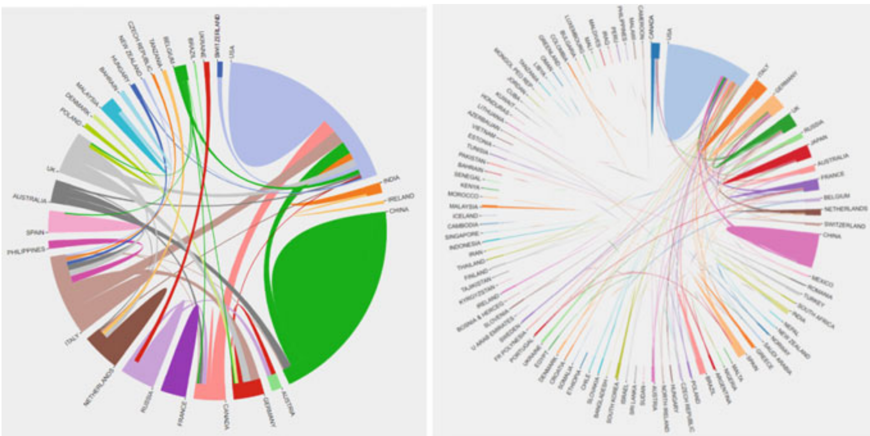

Fig. 26.1 Digital Earth research came from many countries in the world. The area shown for each country corresponds to its percentage contribution, and the linkages show the collaborations between different countries. China and the U.S. are in the top tier, with many cross-country collaborations

activities is reflected in the worldwide distribution, which has engaged all developed countries and many developing countries, with the U.S. and China as the top-tier contributors (Fig. 26.1). The collaboration between different countries also signifies the internationalization of the Digital Earth effort.

In the remainder of this chapter, we will look at a selection of the major challenges the Society will face, plus we shall do some crystal-ball gazing, and speculate on some of the major new trends in Digital Earth research over the coming years.

26.2 Major Challenges for Digital Earth

26.2.1 Big Data Management in Digital Earth

In discussing the challenges highlighted in earlier chapters of this manual, the authors have demonstrated the tremendous volume, variety, veracity, and velocity (the four Vs) challenges for Big Earth Data (Guo et al. 2017; Yang et al. 2017). The four Vs impose new requirements on computing, data management, information extraction, and knowledge discovery, as well as the detection of events of interest, needed to realize the value (the fifth V) of Big Earth Data for Earth science and applications (Guo et al. 2014; Lee and Kang 2015; Shu 2016;Yang et al. 2019).

According to Filchev et al. (2018), up to 95% of the Earth observation (EO) data present in existing archives has never been accessed, so the potential for increasing exploitation is very large. Many satellite agencies are now changing their data archive holdings to cloud-based or hybrid storage. Maintaining the balance of cost, usage, transmission, and analytical services in the cloud is quite a challenge (Yang et al. 2017).

In the new era of Big Earth Data, geoscience can only achieve its full potential through the fusion of diverse Earth observations and socio-economic data, together with additional information from a vast range of sources. Such data sources include observations obtained at different spectral and spatiotemporal resolutions, and observations from different platforms (e.g., satellite and in situ), orbits, and sensors, the Internet of Things, and also unmanned autonomous vehicles (UAVs) (Pohl and van Genderen 2014). Fusion, given the variety, veracity, and velocity challenges of the data, is only possible with well-designed architectures, reference systems, and standards. Hence, image and data fusion methods will require new and creative solutions to meet the needs of the next generation of Digital Earth, where social science aspects such as volunteered information, citizen science (public participation in scientific research), etc., will need to be fused with Earth observation data from space, air, ground, and subsurface (Pohl and van Genderen 2017). There are still many issues to be resolved first, such as how to ensure that data found in multiple data systems agree with one another. Accuracy of the data and information, currency, and reliability are all aspects likely to be investigated over the coming years in this field of image, data, and information fusion.

A major challenge for the next generation of Digital Earth is that of common standards for transforming the increasingly massive amounts of data (Bermudez 2017). The new Discrete Global Grid System (DGGS) specification of the Open Geospatial Consortium (OGC) provides a concrete way of addressing this challenge, but only addresses the spatial aspect; how the other aspects of orbits, sensors, and spectral and temporal resolution should be standardized still presents a challenge. These issues may demonstrate a path forward towards the realization of the "Digital Twin"—where our engagement and understanding of the physical Earth can seamlessly interact with the Digital Earth, and vice versa (see 5.1 in Chap. 2). Flexible solutions are also needed in the area of the Internet of Things (IoT) for, whilst many government and private organizations are starting to implement IoT solutions, developing an appropriate vision where things will work together, seamlessly and reliably is still a huge challenge (see Chap. 11).

As detailed in Chaps. 6 and 9, addressing the four Vs of Big Earth Data in order to obtain actionable information for end users is computationally intensive (Yang et al. 2008). Utilizing cutting-edge computing is desirable, and how to coordinate the process is a significant challenge. Cloud computing has been adopted in the past few years to address challenges and relevant issues (Yang and Huang 2013). GPU, MPI, Quantum, Edge, and Mobile computing may also assist Digital Earth computing. However, picking the best computing mode and transitioning between different computing modes to best leverage each of them for specific Digital Earth tasks is also still quite a challenge (Yang et al. 2013).

26.2.2 Large-Scale Digital Earth Platform Implementation and Construction

A major challenge for Digital Earth over the coming years will be to develop a new generation of Digital Earth science platforms in order to provide a new impetus for interdisciplinary, cross-scale, macro-scientific discoveries in the era of Big Data and to make planet Earth more sustainable. As Digital Earth platforms use geospatial information infrastructures, the speed of technological progress is one of the main challenges facing the further development of Digital Earth.

It is generally recognised that DE can flourish only if supported by a robust computing infrastructure and good-quality data. As to data, we argue in favour of learning from successful Internet companies, opening access to data and developing interactivity with the users rather than just broadcasting data. By adopting this paradigm (known as Datafication), we can develop ecosystems of public administration, firms, and civil society, enriching the data to make it fit for AI applications responding to DE needs (Craglia et al. 2018).

The Australian 2026 Spatial Industry Transformation and Growth Agenda finds that the age of "viewing everything through an application lens is coming to an end". Instead, platform architectures will be selected primarily to cope with soaring volumes of data and the complexity of data management, not for their ability to support applications. In the report, the authors show how the Digital Earth approach uses a variety of Earth observation data, from the global to the local scale. By using quantitative spatial analysis methods, Digital Earth allows a deeper understanding of global-change mechanisms, allowing us to evaluate global change from the perspectives of regional responses and zonal characteristics caused by the Earth's rotation. Furthermore, the Digital Earth approach enables us to display and demonstrate the global-change mechanisms and their temporal effects, in order to better inform decision makers of potential regional and global schemes for environmental protection.

26.2.3 Strengthening Fundamental Research for Digital Earth

As an evolving discipline, Digital Earth needs the following questions to be answered: What is the basic theory of Digital Earth? What are its core characteristics? What is the difference between Digital Earth and geospatial technology? And what is the relationship between Digital Earth and Big Earth Data? (Guo 2018).

With the development of Digital Earth, it is necessary to gain a profound understanding and make an in-depth analysis of the expanding scope of the concept of Digital Earth, as well as the impacts of Digital Earth on the interdisciplinary sciences and social progress.

We should pay attention to cross-disciplinarily research in the fields of Earth science, information science, space science and related technologies to broaden the research directions of Digital Earth, and so further help Earth system research reach new heights.

We should realize that Digital Earth is becoming ever more relevant as the world undergoes a profound digital revolution. The increasing volume of data being amassed by Earth system science and geo-information science is prompting experts to investigate and experiment with highly automated and intelligent systems in order to extract information from enormous datasets, thus driving future innovative research that will greatly benefit from developments in Digital Earth technologies and systems (Guo 2017).

It should be realized that Digital Earth can help to bridge the information gap for the general public by integrating data and information from multiple sources including those from space, social networks, and economic data. By developing intelligent models and data-intensive computing algorithms, Digital Earth can generate useful information and scientific knowledge to support the functioning of social services.

As we enter this new age, Digital Earth has been endowed with the new mission of integrating natural and social sciences so that it can respond to the challenges of global sustainability, environmental change and digital economic society that human beings are facing. Digital Earth is being pushed towards contributing to the discovery of new knowledge that can support our understanding of the planet and enable us to live on it in a sustainable manner (Guo et al. 2014).

26.2.4 Developing an Ecosystem for Digital Earth

For the development of Digital Earth systems, an ecosystem should include scientists, engineers for implementation, and users, as well as applications that make use of the Digital Earth system services. Furthermore, new aspects such as privacy, security, education, and training, which have often been ignored in the past, should be put on the "to-do-list".

