Introduction to LiDAR Remote Sensing

Cheng Wang, Xuebo Yang, Xiaohuan Xi, Sheng Nie,
and Pinliang Dong

First published 2024

ISBN: 978-1-032-67150-5 (hbk)
ISBN: 978-1-032-67152-9 (pbk)
ISBN: 978-1-032-67151-2 (ebk)

Chapter 1

Introduction

DOI: 10.1201/9781032671512-1

高等教育出版社
HIGHER EDUCATION PRESS

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

1 Introduction

1.1 INTRODUCTION TO LiDAR

1.1.1 LiDAR

The word "laser" comes from "light amplification by stimulated emission of radiation." In 1916, Albert Einstein discovered that a single photon of light passing through a substance could stimulate the emission of further photons. Specifically, the electron in the atom absorbs energy and jumps from the low energy level to the high energy level. Then when it goes back from the high energy level to the low energy level, the energy is released in the form of photons.

When mentioning lasers, many people think of laser weapons, laser cutting, laser welding, laser surgery, etc. It seems that laser is a kind of light that is extremely lethal to the human body. In fact, lasers are categorized into Classes I to IV based on how safe they are for the user (Table 1.1).

The maximum permissible exposure (MPE) is used to determine the laser safety class, which is defined as the maximum level of exposure to the human eye or skin immediately or over a long period of time without damage occurring under normal circumstances. Note that the MPE value is not suitable for medical treatment of patients or for cosmetic purposes. The MPE value is related to many factors, such as the safety level of the laser used in the instrument, the laser wavelength, the output power, the pulse duration, the repetition frequency, and the time of exposure to the laser radiation.[1]

Light detection and ranging (LiDAR) is a product of a combination of laser technology and photoelectric detection technology. It uses a laser as a light source to transmit high-frequency laser pulses to the target and a photodetector as a device to receive the returned signal from the target. In terms of the working principle, LiDAR is similar to a traditional microwave radar. The difference is that the former uses laser (e.g., 532-nm or 1064-nm wavelengths) as the carrier to measure the distance and orientation and to identify the target through the position, radial velocity, target scattering, and other characteristics. LiDAR has a very large number of functions and a wide range of applications. If not specified, this book only deals with the range measurement function of the LiDAR system and its land applications.

1.1.2 Characteristics of LiDAR

1.1.2.1 Advantages

a. Active remote sensing. LiDAR systems actively emit high-frequency laser pulses to the object surface being measured and receive the laser signal back from the object surface.
b. Obtain three-dimensional (3D) spatial information of surface objects quickly and directly. This is the most important advantage that distinguishes LiDAR from other traditional remote sensing technologies.

DOI: 10.1201/9781032671512-1

TABLE 1.1
Laser Safety Classes

Laser Class	Safety	Power (mW)	Specificities
Class I	Safe	<0.4	Non-hazardous to human eyes; used for laser presentations, displays, mapping, collimation, leveling, etc.
Class II	Minor hazard	0.4–1	Causes dizziness if looked at directly; need to protect by blinking eyes; avoid observation with telescopic equipment; also used for laser displays.
Class III	a Hazard	1–5	Cannot look at directly into or shine in the human eye; avoid pedestrians when working.
	b Hazard	5–500	Dangerous to aim directly at someone's eyes.
Class IV	Severe hazard	>500	High-energy continuous laser; fire hazard; used for surgery, laser cutting, welding, and other mechanical processes.

c. Good directionality, high angular resolution, high distance resolution, and high velocity resolution. The direction of laser emission is usually limited to a solid angle with a few milliradians, which greatly improves the laser intensity in the emitted direction of illumination. It is also the important basis for laser collimation, guiding, and ranging.

d. Insensitive to electromagnetic interference and strong anti-interference ability. The laser propagates in a straight line. The beam is very narrow and well concealed. The divergence angle is small and the energy is concentrated, which ensure extremely high detection sensitivity and high resolution.

e. Good low-altitude detection performance. Microwave radar is susceptible to the echoes of various objects, and there is a dead zone when detecting at low altitude. In contrast, the laser signal is reflected only when the target is irradiated by LiDAR and is not affected by other objects.

f. Strong penetrability. High-frequency laser pulses can penetrate the small gaps in a vegetation canopy to reach the ground. Blue or green lasers can penetrate a certain depth of water to obtain underwater topography and water quality information, which plays a role in underwater topographic mapping and water quality monitoring in offshore and inland rivers and lakes.

1.1.2.2 Differences with Other Ranging Means

a. Comparison with close-up photogrammetry or aerial photogrammetry.

The form of acquired data is different. LiDAR directly obtains a 3D point cloud, while photogrammetry obtains images and photographs. The means of data acquisition is different. The LiDAR system uses the position and orientation system (POS) to directly calculate the 3D coordinates of the target, and the ground control and field work have less of a workload.

Photogrammetry needs to match the homonymous points. The data solving method, measurement accuracy, and requirements for the measurement environment are also different. The photogrammetry has high requirements for environmental light, temperature, etc., while the LiDAR is not sensitive to these factors.

b. Comparison with microwave radar.

Compared with microwave radar with similar functions, the LiDAR system is smaller and lighter. For example, many unmanned aerial vehicles (UAVs) carry light and small LiDAR systems less than 1 kg. In addition, the LiDAR system has high pulse frequency, long measurement distance, high measurement precision, good directionality, strong anti-interference ability, and a certain degree of covertness.

c. Comparison with total station.