Many Digital Earth datasets, such as volunteered geographic information (Goodchild 2007), raise issues of privacy, security of business, intellectual merit, or intelligence. It is a big challenge to provide proper access to such data and to protect such information from misuse by unauthorized users. The adoption of a datafication approach (i.e., shifting the focus from data sharing to intelligence generation in a collaborative way) promises to address these challenges.

All the challenges relating to the future of Digital Earth, as described above, plus the many new opportunities and trends described below, will demand a large increase in the number of scientists, academics, and business professionals to be trained and educated in the Digital Earth concept in all its many facets; none more so than in the field of citizen science, as explained and shown in the education chapter of the Manual. Young people are the key to developing solutions to meet such challenges. Especially challenging for ISDE will be the need to attract younger researchers and post-graduate students to become involved in defining how Digital Earth moves forward.

26.2.5 Addressing Social Complexities

The increasing complexity of the Digital Earth system, and the engagement of an ever-increasing number of people in building and using the system, will require a sophisticated approach for leveraging advances in the relevant social and natural sciences, to facilitate a sustainable rate of progress (see Chap. 12 Social Media and Social Awareness). The challenges include cross-cultural and cross-jurisdiction boundaries, disparate languages, interdisciplinary gaps, and potential misunderstanding (Lane et al. 2009). The engagement of social media and citizen science in providing more real-time and social data also pose privacy and related concerns (see Chap. 18 on Citizen Science in Support of Digital Earth). Engendering trust in the quality of data and information is a significant challenge when massive numbers of users are contributing data and the information extraction process passes through many steps that include human intervention. Developing proper models for the measurement of accuracy or quality is a key to ensure trust (Goodchild and Li 2012).

The advance of Digital Earth will expose many of the privacy concerns associated with Big Data, such as fine-resolution imagery and data on personal activities at fine spatiotemporal resolution. How to properly avoid the exposure of personal information to unauthorized users needs both research and policy attention. Ethical issues may also be brought up when such information is viewable across cultural and jurisdiction boundaries or across religious groups (Gross and Acquisti 2005). How to develop methods to measure privacy exposure and to protect privacy is a challenge presented in Chap. 25.

In addition to the social concerns raised by Digital Earth, other social challenges (such as counter-terrorism and presidential election analyses; Braha and de Aguiar 2017) can be addressed by developing new methodologies (such as social network analyses and social simulations) using a Digital Earth platform or systems. Such advances would also benefit initiatives of significant social complexity, such as the implementation of the United Nations' 17 sustainability goals.

26.2.6 Diversified Curricula Toward Digital Earth Education

With Digital Earth being embraced in our society, there has been a classic continuum of education (from K−12 to higher education) moving toward training/professional development such as internships, certificates and professional certifications (see Chap. 24 Digital Earth Education). Because of the difficulties related to data accessibility, interdisciplinary connections, and the natural as well as the social context of Digital Earth, it is challenging to build an overarching framework for the transformation.

There is a need in K−12 education to improve pre-service teaching training programs by including more geography and DE technologies in classrooms to better reflect this rapidly evolving geospatial world. Curriculum development is driven by up-to-date learning objectives and the encouragement of greater DE applications. In higher education, various curriculum development efforts such as experiential learning courses and certificates have been introduced. To promote professional development, the interaction and partnership between higher education, non-profit organizations and the geospatial industry are closer than ever. However, there remain discrepancies between academic education and the career readiness of the next generation. Misrepresentation of competencies and credentials in the curricula may make our students "*well educated but poorly trained*" or "*well trained but poorly educated*" (Burrus 2016). (A) diversified standard(s) is/are thus required to evaluate and guide future curriculum development, and to bridge the gaps between academia and industry, education and training, knowledge and skills, etc.

Reflecting the interdisciplinary nature of Digital Earth, we call for society-wide efforts within the ISDE to establish its unique body of knowledge (BoK). A hierarchical BoK structure may cover a wide range of knowledge from general geospatial education to skill-driven competencies. This BoK will provide fundamental guidance to future DE education.

26.3 New Opportunities and Future Trends in Digital Earth

26.3.1 New Technologies

(1) IoT

IoT has been developing rapidly in recent years, with billions of connected devices being developed and deployed in different domains and regions (such as urban traffic, ecosystem monitoring, and driverless cars). These devices not only sense essential elements of our Earth environment, but also provide processing capabilities at the edge of the networked environment, pushing innovative paradigms for distributed computing, such as edge and fog computing. As IoT matures it will be possible to link EO data with 3D data and with airborne, UAV, and both surface and underground data, just as Al Gore envisaged twenty years ago. IoT is becoming a global infrastructure, enabling advanced services through the interconnection of things that belong to both the physical and virtual worlds. IoT will significantly contribute to implementing a sort of "digital nervous system of the globe, actively informing on events happening on (or close to) the Earth's surface by connecting to sensor networks and situation-aware systems" (Craglia et al. 2012).

(2) Blockchain

Blockchain was developed to support the bitcoin currency, and has the characteristics of decentralization, persistence, anonymity, and auditability. These characteristics provide a potential solution to the data security and privacy problems in Earth data, and different aspects of these are being investigated to support Digital Earth. However blockchain relies on very intensive computing, and absorbs vast amounts of electrical energy. As such it is clearly not sustainable or scalable. The example of blockchain raises a fundamental question for Digital Earth: while it is a powerful way of addressing the sustainability problems facing humanity, it nevertheless requires growing investment in technology and growing power consumption, creating its own sustainability problem.

(3) Virtual Reality/Augmented Reality/Mixed Reality

The demand for all types of interactive experiences, whether from scientists, business people, government decision makers, or ordinary citizens, will continue to grow (notwithstanding the issues raised in the previous paragraph). The foundation of VR/AR/MR lies in geospatial technology. For example, geospatial technology is contributing to the market for wearable technology, which enables users to track their steps, heart rate, etc., and thus helps them to have a better understanding of their activities during the day.

(4) Artificial Intelligence

Artificial intelligence (AI), a broad term that includes deep learning, knowledge graphs, and brain-inspired computing, is one of the most prominent technologies currently being advanced. It is a hot topic for researchers and offers great opportunities for Digital Earth knowledge discovery, but is also raising a number of important concerns even among the world's greatest technological minds (Craglia et al. 2018). While generalizability across space and time has always been a requirement of basic science, AI requires a somewhat looser interpretation of the term, and its popularity may even have a fundamental effect on the conduct of science and its epistemological underpinnings. The strength of AI may lie in prediction, whereas science has long emphasized explanation and understanding. It is also far from clear what role the principles of geographic information science—spatial dependence, spatial heterogeneity, etc.—can play in an AI that is virtually theory-free.

The development of AI is strongly linked to an exponential increase in the availability and quality of data on which AI applications are built. The development of new connectivity via 5G, new computing infrastructure, and sensor networks in the Internet of Things offers major opportunities to create ecosystems of shared data across the public sector, commercial sector, and civil society so that AI applications address the most pressing needs of our planet and society, at both local and global levels (Craglia et al. 2018).

(5) Hyper-Connectivity

The volume of available data is now growing at an unprecedented pace. Worldwide, citizens, public administration, and private companies generate and store a vast volume of data daily. A driving factor behind this is certainly increasing Internet connectivity. In the past, the Internet evolved from a network of online resources—today, there exist more than 1 billion websites (Netcraft 2019) targeted by over 6 billion Google queries per day (Internet Live Stats 2019)—to a global social network, connecting people and communities worldwide. In 2018 there were more than 2.3 billion Facebook (Facebook 2019) and 321 million Twitter (Twitter 2019) active users monthly; every day, around 4 billion videos are viewed on Youtube (MerchDope 2019), and 95 million photos and videos are shared on Instagram (Instagram 2019). According to some global market experts, in 2025 each connected person will have at least one data interaction every 18 s (IDC and Seagate 2018). For example, digital payments are expected to hit 762 billion by 2020 (Capgemini and BNP Paribas 2018), while Internet devices carried by individuals (e.g., smartphones or wearable technology) will continuously record and upload to the Internet data on humans' behaviour (digital "footprints"), such as location, physical activity, and health status.

(6) 5G, Fog/Edge Computing

Many connected devices (including those using AI) require the transmission of huge amounts of data to the cloud for storage and processing. The advent of the 5G (the fifth generation of mobile wireless technologies) network will dramatically increase this demand in the next few years—and, in particular, demand for real-time processing services. Critical applications using IoT devices (for example in sectors like health, energy, or automobiles) will depend on the reliability of communication networks. In addition to time latency, this raises other important challenges, such as security, privacy, and energy efficiency for data moving and processing. For these reasons, novel data computing architectures have been introduced—in particular, fog and edge computing. The advent of 5G will be disrupting for mobile connectivity, because not only will it deliver faster broadband to consumers, it will also enable emerging technologies such as autonomous vehicles and the IoT to become a reality for both industries and consumers. Meanwhile, we should consider the environmental impact of 5G on energy consumption and human exposure.