Both LiDAR and a total station can achieve accurate measurement of irregular objects. However, the LiDAR uses non-contact measurement, without setting up reflective prisms, and can carry out the measurement of complex geometric objects and hazardous areas that are difficult for personnel to reach. LiDAR collects high-density, high-resolution data with high efficiency, while a total station measures the objects through the coordinate points connected in a line. When measuring irregular objects such as arcs, it is necessary for a total station to measure a large number of points through multiple operations, while the LiDAR can complete the measurement in only a single scan.

1.1.2.3 Disadvantages

LiDAR technology has obvious advantages, but also has limitations. First, the laser is affected by weather and atmosphere. For example, a laser pulse is sharply attenuated in bad weather such as heavy rain, thick smoke, and dense fog. Atmospheric turbulence may reduce the measurement accuracy of LiDAR. Second, the narrow beam of LiDAR makes it difficult to search for targets, which affects the target interception probability and the detection efficiency. Third, the discrete 3D point cloud acquired by LiDAR is slightly inferior to the traditional 2D remote sensing images for land cover classification.

1.1.3 Classification of LiDAR

After more than half a century of development, there are many types of LiDAR nowadays, which are usually categorized according to the mounting platform, detection mode, and use.

1.1.3.1 Classification by Mounting Platform

Three categories—space-based, air-based and ground-based LiDAR—are available. The space-based LiDAR is also referred to as spaceborne LiDAR, using satellites, space shuttles, or space stations as a platform (most are satellite platforms). The spaceborne LiDAR has a wide range of observations, which meets the large-scale applications. The air-based LiDAR is usually called airborne LiDAR, mainly using

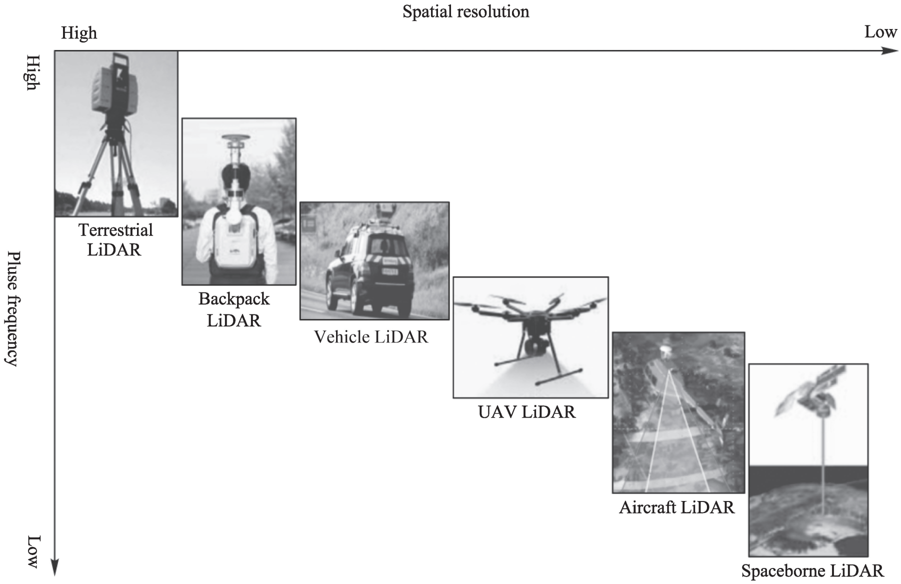

FIGURE 1.1 Characteristics of LiDAR systems with different platforms.

fixed-wing aircraft, helicopters, drones, and other aircraft as platforms, characterized by high efficiency and high point density and is especially suitable for 3D information acquisition of long-distance linear-shaped objects. The ground-based LiDAR mainly includes terrestrial (tripod fixed), shipborne, vehicle-mounted, backpack, and handheld laser scanners, characterized by comprehensive target information acquisition (including indoor space) and flexible access. With the continuous expansion of the visible range of the mounted platform (or the increased elevation of the mounted platform), the laser pulse sampling frequency transitions from high frequency to low frequency, the spatial resolution changes from high to low, and the observation range goes from small scale to regional scale, up to the global scale (Figure 1.1).

1.1.3.2 Classification by Ranging Mode

There are two categories: pulsed LiDAR and phased LiDAR. The former measures by using the round-trip propagation time difference between the transmitted and received laser pulses, characterized by simple and straightforward, long measurement distances. The latter uses the radio frequency to modulate the laser pulse amplitude and measures the phase delay produced in the round-trip process by which the modulated laser detects the target. Then the distance between the LiDAR and target is calculated by the modulated laser wavelength. The phased LiDAR is characterized by a short measurement distance and high pulse frequency.

1.1.3.3 Classification by Laser Medium

There are two categories: gas LiDAR and solid-state LiDAR. Gas LiDAR uses gas or vapor as a working substance to generate a laser, usually represented by a CO_2 laser.

It is characterized by good coherence, a narrow beam, small field of view, strong anti-interference ability, good atmospheric transmission performance, compatibility, and safety in use. The solid-state LiDAR is further divided into semiconductor LiDAR and diode-pumped solid-state LiDAR. The former considers a laser bar as the basic unit, with high output power, operating current, and loss of heat. The latter uses the YAG laser as a representative, which integrates the diode-pumped solid-state laser with high repetition frequency and high peak power and the high sensitivity avalanche diode detector. It is characterized by small size, light weight, and low price.

1.1.3.4 Classification by Use

Uses include ranging LiDAR, fire control LiDAR, shooting range LiDAR, tracking and identification LiDAR, poison detection LiDAR, multifunctional tactical LiDAR, meteorological LiDAR, and navigation LiDAR, among others. The LiDAR in this book refers to ranging LiDAR if not otherwise specified.

1.1.3.5 Classification by Footprint Size

There are categories: large-footprint LiDAR and small-footprint LiDAR. Large-footprint LiDAR usually refers to LiDAR with a ground footprint diameter of more than 10 m, such as the NASA's spaceborne LiDAR—GLAS (Geoscience Laser Altimeter System) with a 70-m footprint diameter and China's Gaofen-7 satellite laser altimeter with a 17-m footprint diameter. Generally, the large-footprint LiDAR has a low footprint density and cannot image the target. However, it can get the data on a regional or global scale, which shows a significant advantage in large-scale geoscientific applications. Small-footprint LiDAR has a footprint diameter of centimeters or even millimeters. The system transmits pulses at a high frequency (currently up to 2000 kHz), resulting in high point density and high data accuracy.

1.1.3.6 Classification by Detection and Recording Method

There are three categories: discrete return LiDAR, full-waveform LiDAR, and photon counting LiDAR. Discrete return LiDAR is the most common and most widely used commercially. For example, building 3D reconstruction for digital cities, high-precision map production for autonomous driving, and cultural heritage digitization 3D reconstruction are all based on point cloud data acquired by discrete return LiDAR systems. Full-waveform LiDAR samples the returned signal continuously, records more detailed information, and acquires the entire object's vertical profile. Photon counting LiDAR is different from the first two. It uses a micro-pulse laser with high repetition frequency and highly sensitive single-photon detectors to record the returned signals (at a single-digit photon level) as the photon points. It has the advantage of being able to detect space targets at long distances with lower laser energy.

1.1.3.7 Classification by Detection Objects

This is categorized into atmospheric LiDAR, oceanic LiDAR, and land LiDAR. The emitted laser pulses of atmospheric LiDAR interact with the aerosols in the atmosphere and various components. Then the backward scattering signals are received by the detector and then processed and analyzed, to provide the information of atmospheric physical elements. The main applications of atmospheric LiDAR include clouds, aerosols and boundary layer detection, detection of atmospheric composition, temperature detection, and so on. The working principle of oceanic LiDAR is that the emitted laser beam penetrates the seawater and produces various scattering and fluorescence, and the received signals are used to retrieve the sound speed; temperature; salinity distribution parameters; and oil, gas, and hydrocarbon indicators of the marine boundary layer. The laser pulse of the land LiDAR detects surface objects such as trees, roads, bridges, and buildings. Sometimes, a portion of the laser is reflected and recorded by the LiDAR receiver, which then calculates the distance from the LiDAR to the object and provides accurate 3D coordinates of the detected object by combining the attitude and position information. If not specifically indicated, this book deals with land LiDAR; atmospheric LiDAR and oceanic LiDAR are not discussed.

1.1.4 Development History of LiDAR

In the 1960s, American scientist Theodore Harold (Ted) Maiman[2] first introduced laser into the practical field and built the world's first laser equipment. In 1989, the University of Stuttgart, Germany, developed the world's first airborne LiDAR prototype. Since the 21st century, LiDAR has entered a period of booming development. Particularly after 2015, LiDAR development efforts have boomed over the world, and various mature commercialized LiDAR products have been introduced. This section summarizes the development of LiDAR in three stages: emergence, development, and explosion.

1.1.4.1 Emergence Period (1960–1990)

The origin of the laser is traced back to 1916. When Albert Einstein first proposed the concept, he theoretically predicted the possibility of laser generation. In 1960, the world's first laser was introduced, followed by the emergence of various types of lasers, such as semiconductor lasers, helium-neon gas lasers, and CO_2 lasers. Their application fields are increasingly wide-ranging, including laser printing, phototypesetting, display, distance measurement, barcode scanning, industrial detection, fiber optic communications, etc. Lasers are known as one of the major scientific and technological discoveries in the 20th century.

After the emergence of laser, scientists applied it to target ranging, bathymetry, tracking, etc. In 1964, the U.S. National Aeronautics and Space Administration (NASA) launched the "Explorer-22" satellite, which first achieved laser ranging by using the carrier's corner reflector. In 1968, Syracuse University in the United States constructed the world's first laser bathymetric measurement system to achieve ocean near-shore bathymetry. In 1969, *Apollo* researchers in the United States used the laser reflector placed on the Moon to accurately measure the distance between the Earth and the Moon. In 1975, Riegl started to produce solid-state diode lasers and laser rangefinders. In the 1980s, the global positioning system (GPS), chronometers, and high-precision inertial measurement units (IMUs) came out successively, which made it possible to obtain precise, real-time positioning and orientation in the process of laser measurement and directly promoted the emergence of the LiDAR system. In 1989, Professor Ackermann[3] of the University of Stuttgart, Germany, developed the prototype of the LiDAR system. This was the world's first airborne laser scanner that combines laser scanning technology with real-time positioning and orientation technology, which is a milestone in the development of LiDAR.