(7) Progress in Computing and Microelectronics

Big Data analytics and AI require new types of computing to address emerging needs—for example, to support parallel and tensor processing, overcome the traditional computer architecture latency problem, embed machine learning, deploy processor-in-memory, 4D virtual reality and augmented reality, to visualize and, notably, to consume less energy. Traditional CPUs have been replaced by innovative (and green) processing technologies, often developed by big ICT companies (e.g., Google, Facebook, Apple, Intel, Tesla) that are better suited to AI. These technologies include GPU, TPU, cloud chips, neuromorphic computing, reversible computing, and quantum computing. Recent developments also include field-programmable gate arrays (FPGAs) and application-specific integrated circuits (ASICs) as the next primary chips for AI/ML. The main idea behind FPGAs is that they are reconfigurable: the chip hardware wiring can be changed as easily as writing code.

(8) In-memory Computing

In-memory computing stores data in RAM rather than in databases hosted on disks. This eliminates the I/O latency and the need to implement database transactions reliability and consistently. This technology speeds data access exponentially because RAM-stored data is available instantaneously, while data stored on disks is limited by network and disk speeds. In-memory computing requires that massive amounts of data be cached, enabling extremely fast response times, and that session data be stored to help achieve optimum performance; for instance, see HP in-memory solutions. This approach allows quick analysis of massive volumes of data in real time at very high speeds, and also supports the detection of patterns.

26.3.2 New Services

There are many new trends involving the development of innovative products by government departments, space agencies, and private companies. These offer fundamentally new services based on machine learning, and also integration with related services and technologies, such as navigation, geolocation, artificial intelligence, IoT, Big Earth Data, blockchain, and many others.

It is clear that the new, disruptive technology trends will transform many strategies across the globe. At the intersection of technology, government, science, and industry, clashes and resistance to change may impede progress in finding solutions to many of the world's most vexing problems. On the other hand, it is clear that new technologies can sometimes create more problems than they solve when not all of their consequences are anticipated.

26.3.3 New Applications

With advances in Earth system science, the need for sustainable development has been well understood in the scientific community, in government, and in human society. Digital Earth will serve as an enabling platform and system for Earth system science as well as research into global climate change.

With regard to the challenges facing the use of Digital Earth in studying climate and environmental changes, we have seen in earlier chapters of the manual (e.g., Chap. 14) that, due to cloud cover, aerosols in the atmosphere, seasonal snow cover, sensor failure, and limited observation geometry, existing remote sensing products suffer from noise, and time and space discontinuity. These defects severely constrain the study of land-surface processes and climate change simulations that are driven by spatial data parameters, and therefore reduce the reliability of climate-change projections. It is necessary to synthesize multi-sensor remote sensing data to obtain high-quality and spatiotemporally continuous data on land-surface parameters. This will allow more accurate evaluation of the spatiotemporal variation of climate-sensitive parameters, improve the accuracy of climate models, and also allow the accurate monitoring of the locations of disturbances, the extent of their impact, and the consequent future changes (e.g., Shupeng and van Genderen 2008). This challenge also applies to the utilization of Digital Earth to support most advances in geoscience (Yang and Huang 2013).

Digital Earth should evolve in a sustainable way by considering the vision, technology, workforce, policy, and many other aspects; for example, how to apply, adapt, and integrate the U.N.'s Sustainable Development Goals (SDGs) into the next Digital Earth system (Anderson et al. 2017; Scott and Rajabifard 2017). Among the 17 goals, at least 8 could be realized by benefiting in different ways from Digital Earth Data. These goals include clean water, affordable energy, sustainable cities, climate change, life below water, life on land, good health, and peace. Digital Earth can play a very important role in these fields (Guo 2017).

26.3.4 New Paradigms

The Web has seen many developments, connecting more and more elements of our society, and, all the time, creating new business intelligence. Today, the Web enables the externalization of practically any digital capability and service, moving most of society's transactions and processes onto the network by exploiting the platform economy, hyper-connectivity, and Cloud computing. IoT and 5G are promising to further expand the Web by connecting vast numbers of devices and generating new business intelligence. In the future, simple objects (e.g., devices), complex real-time systems (e.g., moving vehicles), and sophisticated analytical and forecasting models will all be online and exchanging information. Real-world objects (sensing and acting upon the physical world) will be represented in the virtual world, and their interconnection will enable advanced services. Enabling technologies include mobile technology (5G), cloud computing (virtual computing), big data, and AI (deep analytics).

This will lead to an ecosystem of diverse (Internet-based) platforms and domain applications, which is termed the Web of Things (WoT) by W3C. WoT aims to connect real-world objects and systems to the Web, creating a decentralized IoT where things are linkable, discoverable, and usable (W3C 2019). In such a framework, a promising interaction pattern is called a digital twin: a digital model of a real connected object or a set of objects representing a complex domain environment. Depending on its complexity, a digital representation (i.e., the twin) may reside in a cloud or on an edge system. A digital twin can be used to represent real-world things and systems that may not be continuously online, or to run simulations of new applications and services before they are deployed to the real world.

In the future, it might be possible to connect (in the virtual world) diverse digital twins representing extremely complex and vast domains, such as natural phenomena and social processes. Virtual forms of future digital twins might even be developed to model the Earth domain, a digital twin of our planet, or Earth twin. This paradigm would support the ISDE's vision of Digital Earth as "multiple connected infrastructures based on open access and participation across multiple technological platforms addressing the needs of different audiences".

26.3.5 New Challenges

(1) ***Sustainability challenges***

The digital transformation of our society is facing an increasing problem: the severe mismatch between the processing and storage needs of the escalating volumes of data available, and the need to have a sustainable energy footprint. A report prepared for Greenpeace (2012) claimed that if the cloud were a country, it would have the fifth largest energy demand in the world, while Vidal (2017) suggested that the data tsunami could consume one fifth of global electricity by 2025. Trust (including cyber-security) and ICT energy consumption will be two important determinants of the long-term sustainability of the next digital (r)evolution. The constant innovation in digital technologies promises to address sustainability issues; however, side and rebound effects must also be considered. For instance, while blockchain promises to address some important security and trust issues, ledger-based networks (like blockchain technology) still remain to be investigated, in particular, in terms of their energy consumption (Nascimento et al. 2018). Another valuable example is represented by the development of green (i.e., less energy- consuming) devices, which, as they become cheaper, will likely have the effect of increasing the number of devices being commercialized and the amount of time for which they are used. Finally, concerns have already been raised about the environmental impact of 5G technology, especially in relation to energy consumption and human health issues (Van Chien et al. 2016): unlike 4G networks, 5G uses extremely high frequencies that do not travel as far as 4G waves, and, therefore, requires much smaller cells and a higher density of transmitters.

(2) ***Ethical and security challenges***

It is important to think about how the digital transformation of our society (and in particular the adoption of AI) might bring new challenges in relation to individual human beings. In this context, it is crucial to consider how the concepts of autonomy and the identity of individuals as well as security, safety, and privacy issues might change. AI systems are currently limited to narrow and well-defined tasks, and their technologies inherit imperfections from their human creators, such as the well-recognised bias effect present in data. Ethical and secure-by-design algorithms are crucial to building trust in this disruptive technology, but we also need the broader engagement of civil society in the values to be embedded in digital transformation and future developments (Craglia et al. 2018).

(3) ***New governance challenges***

The development of DE and the digital transformation of our society provide many new opportunities for a deeper understanding of both physical and social phenomena, and new tools for collective action. As we see in the environmental domain, however, it takes a long time and a consistent effort to forge a shared view of both problems and solutions, and to reach agreements which, even then, are not without setbacks and challenges. Digital transformation adds a new dimension to the governance challenge because it reshuffles the power relationships between governments, the commercial sector, and civil society. Increasingly, the control of data conveys power. Whilst many governments have begun to realize that their ability to understand and govern society is diminishing, the IoT and AI revolution may bring new actors into the game: machine-to-machine data generation, elaboration, and autonomous action may give machines an agency as yet unforeseen, challenging further the ability to govern the system. This, therefore, requires a collective response by the international community, including the setting of new ground rules to ensure continued human control of the direction of travel and how to get there.

26.4 Conclusions

When the concept of Digital Earth was first mooted, it had several drivers, including scientific questions, technological developments, critical thinking about the domain, and our capabilities for content handling. The challenges of the concept have driven us to adopt new technologies and approaches, and to develop new solutions. All these new Digital Earth technologies and the multitude of new Earth observation data from satellites offer new possibilities for DE scholars to advance our understanding of how the ocean, atmosphere, land, and cryosphere operate and interact as part of an integrated Digital Earth system. They also bring both challenges and opportunities to career preparedness for the next generation, especially to curriculum development for education at all levels.

Since the vision put forward by Al Gore, which he illustrated by imagining a young girl experiencing the Earth through the medium of virtual reality, many advances have been made at various levels and in various aspects, but we are still some distance from the ultimate Digital Earth as envisioned by Gore. While technology has advanced in leaps and bounds, and an approximation to Digital Earth is now available to anyone through readily available devices, a host of new challenges present themselves. Technology which was once seen as a utopian solution to many human problems is now recognized as having the potential to create almost as many problems as it solves. Future research will need to focus not only on the technology and on the science that it makes possible, but also on its societal context: on its sustainability, on equity of access, and on the dystopias it can create alongside the utopias. Meanwhile we can expect that a steady stream of new technologies will sustain interest and ensure steady progress toward the dream of a Digital Earth.

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John van Genderen is a Professor from the ITC, who has been involved in Digital Earth since the first ISDE Symposium in Beijing in 1999. His main research is in Remote Sensing Image Fusion, and in transfer of technology to Less Developed countries. He has carried out EO projects in some 140 countries.

Michael F. Goodchild is Emeritus Professor of Geography at the University of California, Santa Barbara. He is also Distinguished Chair Professor at the Hong Kong Polytechnic University and Research Professor at Arizona State University, and holds many other affiliate, adjunct, and honorary positions at universities around the world. Until his retirement in June 2012, he was Jack and Laura Dangermond Professor of Geography, and Director of UCSB's Center for Spatial Studies. He received his BA degree from Cambridge University in Physics in 1965 and his Ph.D. in geography from McMaster University in 1969, and has received five honorary doctorates. He was elected member of the National Academy of Sciences and Foreign Member of the Royal Society of Canada in 2002, member of the American Academy of Arts and Sciences in 2006, and Foreign Member of the Royal Society and Corresponding Fellow of the British Academy in 2010; and in 2007, he received the Prix Vautrin Lud. He was editor of *Geographical Analysis* between 1987 and 1990 and editor of the Methods, Models, and Geographic Information Sciences section of the *Annals of the Association of American Geographers* from 2000 to 2006. He serves on the editorial boards of 10 other journals and book series, and has published over 15 books and 500 articles. He was Chair of the National Research Council's Mapping Science Committee from 1997 to 1999, and of the Advisory Committee on Social, Behavioral, and Economic Sciences of the National Science Foundation from 2008 to 2010. His research interests center on geographic information science, spatial analysis, and uncertainty in geographic data.

Huadong Guo is a Professor of the Chinese Academy of Sciences (CAS) Institute of Remote Sensing and Digital Earth (RADI), an Academician of CAS, a Foreign Member of Russian Academy of Sciences, a Foreign Member of Finnish Society of Sciences and Letters, and a Fellow of TWAS. He presently serves as President of the International Society for Digital Earth (ISDE), Member of UN 10-Member Group to support the Technology Facilitation Mechanism for

SDGs, Director of the International Center on Space Technologies for Natural and Cultural Heritage under the Auspices of UNESCO, Science Committee Member of the Integrated Research on Disaster Risk (IRDR) Program of ISC and UNDRR, Chair of the Digital Belt and Road Program (DBAR), Chairman of the International Committee on Remote Sensing of Environment, and Editor-in-Chief of the *International Journal of Digital Earth* and the journal of *Big Earth Data* published by Taylor & Francis. He served as President of ICSU Committee on Data for Science and Technology (CODATA, 2010–2014) and Secretary General of ISDE (2006–2014). He specializes in remote sensing, radar for Earth observation and Digital Earth science. He is the Principal Investigator of Moon-based Earth Observation Project of National Natural Science Foundation of China and the Chief Scientist of the Big Earth Data Science Engineering Project of CAS. He has published more than 400 papers and 17 books, and is the principal awardee of 16 domestic and international prizes.

Chaowei Yang is Professor of GIScience at George Mason University, where he established and directs the NSF spatiotemporal innovation center. His academic activities include spatiotemporal computing research, future GIScience leader education, and Geoinformatics outreach.

Stefano Nativi is the Big Data Lead Scientist of the Joint Research Centre of the European Commission. He researches the enabling technologies of Digital Transformation and Data Ecosystems. He founded the Earth and Space Sciences Informatics division of the European Geosciences Union (EGU). He has taught at the universities of Padua, Florence and Jena. He is member of the ISDE Council.

Lizhe Wang is a "ChuTian"Chair Professor at School of Computer Science, China University of Geosciences (CUG). Prof. Wang received B.E. & M.E from Tsinghua University and Doctor of Eng. from University Karlsruhe (Magna Cum Laude), Germany. His main research interests include remote sensing image processing and spatial data processing.

Cuizhen Wang is a Professor of Geography at the University of South Carolina, USA, with primary research in bio-environmental remote sensing and Big Earth Data. She is a USGIF Subject Matter Expert in Remote Sensing and Image Analysis, a member of the DBAR Coastal Work Group and the Director of the ICoE on Big Earth Data for Coasts.

Appendix A
International Society for Digital Earth (ISDE) History and Milestones

In May 2006, the International Society for Digital Earth (ISDE) was officially inaugurated in Beijing, China. The 1st ISDE Executive Committee Meeting was held on May 21, 2006. ISDE is a non-political, non-governmental and not-for-profit international organization principally promoting academic exchange, science and technology innovation, education, and international collaboration towards Digital Earth.

On August 13, 2007, Mr. Al Gore was awarded the Special Advisor of the International Society for Digital Earth at the occasion of his visit to the Chinese Academy of Sciences in Beijing and gave a presentation entitled "Climate Change and Environmental Protection".

In March 2008, the *International Journal of Digital Earth* was launched by the International Society for Digital Earth jointly with Taylor & Francis Group.

In August 2009, the *International Journal of Digital Earth* was accepted in the SCI-Expanded.

In November 2009, the International Society for Digital Earth was accepted as a new member of the Group on Earth Observations (GEO) at the Sixth Plenary Session of GEO, held on November 17–18, 2009 in Washington, becoming the 58th Participating Organization of GEO.

In 2010, the *International Journal of Digital Earth* gained its first Impact Factor of 0.864.

In August 2010, the third edition text book "Geographic Information Systems and Science" described the International Society for Digital Earth as a key international organization in Digital Earth field.

In November 2010, on behalf of the International Society for Digital Earth, Prof. Huadong Guo stated the ISDE's future roles and actions in Global Earth Observation System of Systems (GEOSS) at the 7th Plenary Session of the Group on Earth Observations held in Beijing.

In March 2011, the "Workshop on Digital Earth Vision to 2020" organized by the ISDE secretariat was held in Beijing, China. The main achievements of this meeting were published in two important journals. One is the paper entitled "*Digital Earth 2020: towards the vision for the next decade*" published in the *International Journal*

H. Guo et al. (eds.), *Manual of Digital Earth*,
https://doi.org/10.1007/978-981-32-9915-3

of Digital Earth in 2011, and another paper is "*Next-Generation Digital Earth*" published in the *Proceedings of the National Academy of Sciences* in 2012.

In October, 2011, the International Society for Digital Earth and the ICSU Committee on Data for Science and Technology signed a Memorandum of Understanding of the CODATA Hand-in-Hand Program at the Centre of Earth Observation and Digital Earth (CEODE), Chinese Academy of Sciences in Beijing.

In 2015, the *International Journal of Digital Earth* received its Impact Factor of 3.291, ranking the 4th in Remote Sensing Category, and 7th in Geography category.

In January 2017, the International Society for Digital Earth has been formally admitted to be an International Scientific Associate Member of the International Council for Science (now is the International Science Council), becoming one of its 24 International Scientific Associate members, and one of its 167 members.

In December 2017, the International Society for Digital Earth published a new journal, namely *Big Earth Data*.

In February 2018, the inauguration ceremony of the *Big Earth Data* journal was held together with the launching ceremony of the Big Earth Data Science Engineering Project (CASEarth) of the Chinese Academy of Sciences.

In June 2019, The International Journal of Digital Earth received the highest SCI impact factor, 3.985, since its inauguration in 2008.

In August 2019, the International Society for Digital Earth is accepted as a new member of the United Nation Committee of Experts on Global Geospatial Information Management—Geospatial Societies (UN-GGIM GS).

Appendix B
International Symposium on Digital Earth and Digital Earth Summit

International Symposium on Digital Earth

From November 29 to December 2, 1999, the 1st International Symposium on Digital Earth was hosted by the Chinese Academy of Sciences in Beijing, with the theme of Towards Digital Earth. A milestone document—the *1999 Beijing Declaration on Digital Earth*, was officially approved at the symposium. The former Vice Premier of China, Li Lanqing, attended the opening ceremony and delivered a speech. More than 500 delegates from 27 countries attended this symposium. Prof. Yongxiang Lu was the Chair and Prof. Huadong Guo was the Secretary General of this Symposium.

On December 2, 1999, an International Steering Committee of the International Symposium on Digital Earth was established to organize the subsequent series of symposia in the coming years. Prof. Yongxiang Lu and Prof. Huadong Guo were elected the Chairman and Secretary General of the Committee, respectively. It was suggested that the International Symposium on Digital Earth be held every two years, rotating among countries.