1.1.4.2 Development Period (1990–2000)

Since the 1990s, LiDAR system development has entered a period of rapid development. In 1993, TopScan in Germany and Optech in Canada launched the first commercial airborne LiDAR: ALTM1020 (Airborne Laser Topographic/Terrain Mapping) system, marking the official entrance of the LiDAR system to the commercial stage. Azimuth in the United States began the development of a LiDAR system in 1997. Leica acquired Azimuth in 2001 and launched the ALS40, ALS50, and ALS60 systems (Airborne Laser System). In 1995, Saab in Sweden developed a bathymetric LiDAR system: HAWK Eye. In 1996, Riegl in Austria launched a series of laser scanners that were used on board aircraft, vehicles, and ships.

China started LiDAR-related research in the same period. Professor Li Shukai's team in the Institute of Remote Sensing Applications of the Chinese Academy of Sciences developed the principal prototype of an airborne 3D LiDAR imaging system. After that, China's Zhejiang University, Harbin Institute of Technology, Shanghai Institute of Optics and Fine Mechanics of the Chinese Academy of Sciences, Shanghai Institute of Technical Physics of the Chinese Academy of Sciences, and other institutions all carried out LiDAR system developments.

1.1.4.3 Explosion Period (2000–2020)

Upon entering the 21st century, the global demand for LiDAR technology in various application fields is growing rapidly at a rate of 30% per year. The international LiDAR markets show a blossoming state.

Leica entered the LiDAR field in 2001. It renamed the AeroSensor as ALS40 and produced the ALS50 in 2003, which was upgraded to ALS50-II two years later. In October 2006, the company introduced a new laser transmitter/receiver technology, multiple pulses in air (MPiA), which greatly improved the laser point cloud density and was applied to the ALS70 and ALS80 systems. In 2005, the Blom company introduced the HAWK Eye II airborne LiDAR bathymetry system, which employed two lasers: a 532-nm laser (with a receiver frequency of 4 kHz) for underwater detection and a 1064-nm laser (with a receiver frequency of 6.4 kHz) for shoreline surveys. The German IGI company developed the LiteMapper 2800 and LiteMapper 5600 systems. Starting from 1996, Riegl successively launched a series of laser scanners that can be used for airborne, vehicle-mounted, and ship-mounted measurements, such as the LMS-Q140, LMS-Q560, and a series of terrestrial 3D laser scanning systems, such as VZ400, VZ1000, and ultra-long-range VZ4000 and VZ6000, as well as the dual-channel, dual-band airborne LiDAR system VQ-1560i.

With the popularization of UAVs, airborne LiDAR systems have developed toward lightweight and small-sized configurations. The UAV LiDAR systems that are small, lightweight, and inexpensive have risen rapidly. In 2014, Riegl in Austria released the

VUX-1 scanner, which is the world's first lightweight and small-sized UAV LiDAR, weighing just 3.6 kg. In 2014, Hokuyo in Japan launched the UXM-30LXH-EWA system, weighing 0.8 kg, followed by UST-10LX/20LX, UXM-30LAH-EWA, UST-05LA, etc., most of which are less than 1 kg.

China's commercialized LiDAR systems are rising rapidly and catching up with international standards. Under the support of the Special Program for the Development of Major Scientific Instruments and Equipment of Ministry of Science and Technology of the People's Republic of China, the Shanghai Institute of Optics and Fine Mechanics of the Chinese Academy of Sciences has developed an airborne dual-frequency LiDAR system (He et al., 2018). The Institute of Microelectronics of the Chinese Academy of Sciences has successively developed airborne, vehicle-borne, and ground-based LiDAR systems as well as a mid- and long-range airborne LiDAR: Mars-LiDAR (Li et al., 2013). Several of China's enterprises have achieved remarkable results in the industrialization of LiDAR. Since 2005, Beijing Beike Tianhui Technology Co., Ltd. has launched airborne (A-Polit), vehicle-mounted (R-Angle), and point-station (U-Arm) LiDAR, as well as lightweight and small-scale LiDAR systems: Clouds series and Genius series. Since 2012, Wuhan Haida Digital Cloud Technology Co., Ltd. has launched the self-developed terrestrial laser scanner HS, vehicle-mounted mobile measurement system HISCAN, airborne laser measurement system ARS, and "Zhihui" series of airborne products. Aolunda Technology Co., Ltd. in Chengdu, China, launched the CBI series of LiDAR measurement systems, as well as lightweight CBI-120P and CBI-200P series products in 2019. The Shenzhen DJI Company released the DJI L1 system in October 2020, which integrated the Livox LiDAR and others. For more commercialized LiDAR systems, see Section 1.2.2.