In June 2001, the 2nd International Symposium on Digital Earth was held in New Brunswick, Canada, with the theme of Beyond Information Infrastructure. More than 700 delegates from 30 countries attended the symposium.

In September 2003, the 3rd International Symposium on Digital Earth was held in Brno, Czech Republic, with the theme of Information Resources for Global Sustainability. About 250 delegates from 34 countries participated in the symposium.

In March 2005, the 4th International Symposium on Digital Earth was held in Tokyo Japan, with the theme of Digital Earth as a Global Commons. About 350 delegates from 36 countries attended the symposium.

In June 2007, the 5th International Symposium on Digital Earth was held in Berkeley USA, with the theme of Bring Digital Earth down to Earth. About 390 delegates from 28 countries attended this symposium. The 2nd ISDE Executive Committee Meeting was held on June 4, 2007 at Regents Room in Durant Hotel, co-chaired by Dr. Marc D'Iorio and Prof. Milan Konecny.

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In September 2009, the 6th International Symposium on Digital Earth was held in Beijing, China, with the theme of Digital Earth in Action. The *2009 Beijing Declaration on Digital Earth* was fully adopted at the symposium. More than 1000 delegates from 40 countries attended this symposium. The 4th ISDE Executive Committee Meeting was held on September 9, 2009, Prof. Yongxiang Lu chaired the meeting.

To celebrate the 10th anniversary of Digital Earth, some individuals and organizations were rewarded for their special contributions to the development of Digital Earth at the opening ceremony. The "Digital Earth Science and Technology Contribution Award" was presented to the late Prof. Shupeng Chen, Prof. Guanhua Xu, and Prof. Michael Goodchild; the "Contribution Award for Enterprises in Digital Earth" was presented to Google Earth, Map and Local, and Google Inc.; the "Digital Earth Medal" was presented to Prof. John van Genderen; the "International Digital Earth Series Symposia and Summits Organization Award" was presented to the organizers of five International Symposia on Digital Earth, and two Digital Earth Summits.

In August 2011, the 7th International Symposium on Digital Earth was held in Perth, Australia, with the theme of The Knowledge Generation. Over 800 experts from worldwide attended the symposium. The 6th ISDE Executive Committee Meeting was held on August 22, 2011 at Landgate Cloister, chaired by Prof. John Richards.

In August 2013, the 8th International Symposium on Digital Earth was held in Sarawak, Malaysia, with the theme of Transforming Knowledge into Sustainable Practice. Over 360 experts and scholars from 35 countries and regions attended this symposium. The 8th ISDE Executive Committee Meeting was held on August 25, 2013 at Borneo Convention Centre, Kuching, Malaysia.

In October 2015, the 9th International Symposium on Digital Earth was held in Halifax, Canada, with the theme of Towards a One-World Vision for the Blue Planet. About 300 delegates of scientists, engineers, technologists, and environmental managers from 28 countries around the world gathered at the symposium. The 10th ISDE Executive Committee Meeting was held on October 4, 2015 at the World Trade and Convention Centre, Halifax, Canada, chaired by Prof. Huadong Guo.

In April 2017, the 10th International Symposium on Digital Earth was held in Sydney, Australia, with the theme of Digital Transformation – Our Future. More than 600 people from 27 counties participated in the event. The 12th ISDE Council Meeting was held on April 4, 2017 at the Sydney International Convention Center, Australia, chaired by Prof. Huadong Guo.

In September 2019, the 11th International Symposium on Digital Earth will be held in Florence, Italy, with the theme of Digital Earth in a Transformed Society.

Digital Earth Summit

In August 2006, the 1st Digital Earth Summit was held in Auckland, New Zealand, with the theme of Digital Earth Summit on Sustainability. The former New Zealand

Prime Minister, Rt Hon Helen Clark, delivered a speech at the opening ceremony. More than 380 delegates from 35 countries attended the summit.

In November 2008, the 2nd Digital Earth Summit was held in Potsdam, Germany, with the theme of Geoinformatics: Tools for Global Change Research. More than 120 delegates from 15 countries attended this summit. The 3rd ISDE Executive Committee Meeting was held on November 13, 2008 at Vortagsraum, Building A31, GFZ, Potsdam, Germany.

In June 2010, the 3rd Digital Earth Summit was held in Nessebar Bulgaria, with the theme of Digital Earth in the Service of Society: Sharing Information, Building Knowledge. There are nearly 100 researchers from 11 countries registered at this submit. The 5th ISDE Executive Committee Meeting was held at Arsena Hotel, Nessebar, Bulgaria on June 11, 2010, co-chaired by Prof. Huadong Guo and Prof. Milan Konecny.

In September 2012, the 4th Digital Earth Summit was held in Wellington, New Zealand, with the theme of Digital Earth and Technology. Around 200 delegates from more than 20 countries gathered at this summit. The 7th ISDE Executive Committee Meeting was held on September 1, 2012 at the Square Affair Suite, Wellington Town Hall.

In November 2014, the 5th Digital Earth Summit was held in Nagoya, Japan, with the theme of Digital Earth for Education Sustainable Development. More than 100 participants from 22 countries attended this summit. The 9th ISDE Executive Committee Meeting was held on November 8, 2015 in Nagoya.

In July 2016, the 6th Digital Earth Summit was held in Beijing, China, with the theme of Digital Earth in the Era of Big Data. About 300 delegates of scientists, engineers, technologists, and scholars from 30 countries attended the summit. The 11th ISDE Council Meeting was held on July 6, 2016 at Beijing International Convention Center, China.

To celebrate the 10th anniversary of ISDE, seven ISDE honors/awards were granted to those who made great contribution to the development of Digital Earth. The "ISDE Fellow" was granted to Prof. Yongxiang Lu and Prof. Michael F. Goodchild; the "ISDE Honorary Member" was granted to Mr. Yong Shang; the "ISDE Life Member" was granted to Prof. Yuntai Chen, Mrs. Davina Jackson, Prof. John van Genderen, Prof. Jean Sequeira, Dr. Gábor Remetey-Fülöpp, Prof. Shu Sun, Prof. Tim Foresman and Prof. Guanhua Xu; the "ISDE Special Contribution Award" was granted to Prof. Qinmin Wang; the "Digital Earth Science/Technology Contribution Award" was granted to Dr. Alessandro Annoni and Prof. Deren Li; the "ISDE Service Award" was granted to Prof. Changlin Wang, Prof. Milan Konečný, Dr. Mario Hernandez and Dr. Fred Campbell (Posthumously Awarded); the "ISDE Conference Organizing Award" was granted to Prof. Huadong Guo, Prof. Temenoujka Bandrova, Dr. Peter Woodgate, Dr. Richard Simpson, Prof. Mazlan bin Hashim, Prof. Hiromichi Fukui and Prof. Hugh Millward.

In April 2018, the 7th Digital Earth Summit was held in EI Jadida, Morocco, with the theme of Digital Earth for Sustainable Development in Africa. Around 200 attendees from worldwide participated in this summit. The 13th ISDE Council Meeting was held on April 16, 2018, chaired by Prof. Huadong Guo.

Appendix C
The Organization of the International Society for Digital Earth (ISDE)

ISDE Bureau (2015–2019)

President
Huadong Guo, Chinese Academy of Sciences, China
Vice President
Alessandro Annoni, Joint Research Center, Europe Commission
John Townshend, University of Maryland, USA
Secretary General
Mario Hernandez, Future Earth Engagement Committee, Mexico
Treasurer
Zaffar Sadiq Mohamed-Ghouse, Cooperative Research Centre for Spatial Information, Australia
Executive Director
Changlin Wang, Chinese Academy of Sciences, China
Other Member
Claudia Kuenzer, German Aerospace Center, Germany

ISDE Councilors (2015–2019)

Alessandro Annoni, Joint Research Center, European Commission
Changlin Wang, Chinese Academy of Sciences, China
Claudia Kuenzer, German Aerospace Center, Germany
Eugene N. Eremchenko, Lomonosov Moscow State University, Russia
Hiromichi Fukui, Chubu University, Japan
Huadong Guo, Chinese Academy of Sciences, China
Joel I. Igbokwe, Nnamdi Azikiwe University, Nigeria
John Townshend, University of Maryland, USA
Josef Strobl, University of Salzburg, Austria

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Mario Hernandez, Future Earth Engagement Committee, Mexico
Markku Kulmala, University of Helsinki, Finland
Richard Simpson, Meta Moto Pty Ltd, Australia
Stefano Nativi, Joint Research Centre, European Commission
Sven Schade, Joint Research Centre, European Commission
Temenoujka Bandrova, University of Architecture, Civil Engineering and Geodesy, Bulgaria
Zaffar Sadiq Mohamed-Ghouse, Cooperative Research Centre for Spatial Information, Australia

ISDE Executive Committee (2014–2015)

Officers
President
John Richards, Australian National University, Australia
Vice President
Milan Konečný, Masaryk University, Czech Republic
Secretary General
Huadong Guo, Chinese Academy of Sciences, China
Treasurer
Mario Hernandez, Future Earth Engagement Committee, Mexico
Executive Director
Changlin Wang, Chinese Academy of Sciences, China
Other Members
Peter Woodgate, Cooperative Research Centre for Spatial Information, Australia
Alessandro Annoni, Joint Research Center, Europe Commission
Yola Georgiadou, University of Twente, The Netherlands

Members
Alessandro Annoni, Joint Research Centre, European Commission
Bernhard Hoefle, University of Heidelberg, Germany
Changlin Wang, Chinese Academy of Sciences, China
Hiromichi Fukui, Chubu University, Japan
Huadong Guo, Chinese Academy of Sciences, China
Hugh A. Millward, Saint Mary's University, Canada
Jean Sequeira, University of Marseilles, France
Joel I. Igbokwe, Nnamdi Azikiwe University, Nigeria
John Townshend, Maryland University, USA
Josef Strobl, University of Salzburg, Austria
Manfred Ehlers, University of Osnabrueck, Germany
Mario Hernandez, Future Earth Engagement Committee, Mexico
Markku Kulmala, University of Helsinki, Finland
Milan Konečný, Masaryk University, Czech Republic

Parodi Luciano, Ministry of Foreign Affairs, Chile
Peter Woodgate, Cooperative Research Centre for Spatial Information, Australia
Rebecca Moore, Google, USA
Richard Simpson, Spatial Industries Business Association, New Zealand
Sven Schade, Joint Research Centre, European Commission
Temenoujka Bandrova, University of Architecture, Civil Engineering and Geodesy, Bulgaria
Tim W. Foresman, International Centre for Remote Sensing Education, Inc. USA
Vladimir Tikunov, Lomonosov Moscow State University, Russia
Zaffar Sadiq Mohamed-Ghouse, Cooperative Research Centre for Spatial Information, Australia

ISDE Executive Committee (2011–2014)

President
John Richards, Australian National University, Australia
Vice President
Michael F. Goodchild, University of California, Santa Barbara, USA
Milan Konečný, Masaryk University, Czech Republic
Secretary General
Huadong Guo, Chinese Academy of Sciences, China
Treasurer
Fred Campbell, Canada FC Consultant Ltd., Canada

Members
Alessandro Annoni, Joint Research Centre, European Commission
Armin Gruen, Federal Institute of Technology, Switzerland
Changchui He, FAO for Asia and Pacific Regions
Changlin Wang, Chinese Academy of Sciences, China
David Rhind, City University, United Kingdom
Gabor Remetey-Fülöpp, Hungarian Association for Geo-information, Hungary
Guanhua Xu, Ministry of Science and Technology, China
Hiromichi Fukui, Keio University, Japan
Jean Sequeira, University of Marseiles, France
John Townshend, Maryland University, USA
Ling Bian, University at Buffalo, State University of New York, USA
Luke Driskell, Louisiana State University, USA
Manfred Ehlers, University Osnabrück, Germany
Mario Hernandez, Remote Sensing Unit, UNESCO
Peter Woodgate, Cooperative Research Center for Spatial Information, Australia
Richard Simpson, University of Auckland, New Zealand

Temenoujka Bandrova, University of Architecture, Civil Engineering and Geodesy, Bulgaria
Terence van Zyl, University of the Witwatersrand, South Africa
Tim W. Foresman, International Center for Remote Sensing Education, USA
Vladimir Tikunov, Lomonosov Moscow State University, Russia
Yola Georgiadou, University Twente, The Netherlands
Yuntai Chen, State Seismological Bureau, China

ISDE Executive Committee (2006–2011)

President
Yongxiang Lu, Chinese Academy of Sciences, China
Vice President
Marc D'Iorio, Geological Survey of Canada, Canada
Milan Konečný, Masaryk University, Czech Republic
Secretary General
Huadong Guo, Chinese Academy of Sciences, China

Members
Adigun Ade Abiodun, United Nations Committee on the Peaceful Uses of Outer Space
Alessandro Annoni, Joint Research Centre, European Commission, Italy
Armin Gruen, Federal Institute of Technology, Switzerland
Changchui He, FAO for Asia and Pacific Regions
David Rhind, City University, United Kingdom
Fred Campell, Canada FC Consulting, Canada
Gabor Remetey-Fülöpp, Hungarian Association for Geo-information, Hungary
Guanhua Xu, Ministry of Science and Technology, China
Hiromichi Fukui, Keio University, Japan
Jean Sequeira, University of Marseiles, France
John L. van Genderen, ITC, the Netherlands
John Townshend, Maryland University, USA
Manfred Ehlers, University Osnabrück, Germany
Mario Hernandez, Remote Sensing Unit, UNESCO
Mike Goodchild, University of California, Santa Barbara, USA
Peter Woodgate, Cooperative Research Center for Spatial Information, Australia
Richard Simpson, University of Auckland, New Zealand
Shupeng Chen, Chinese Academy of Sciences, China
Tim W. Foresman, International Center for Remote Sensing Education, USA
Vincent Tao, Microsoft Corporation, USA
Werner Alpers, University of Hamburg, Germany
Yuntai Chen, State Seismological Bureau, China

National and Regional ISDE Chapters

Chinese National Committee of the International Society for Digital Earth
Established in Beijing in May 2006
Australian Chapter of the International Society for Digital Earth
Approved by ISDE Executive Committee in Nagoya, Japan, November 2014
European Chapter of the International Society for Digital Earth
Approved by ISDE Executive Committee in Nagoya, Japan, November 2014
Japan Chapter of the International Society for Digital Earth
Approved by ISDE Council in Sydney, Australia, April 2017
Russian Chapter of the International Society for Digital Earth
Approved by ISDE Council in El Jadida, Morocco, April 2018

ISDE Secretariat

Changlin Wang, Zhen Liu, Jingna Liu, Hao Jiang, Linlin Guan
Institute of Remote Sensing and Digital Earth
Chinese Academy of Sciences, China

Appendix D
Journals Published by the International Society for Digital Earth

International Journal of Digital Earth

The *International Journal of Digital Earth* (IJDE) is one of the academic journals of the International Society for Digital Earth, which is sponsored by the Institute of Remote Sensing and Digital Earth of Chinese Academy of Sciences and jointly published by Taylor & Francis Group. IJDE was launched in March 2008, and accepted for coverage in the Science Citation Index Expanded (SCI-E) in August 2009. Its latest Impact Factor is 3.985 for the year of 2018. The Editor-in-Chief is Prof. Huadong Guo, the Executive Editor is Prof. Changlin Wang, the editors are Dr. Zhen Liu and Dr. Linlin Guan.

IJDE aims to publish research findings on Digital Earth theories, technologies and applications, which improve the understanding of the Earth and support knowledge-based solutions to improve human conditions, protect ecological services and support future sustainable development for environmental, social, and economic conditions.

IJDE is an international peer-reviewed journal. It encourages submissions covering, but not limited to the following areas:

- Progress visions for Digital Earth frameworks, policies, and standards;
- Explore geographically referenced 3D, 4D, or 5D models to represent the real planet, and geo-data-intensive science and discovery;
- Develop methods that turn all forms of geo-referenced data, from scientific to social, into useful information that can be analyzed, visualized, and shared;
- Present innovative, operational applications and pilots of Digital Earth technologies at a local, national, regional, and global level;
- Expand the role of Digital Earth in the fields of Earth science, including climate change, adaptation and health related issues,natural disasters, new energy sources, agricultural and food security, and urban planning;
- Foster the use of web-based public-domain platforms, social networks, and location-based services for the sharing of digital data, models, and information about the virtual Earth; and

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- Explore the role of social media and citizen provided data in generating geo-referenced information in the spatial sciences and technologies.

Journal website: http://www.tandfonline.com/toc/tjde20/current.

Big Earth Data

The journal of *Big Earth Data* is an interdisciplinary, open access and peer-review academic journal. Launched in December 2017, this journal is published by the International Society for Digital Earth jointly with the Institute of Remote Sensing and Digital Earth of Chinese Academy of Sciences, the Big Earth Data Science Engineering Project of Chinese Academy of Sciences, the Taylor & Francis Group and the Science Press. The Editor-in-Chief is Prof. Huadong Guo, the Executive Editor-in-Chief is Prof. Changlin Wang, the editors are Dr. Linlin Guan and Dr. Zhen Liu.

Aiming to provide an efficient and high-quality platform for promoting 'big data' sharing, processing and analyses, thereby revolutionizing the cognition of the Earth's systems, the journal *Big Earth Data* was inaugurated. To showcase the benefits of data-driven research, submissions on the applications of 'big Earth data' in exploring the Earth's history and its future evolution are highly encouraged. *Big Earth Data* supports open data policy and serves as a direct link between the published manuscript and its relevant supporting data in the advancement of data sharing and reuse.