At the beginning of the 21st century, countries around the world aimed at the development and application of spaceborne LiDAR. In general, most of spaceborne LiDAR systems are still led by the national space sectors and have not yet been commercialized. NASA launched the world's first spaceborne laser altimeter ICESat-1 (Ice, Cloud and Land Elevation Satellite)/GLAS (Geoscience Laser Altimeter System) in 2003, the first spaceborne photon-counting LiDAR ICESat-2/ATLAS (Advanced Topographic Laser Altimeter System) in 2018, and GEDI (Global Ecosystem Dynamics Investigation) on board the International Space Station (ISS) in 2018. These spaceborne LiDAR systems provide a reliable data source for research on the production of global control points, changes in polar ice caps, and monitoring of lake levels, as well as the estimation of global forest heights, biomass, and carbon stocks. Some satellite missions of China also carried LiDAR systems. The laser altimeter developed by the Shanghai Institute of Technical Physics and the Shanghai Institute of Optics and Fine Mechanics was carried on Chang'e-1 and Chang'e-2, effectively acquiring the elevation data of the north and south poles of the Moon. The Chang'e-4 carried a laser 3D imager and a laser ranging sensor, which were instrumental in the soft landing on the back of the Moon, providing not only high-precision terrain information but also achieving autonomous obstacle avoidance. The main payloads of China's Gaofen-7 satellite and carbon monitoring satellite for terrestrial ecosystems also include laser altimetry. Other spaceborne LiDAR programs are being planned or deployed around the world.

1.2 LiDAR SYSTEM

1.2.1 LiDAR System Composition

The composition of a LiDAR system with various platforms is slightly different, but their cores are inseparable from the laser scanning system. Figure 1.2 shows the typical spaceborne, airborne, and terrestrial LiDAR and their system composition.

This section introduces the basic components of an airborne LiDAR system as an example (Figure 1.3): the laser scanner, the global navigation satellite system (GNSS), the inertial navigation system (INS), and the monitoring and control system.

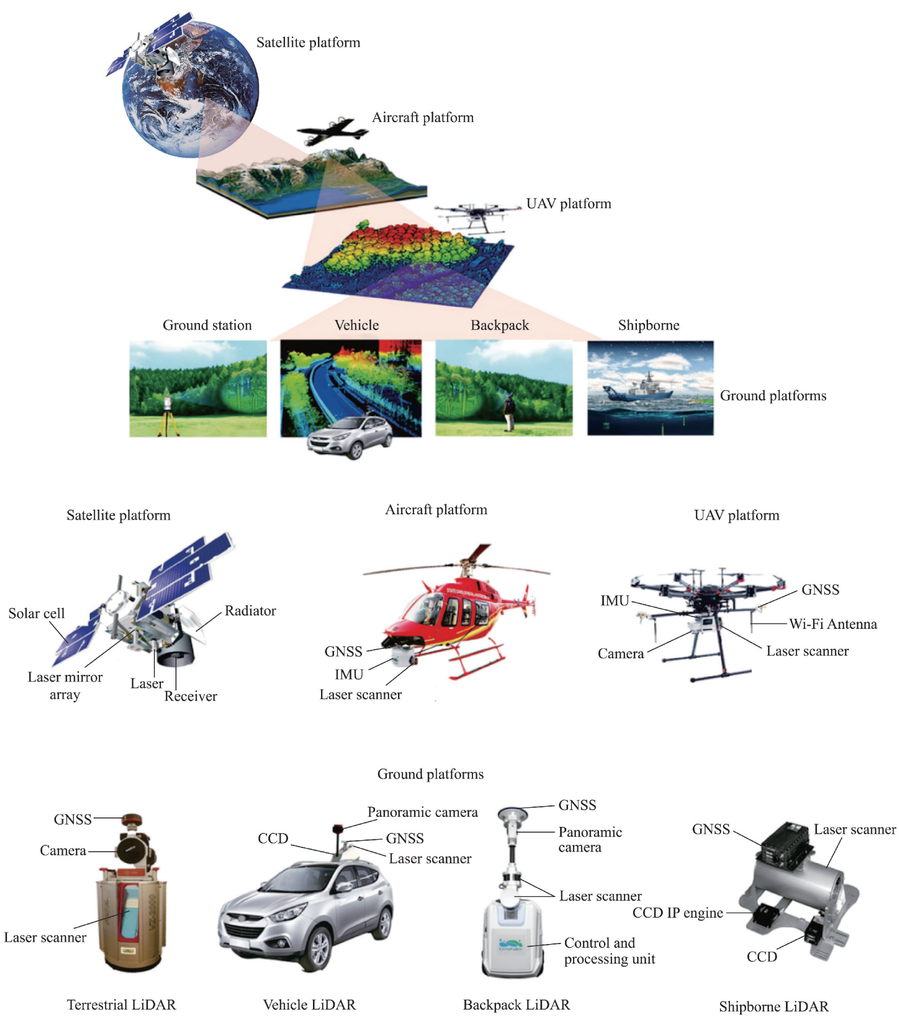

FIGURE 1.2 LiDAR system composition for different platforms.

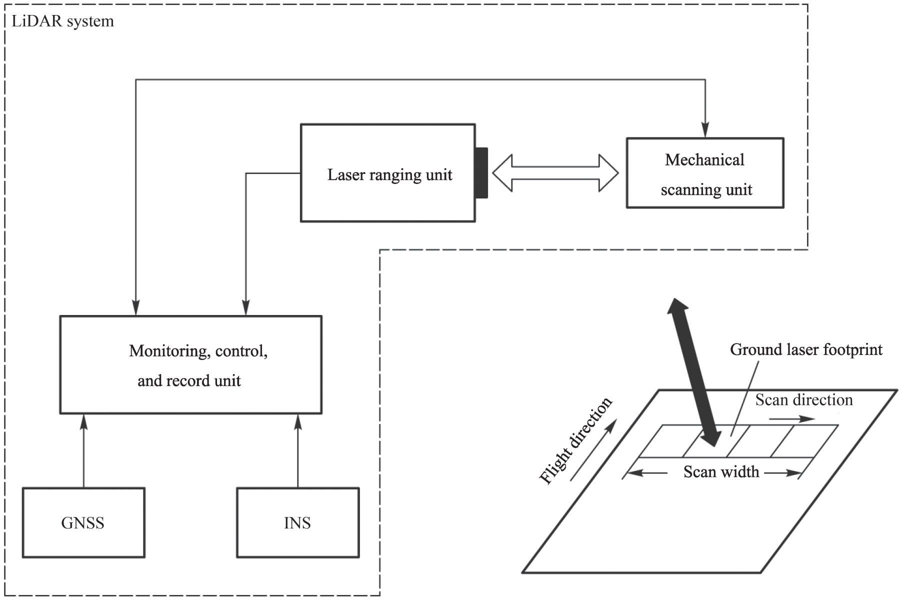

FIGURE 1.3 Airborne laser scanning system composition.

1.2.1.1 Laser Scanning System

The laser scanning system includes a laser ranging unit and a mechanical scanning device. The laser ranging unit consists of a laser transmitter and receiver, which are used for transmitting and receiving laser signals and determining the distance from the target to the LiDAR, the number of returns, and the laser return intensity. The transmitted and received laser beams share the same optical aperture to ensure that the transmitted and received optical paths are the same. The laser beam is usually very narrow with a very small divergence angle. The range of irradiation to the ground is the laser footprint. When the laser is reflected by the ground object, part of the signal returns to the receiver and is recorded by the recording unit. The mechanical scanning device launches out the laser beam from different directions by mechanical rapid rotation. The scanning modes mainly include swing mirror scanning, rotating prism scanning, elliptical scanning, fiber scanning, etc. For details, see Section 2.3.2.

1.2.1.2 Global Navigation Satellite System

The GNSS is a space-based radio navigation and positioning system that provides users at any location on the Earth's surface or in near-Earth space with all-day 3D space coordinates and time. The GNSS usually consists of one or more constellations of satellites and their augmentation systems required to support particular functions. The major GNSS systems around the world include China's Beidou, the United States' GPS, Russia's GLONASS (Global Navigation Satellite System), and the European Galileo system. The main roles of GNSS in LiDAR systems are threefold: first, to achieve time synchronization with the IMU and the laser; second, to combine with the IMU data for navigation and resolving trajectories to improve position and orientation accuracy; and third, to provide navigation data to the flight platform.

1.2.1.3 Inertial Navigation System

The INS consists of the IMU and the navigation processor. IMU is a general term for inertial units such as gyroscopes and accelerometers used to measure attitude. It usually consists of three accelerometers and three gyroscopes, digital circuits, central processing unit (CPU), and so on. Its role is to measure the attitude information of the scanner at the moment of laser emission, including pitch angle, roll angle, and heading angle. The INS and GNSS constitute the POS, providing position and attitude information, the accuracy of which directly determines the accuracy of the point cloud data acquired by the LiDAR system.

1.2.1.4 Monitoring and Control System

The monitoring and control system controls the working condition of the laser scanner, GNSS, and IMU. Its core is designed to keep the coordinated and synchronized work of the LiDAR system and store the acquired data. The acquired data includes (1) distance and intensity data, (2) position and attitude data from the GNSS system and INS system, and (3) auxiliary data.

1.2.2 Major Commercial LiDAR Systems

The spaceborne LiDAR systems usually have a high development cost and maintenance cost. Coupled with their limitations of applications (most for scientific research), the spaceborne LiDAR systems have not been commercialized. Hence, this section introduces commercial airborne and terrestrial LiDAR systems.

Tables 1.2–1.5 list some commercial airborne and terrestrial LiDAR systems. It is seen that, with more than a decade of development, the main performance parameters of the devices have been greatly improved, and most of the systems are lightweight, small, and easy to use.

1.2.3 Data Format and Processing Software

1.2.3.1 Data Format

As mentioned before, there are many types of LiDAR and various data forms, such as full waveform data, photon counting data, and discrete point cloud data, among which discrete point cloud data are the most widely used. This subsection focuses on several common discrete point cloud data formats, such as formats specifically designed for storing point cloud data (LAS/LAZ, PTS/PTX, PCD, etc.) and file

TABLE 1.2
Some Airborne LiDAR Systems

Manufacturer	**Optech**	**IGI**	**Leica Geosystems**	**Riegl**	**TopoSYS**	**TopEye**	**Fugro**	**Velodyne**
Systems	ALTM Gemini/3100	LiteMapper/5600	ALS70	LMSQ1560	Harrier 56/24, Falcom III	TopEye Mk II	FLI-MAP 400	Puck LITE
Laser wavelength (nm)	1060	1550	1064	1550	1550	1064	1500	903
Pulse frequency (kHz)	167	40–200	500	800	25–200	1–50	250	300
Maximum scanning angle (°)	50	60	75	60	60	+/– 20, +/– 14 BWD/FWD	60	30
Measuring range (m)	200–4000	30–1800	200–5000	50–5600	30–1000	60–750	50–400	10–500
POS post-processing software	POS PAC	AEROoffice	GrafNav/IPAS Pro	AEROoffice/ POS PAC	Applani× Pos /Pac	POS GPS TopEye PP	GrafNav/IPAS Pro	POS PAC
Post-processing software	DASHMap	AEROoffice, GeocodeWF, TerraScan, TerraModeler	Leica ALS Post Processor, TerraScan/ TerraModeler	RiPROCESS560	TopPIT	TopEye PP&TASQ	FLIP7	Vella