The journal publishes research topics on 'big data' studies across the entire spectrum of Earth sciences, including but not limited to Earth Observation, Geography, Geology, Atmospheric Science, Marine Science, Geophysics, Geochemistry and so on. It accepts original research articles, review articles, data papers, technical notes and software. Along with research papers and data papers describing data sets, the journal also publishes paper-related data sets deposited in the public repositories.

Big Earth Data is an Open Access electronic online journal.

Journal website: http://www.tandfonline.com/toc/tbed20/current.

Appendix E
The Digital Earth: Understanding Our Planet in the 21st Century

The Speech Delivered by the Former US Vice President, Al Gore at the California Science Center, Los Angeles, California, on January 31, 1998.

A new wave of technological innovation is allowing us to capture, store, process and display an unprecedented amount of information about our planet and a wide variety of environmental and cultural phenomena. Much of this information will be "georeferenced"—that is, it will refer to some specific place on the Earth's surface.

The hard part of taking advantage of this flood of geospatial information will be making sense of it.—turning raw data into understandable information. Today, we often find that we have more information than we know what to do with. The Landsat program, designed to help us understand the global environment, is a good example. The Landsat satellite is capable of taking a complete photograph of the entire planet every two weeks, and it's been collecting data for more than 20 years. In spite of the great need for that information, the vast majority of those images have never fired a single neuron in a single human brain. Instead, they are stored in electronic silos of data. We used to have an agricultural policy where we stored grain in Midwestern silos and let it rot while millions of people starved to death. Now we have an insatiable hunger for knowledge. Yet a great deal of data remains unused.

Part of the problem has to do with the way information is displayed. Someone once said that if we tried to describe the human brain in computer terms, it looks as if we have a low bit rate, but very high resolution. For example, researchers have long known that we have trouble remembering more than seven pieces of data in our short-term memory. That's a low bit rate. On the other hand, we can absorb billions of bits of information instantly if they are arrayed in a recognizable pattern within which each bit gains meaning in relation to all the others—a human face, or a galaxy of stars.

The tools we have most commonly used to interact with data, such as the "desktop metaphor" employed by the Macintosh and Windows operating systems, are not really suited to this new challenge. I believe we need a "Digital Earth". A multi-resolution, three-dimensional representation of the planet, into which we can embed vast quantities of geo-referenced data.

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Imagine, for example, a young child going to a Digital Earth exhibit at a local museum. After donning a head-mounted display, she sees Earth as it appears from space. Using a data glove, she zooms in, using higher and higher levels of resolution, to see continents, then regions, countries, cities, and finally individual houses, trees, and other natural and man-made objects. Having found an area of the planet she is interested in exploring, she takes the equivalent of a "magic carpet ride" through a 3-D visualization of the terrain. Of course, terrain is only one of the many kinds of data with which she can interact. Using the systems' voice recognition capabilities, she is able to request information on land cover, distribution of plant and animal species, real-time weather, roads, political boundaries, and population. She can also visualize the environmental information that she and other students all over the world have collected as part of the GLOBE project. This information can be seamlessly fused with the digital map or terrain data. She can get more information on many of the objects she sees by using her data glove to click on a hyperlink. To prepare for her family's vacation to Yellowstone National Park, for example, she plans the perfect hike to the geysers, bison, and bighorn sheep that she has just read about. In fact, she can follow the trail visually from start to finish before she ever leaves the museum in her hometown.

She is not limited to moving through space, but can also travel through time. After taking a virtual field-trip to Paris to visit the Louvre, she moves backward in time to learn about French history, perusing digitized maps overlaid on the surface of the Digital Earth, newsreel footage, oral history, newspapers and other primary sources. She sends some of this information to her personal e-mail address to study later. The time-line, which stretches off in the distance, can be set for days, years, centuries, or even geological epochs, for those occasions when she wants to learn more about dinosaurs.

Obviously, no one organization in government, industry or academia could undertake such a project. Like the World Wide Web, it would require the grassroots efforts of hundreds of thousands of individuals, companies, university researchers, and government organizations. Although some of the data for the Digital Earth would be in the public domain, it might also become a digital marketplace for companies selling a vast array of commercial imagery and value-added information services. It could also become a "collaboratory"—a laboratory without walls—for research scientists seeking to understand the complex interaction between humanity and our environment.

Technologies Needed for a Digital Earth

Although this scenario may seem like science fiction, most of the technologies and capabilities that would be required to build a Digital Earth are either here or under development. Of course, the capabilities of a Digital Earth will continue to evolve over time. What we will be able to do in 2005 will look primitive compared to the

Digital Earth of the year 2020. Below are just a few of the technologies that are needed:

Computational science: Until the advent of computers, both experimental and theoretical ways of creating knowledge have been limited. Many of the phenomena that experimental scientists would like to study are too hard to observe—they may be too small or too large, too fast or too slow, occurring in a billionth of a second or over a billion years. Pure theory, on the other hand, cannot predict the outcomes of complex natural phenomena like thunderstorms or air flows over airplanes. But with high-speed computers as a new tool, we can simulate phenomena that are impossible to observe, and simultaneously better understand data from observations. In this way, computational science allows us to overcome the limitations of both experimental and theoretical science. Modeling and simulation will give us new insights into the data that we are collecting about our planet.

Mass storage: The Digital Earth will require storing quadrillions of bytes of information. Later this year, NASAs Mission to Planet Earth program will generate a terrabyte of information each day. Fortunately, we are continuing to make dramatic improvements in this area.

Satellite imagery: The Administration has licensed commercial satellites systems that will provide 1-meter resolution imagery beginning in early 1998. This provides a level of accuracy sufficient for detailed maps, and that was previously only available using aerial photography. This technology, originally developed in the U.S. intelligence community, is incredibly accurate. As one company put it, "It's like having a camera capable of looking from London to Paris and knowing where each object in the picture is to within the width of a car headlight."

Broadband networks: The data needed for a digital globe will be maintained by thousands of different organizations, not in one monolithic database. That means that the servers that are participating in the Digital Earth will need to be connected by high-speed networks. Driven by the explosive growth of Internet traffic, telecommunications carriers are already experimenting with 10 gigabit/second networks, and terrabit networking technology is one of the technical goals of the Next Generation Internet initiative. The bad news is that it will take a while before most of us have this kind of bandwidth to our home, which is why it will be necessary to have Digital Earth access points in public places like children's museums and science museums.

Interoperability: The Internet and the World Wide Web have succeeded because of the emergence of a few, simple, widely agreed upon protocols, such as the Internet protocol. The Digital Earth will also need some level of interoperability, so that geographical information generated by one kind of application software can be read by another. The GIS industry is seeking to address many of these issues through the Open GIS Consortium.

Metadata: Metadata is "data about data." For imagery or other georeferenced information to be helpful, it might be necessary to know its name, location, author or source, date, data format, resolution, etc. The Federal Geographic Data Committee is working with industry and state and local government to develop voluntary standards for metadata.

Of course, further technological progress is needed to realize the full potential of the Digital Earth, especially in areas such as automatic interpretation of imagery, the fusion of data from multiple sources, and intelligent agents that could find and link information on the Web about a particular spot on the planet. But enough of the pieces are in place right now to warrant proceeding with this exciting initiative.

Potential Applications

The applications that will be possible with broad, easy to use access to global geospatial information will be limited only by our imagination. We can get a sense of the possibilities by looking at today's applications of GIS and sensor data, some of which have been driven by industry, others by leading-edge public sector users:

Conducting virtual diplomacy: To support the Bosnia peace negotiations, the Pentagon developed a virtual-reality landscape that allowed the negotiators to take a simulated aerial tour of the proposed borders. At one point in the negotiations, the Serbian President agreed to a wider corridor between Sarajevo and the Muslim enclave of Gorazde, after he saw that mountains made a narrow corridor impractical.

Fighting crime: The City of Salinas, California has reduced youth handgun violence by using GIS to detect crime patterns and gang activity. By collecting information on the distribution and frequency of criminal activities, the city has been able to quickly redeploy police resources.

Preserving biodiversity: Planning agencies in the Camp Pendelton, California region predict that population will grow from 1.1 million in 1990 to 1.6 million in 2010. This region contains over 200 plants and animals that are listed by federal or state agencies as endangered, threatened, or rare. By collecting information on terrain, soil type, annual rainfall, vegetation, land use, and ownership, scientists modeled the impact on biodiversity of different regional growth plans.

Predicting climate change: One of the significant unknowns in modeling climate change is the global rate of deforestation. By analyzing satellite imagery, researchers at the University of New Hampshire, working with colleagues in Brazil, are able to monitor changes in land cover and thus determine the rate and location of deforestation in the Amazon. This technique is now being extended to other forested areas in the world.

Increasing agricultural productivity: Farmers are already beginning to use satellite imagery and Global Positioning Systems for early detection of diseases and pests, and to target the application of pesticides, fertilizer and water to those parts of their fields that need it the most. This is known as precision farming, or "farming by the inch."