TABLE 1.3
Some Airborne LiDAR Systems Developed in China

Manufacturer	**Beike Tianhui**	**Haida Digital Cloud**	**Shenzhen DJI**	**Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences**	**Shenzhen University**	**Alundar**
Systems	ALTM Gemini/3100	Zhihui PM-1500	DJI L1	Dual-Band Mapper 5000	Full waveform bathymetry	CBI-200P
Laser wavelength (nm)	1060	1550	905	Land mode: 1550 Ocean mode: 532/1064	532	905
Pulse frequency (kHz)	167	40–200	240	Land mode: 100–400 Ocean mode: 5	10–100	1280
Maximum scanning angle (°)	50	60	95	Land mode: 30 Ocean mode: 15	20	360
Measuring range (m)	200–4000	30–1800	100	Land mode: 300–1600 Ocean mode: 300–1100	200–5000	200
POS post-processing software	POSPac trajectory data processing software	Zhihui airborne LiDAR post-processing software	DJI POS post-processing module	/	/	ALiDAR data processing software

TABLE 1.4
Some Terrestrial 3D Laser Scanner Systems

Manufacturer	**Leica**	**Riegl**	**Optech**	**Faro**	**Z + F**	**Topcon**	**Trimble**
Country	Switzerland	Austria	Canada	United States of Ameria	Germany	Japan	United States of Ameria
Product	ScanStation P30/P40	VZ-1000	ILRIS-3D	Focus S350	Imager 5010	GLS-2000	Trimble TX8
Scan type	Pulsed	Pulsed	Pulsed	Phased	Phased	Pulsed	Pulsed
Maximum pulse frequency (kHz)	1000	300	3.5	976	1016.7	120	1000
Wavelength (nm)	1550	1550	1535	1550	1350	1064	1500
Maximum measuring range (m)	270	1400	1700	0.6–350	0.3–187	350	120
Field of view (horizontal ×vertical) (°)	360 × 270	360 × 100	360 × 110	360 × 300	360 × 320	360 × 270	360 × 317
Ranging accuracy (mm)	1.2 (+10 ppm)	5 @100 m	7 @100 m	1 @25 m	1 @50 m	3.5 @150 m	2 @100 m
Digital camera	Internally	Externally	Internally	Internally	Externally	Internally	Internally
Operating temperature (°C)	–20–50	0–40	0–40	5–40	–10–45	0–40	0–40
Scanning control and data processing Software	Cyclone, Cloudworks	RiScan Pro	ILRIS-3D Polyworks	SCENE, Geomagic, Rhinoceros	Laser Control, Light Form Modeller	ScanMaster	Rrimble FX Controller, 3Dipsos RealWorks

TABLE 1.5
Some Terrestrial 3D Laser Scanner Systems Developed in China

Manufacturer	Haida Digital Cloud	Beike Tianhui	Stonex	Zhongke Tianwei	Hualang 3D	Xunneng Optoelectronic
Product	HS1200	U-Arm1500	X300 Plus	TW-A1000	HL1000	SC500
Scan type	Pulsed	Pulsed	Pulsed	Pulsed	Pulsed	Pulsed
Maximum pulse frequency (kHz)	500	300	40	500	36	36
Wavelength (nm)	1545	1550	915	1064	905	905
Laser safe class	Level 1	Level 1	Level 1	Level 1	Level 1	Level 1
Maximum measuring range (m)	1200	1500	300 @ 80% reflectance	1000	200 @ 90% reflectance	3000 @ 90% reflectance
Field of view (horizontal × vertical) (°)	360 × 100	360 × 300	360 × 180	360 × 300	360 × 100	360 × 300
Ranging accuracy (mm)	5 @100 m	5–8 @100 m	4 @50 m	7 @100 m	1.2 @50 m	1.2 @50 m
Digital camera	Externally	Externally	Internally	Externally	Externally	Internally
Operating temperature (°C)	−20 to 65	−20 to 55	−10 to 50	0–50	0–40	0–40
Scanning control and data processing software	HD 3LS Scene	UIUA, JRC 3D Reconstructor	Si-Scan	/	/	3D Cloud Processor

formats with the capability to represent and store point cloud data, such as model files in the field of computer graphics (e.g., PLY, OFF).

1. LAS/LAZ file format. Laser file format (LAS) is a file format specially designed for 3D point cloud data, managed and maintained by the American Society for Photogrammetry and Remote Sensing (ASPRS). The LAZ file format is a lossless compressed version of LAS. The LAS file format adopts binary storage, which saves the 3D coordinates and intensity of laser points, returns, red-green-blue (RGB), scanning angle, and other information. The LAS is the most widely used point cloud data format.

   In the latest version of LAS 1.4 released by the ASPRS in 2019, the LAS file consists of a public file header area, a variable length record (VLR) area, a point data record area, and an optional extended VLR area. The public file header area contains some records describing the overall situation of the data, such as the number of point records and coordinate boundaries. The VLR area is used to store some variable length data, such as projection information, metadata, waveform packet, and user application data.