The Way Forward

We have an unparalleled opportunity to turn a flood of raw data into understandable information about our society and out planet. This data will include not only high-resolution satellite imagery of the planet, digital maps, and economic, social, and demographic information. If we are successful, it will have broad societal and commercial benefits in areas such as education, decision-making for a sustainable future, land-use planning, agricultural, and crisis management.

The Digital Earth project could allow us to respond to manmade or natural disasters—or to collaborate on the long-term environmental challenges we face.

A Digital Earth could provide a mechanism for users to navigate and search for geospatial information—and for producers to publish it. The Digital Earth would be composed of both the "user interface"—a browsable, 3D version of the planet available at various levels of resolution, a rapidly growing universe of networked geospatial information, and the mechanisms for integrating and displaying information from multiple sources.

A comparison with the World Wide Web is constructive. [In fact, it might build on several key Web and Internet standards.] Like the Web, the Digital Earth would organically evolve over time, as technology improves and the information available expands. Rather than being maintained by a single organization, it would be composed of both publically available information and commercial products and services from thousands of different organizations. Just as interoperability was the key for the Web, the ability to discover and display data contained in different formats would be essential.

I believe that the way to spark the development of a Digital Earth is to sponsor a testbed, with participation from government, industry, and academia. This testbed would focus on a few applications, such as education and the environment, as well as the tough technical issues associated with interoperability, and policy issues such as privacy. As prototypes became available, it would also be possible to interact with the Digital Earth in multiple places around the country with access to high-speed networks, and get a more limited level of access over the Internet.

Clearly, the Digital Earth will not happen overnight.

In the first stage, we should focus on integrating the data from multiple sources that we already have. We should also connect our leading children's museums and science museums to high-speed networks such as the Next Generation Internet so that children can explore our planet. University researchers would be encouraged to partner with local schools and museums to enrich the Digital Earth project—possibly by concentrating on local geospatial information.

Next, we should endeavor to develop a digital map of the world at 1 meter resolution.

In the long run, we should seek to put the full range of data about our planet and our history at our fingertips.

In the months ahead, I intend to challenge experts in government, industry, academia, and non-profit organizations to help develop a strategy for realizing this vision. Working together, we can help solve many of the most pressing problems facing our society, inspiring our children to learn more about the world around them, and accelerate the growth of a multi-billion dollar industry.

Appendix F
1999 Beijing Declaration on Digital Earth and 2009 Beijing Declaration on Digital Earth

Beijing Declaration on Digital Earth
December 2, 1999

We, some 500 scientists, engineers, educators, managers and industrial entrepreneurs from 20 countries and regions assembled here in the historical city of Beijing, attending the first International Symposium on Digital Earth being organized by the Chinese Academy of Sciences with co-sponsorship of 19 organizations and institutions from November 29, 1999 to December 2, 1999, recognize that humankind, while entering into the new millennium, still faces great challenges such as rapid population growth, environmental degradation, and natural resource depletion which continue to threaten global sustainable development;

Noting that global development in the 20th century has been characterized by rapid advancements in science and technology which have made significant contributions to economic growth and social wellbeing and that the new century will be an era of information and space technologies supporting the global knowledge economy;

Recalling the statement by Al Gore, Vice President of the United States of America, on *Digital Earth: Understanding Our Planet in the 21st Century*—and the statement by Jiang Zemin, President of the People's Republic of China, on Digital Earth regarding trends of social, economic, scientific and technological development;

Realizing the decisions made at UNCED and Agenda 21, recommendations made by UNISPACE III and the Vienna Declaration on Space and Human Development, which address, among other things, the importance of the Integrated Global Observing Strategy, the Global Spatial Data Infrastructure, geographic information systems, global navigation and positioning systems, geo-spatial information infrastructures and modeling of dynamic processes;

Understanding that Digital Earth, addressing the social, economic, cultural, institutional, scientific, educational, and technical challenges, allows humankind to visualize the Earth, and all places within it, to access information about it and to understand and influence the social, economic and environmental issues that affect their lives in their neighborhoods, their nations and the planet Earth;

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Recommend that Digital Earth be promoted by scientific, educational and technological communities, industry, governments, as well as regional and international organizations;

Recommend also that while implementing the Digital Earth, priority be given to solving problems in environmental protection, disaster management, natural resource conservation, and sustainable economic and social development as well as improving the quality of life of the humankind;

Recommend further that Digital Earth be created in a way that also contributes to the exploration of, and scientific research on, global issues and the Earth system;

Declare the importance of Digital Earth in achieving global sustainable development;

Call for adequate investments and strong support in scientific research and development, education and training, capacity building as well as information and technology infrastructures, with emphasis, inter alia, on global systematic observation and modeling, communication networks, database development, and issues associated with interoperability of geo-spatial data;

Further call for close cooperation and collaboration between governments, public and private sectors, non-governmental organizations, and international organizations and institutions, so as to ensure equity in distribution of benefits derived from the use of Digital Earth in developed and developing economies;

Agree that, as a follow-up to the first International Symposium on Digital Earth held in Beijing, the International Symposium on Digital Earth should continue to be organized by interested countries or organizations biannually, on a rotational basis.

Beijing Declaration on Digital Earth
September 12, 2009

We scientists, engineers, educators, entrepreneurs, managers, administrators and representatives of civil societies from more than forty countries, international organizations and NGOs, once again, have assembled here, in the historic city of Beijing, to attend the Sixth International Symposium on Digital Earth, organized by the International Society for Digital Earth and the Chinese Academy of Sciences, with co-sponsorship of sixteen Chinese Government Departments, Institutions and international organizations, being held from September 9–12, 2009.

Noting

That Significant global-scale developments on Digital Earth science and technology have been made over the past ten years, and parallel advances in space information technology, communication network technology, high-performance computing, and Earth System Science have resulted in the rise of a Digital Earth data-sharing platform for public and commercial purposes, so that now Digital Earth is accessible by hundreds of millions, thus changing both the production and lifestyle of mankind;

Recognizing

The contributions to Digital Earth made by the host countries of the previous International Symposia on Digital Earth since November 1999, including China, Canada, the Czech Republic, Japan and the USA, and by the host countries of the previous Summit Conferences on Digital Earth, including New Zealand and Germany, for the success of the meetings as well as further promotion of Digital Earth;

Further, that the establishment of the International Society for Digital Earth and the accomplishments of its Executive Committee, the launch of the International Journal on Digital Earth, and its global contribution to cooperation and data exchange;

That the themes of the previous seven meetings: Moving towards Digital Earth, Beyond Information Infrastructure, Information Resources for Global Sustainability, Digital Earth as Global Commons, Bring Digital Earth down to Earth, Digital Earth and Sustainability, Digital Earth and Global Change, and Digital Earth in Action, have laid out a panoramic scenario for the future growth of Digital Earth;

That Digital Earth will be asked to bear increased responsibilities in the years to come, in the face of the problems of sustainable development;

Further Recognizing

That Digital Earth should play a strategic and sustainable role in addressing such challenges to human society as natural resource depletion, food and water insecurity, energy shortages, environmental degradation, natural disasters response, population explosion, and, in particular, global climate change;

That the purpose and mission of the World Information Summit of 2007, the Global Earth Observation System Conference of 2007, and the upcoming United Nations Climate Change Conference of 2009, and that Digital Earth is committed to continued close cooperation with other scientific disciplines;

Realizing

That Digital Earth is an integral part of other advanced technologies including: earth observation, geo-information systems, global positioning systems, communication networks, sensor webs, electromagnetic identifiers, virtual reality, grid computation, etc. It is seen as a global strategic contributor to scientific and technological developments, and will be a catalyst in finding solutions to international scientific and societal issues;

We Recommend

(a) That Digital Earth expand its role in accelerating information transfer from theoretical discussions to applications using the emerging spatial data infrastructures worldwide, in particular, in all fields related to global climate change, natural disaster prevention and response, new energy-source development, agricultural and food security, and urban planning and management;
(b) Further, that every effort be undertaken to increase the capacity for information resource-sharing and the transformation of raw data to practical information and applications, and developed and developing countries accelerate their programs to assist less-developed countries to enable them to close the digital gap and enable information sharing;

(c) Also, that in constructing the Digital Earth system, efforts must be made to take full advantage of next-generation technologies, including: earth observation, networking, database searching, navigation, and cloud computing to increase service to the public and decrease costs;
(d) Further, that the International Society for Digital Earth periodically take the lead in coordinating global scientific research, consultations and popular science promotion to promote the development of Digital Earth;
(e) Expanding cooperation and collaboration between the International Society for Digital Earth and the international community, in particular with inter-governmental organizations, and international non-governmental organizations;
(f) Extending cooperation and integration with Government Departments, the international Scientific and Educational community, businesses and companies engaged in the establishment of Digital Earth;

We Call for
Support from planners and decision-makers at all levels in developing plans, policies, regulations, standards and criteria related to Digital Earth, and appropriate investments in scientific research, technology development, education, and popular promotion of the benefits of Digital Earth.