   Point data records the 3D coordinates and attribute information of each laser point. The LAS 1.4 file format supports Point Data Record Formats (PDRFs) 0–10, for a total of 11 point types, of which PDRFs 6–10 are the recommended point types for use by the ASPRS, and PDRFs 0–5 are used mainly for compatibility with older versions. Each LAS file records only one type of point, identified by the "Point Data Format" field in the public file header area.

   The point coordinates in the LAS file are stored in long integer type (4 bytes), which saves half of the space compared with the double precision floating point type (8 bytes). When the file is read or written, the scaling factor (X_{scale}, Y_{scale}, Z_{scale}) and offset (X_{offset}, Y_{offset}, Z_{offset}) in the public file header are used to convert the long integer values (X_{record}, Y_{record}, Z_{record}) in the point data record area to derive the real coordinate information ($X_{\text{coordinate}}$, $Y_{\text{coordinate}}$, $Z_{\text{coordinate}}$), which is expressed by Equation (1.1).

$$\begin{cases} X_{\text{coordinate}} = X_{\text{record}} \cdot X_{\text{scale}} + X_{\text{offset}} \\ Y_{\text{coordinate}} = Y_{\text{record}} \cdot Y_{\text{scale}} + Y_{\text{offset}} \\ Z_{\text{coordinate}} = Z_{\text{record}} \cdot Z_{\text{scale}} + Z_{\text{offset}} \end{cases} \tag{1.1}$$

   The waveform packets in the LAS file can be stored as extended variable length records (EVLRs) at the end of all point data records to facilitate separation or materialization. The EVLRs are stored in an unsigned, extra-long-integer (8-byte) format that allows more information to be stored than VLRs.

   The LAZ format uses the chunked compression method to reduce the file size. However, the compression reduces file reading and writing efficiency. Hence, the LAZ format is mainly used for situations with a high requirement for storage space and low requirement for read-write efficiency.

2. PCD format. PCD (Point Cloud Data) is the file format of PCL (Point Cloud Library), an open-source programming library for point cloud processing. PCD has two formats: text and binary. It can be used to store and process ordered/disordered point cloud datasets and support *n*-dimensional point type extensions. Compared with other point cloud file formats, PCD can adapt PCL to the greatest extent possible and maximize the performance of PCL applications.

   The PCD format consists of a file header and point data. The file header is saved in ASCII code, which declares and stores information such as the number, attributes, and type of point cloud data. The point data record the coordinates and attributes of the points. Each dimension and attribute of points can be obtained from the "FIELDS" in the file header.
3. PTS/PTX format. PTX and PTS are file formats used by Leica scanners and supporting software, both of which are stored in text format. The PTX file format employs the concept of individual scanning. Each file records one or more groups of point clouds. Generally, each scanning site corresponds to one group of point clouds, and each group of point clouds provides separate header information, including the number of rows and columns, the scanner position, the scanner spindle and the transformation matrix, etc. Based on the header information and stored point coordinates, the users can not only calculate the coordinates of the laser points in the unified coordinate system but also possibly recover the scan line information of each laser point. The PTS file format does not store the original scanning site information and is simpler than the PTX format. Its first line contains the number of point clouds, and subsequent lines contain information of each laser point, including coordinates, intensity, RGB values, etc.
4. Model file format. Model files are generally well standardized and generalized, supported by many software or open-source libraries, and partly applied to the saving of point cloud files, commonly including PLY, OFF, etc. The PLY (Polygon File Format) is a file format used in the field of computer graphics to save a collection of graphical objects with text or binary storage. A typical PLY file consists of a list of *XYZ* coordinate triples of vertices and elements described by vertex list indices. The file includes a file header, a vertex list, a face list, and a list of other elements. The OFF (Object File Format) is a file format that uses polygons to represent the geometry of a model and is stored in text format as well. The OFF file consists of a file header, a vertex list, and a polygon list. Each polygon has any number of vertices, and the number of vertices, facets, and edges is recorded in the header. Compared with the formats specially designed for point clouds such as LAS and PCD, the model file format records the topological relationship between vertices in addition to the coordinates, as well as some other attribute information. For example, the PLY file format can also record the RGB values, normal vectors, and so on.
5. Text format. In addition to the previously mentioned file formats with clear standards, text files are often used to save point cloud data by virtue of their wide compatibility. The commonly used file suffixes include xyz.,

asc., neu., txt., csv., and others. These non-standardized files are more flexible. They use ASCII code to store point cloud data by line. However, when reading them, it is generally necessary to know the file recording rules in advance; otherwise, they cannot be parsed correctly.

1.2.3.2 LiDAR Data Processing Software

In recent years, a variety of advanced LiDAR systems have been emerging, and data acquisition has become more and more convenient. The increasing demand for LiDAR applications has posed a great challenge in terms of the efficient processing of massive point cloud data. There are many software packages for LiDAR data processing, such as TerraSolid and open-source CloudCompare. In addition, some commercial software packages, such as ENVI, ERDAS, ArcGIS, and ArcGIS Pro, have LiDAR data processing and analysis functionality. Also, many research institutes, enterprises, and universities have successively developed LiDAR data processing software with independent property rights, such as Point Cloud Magic and LiDAR360. Table 1.6 lists several popular LiDAR data processing software programs and their functions.

1. TerraSolid. The TerraSolid software is developed by the University of Helsinki, Finland. It is the first commercialized airborne LiDAR data processing software in the world, which is developed based on Bently's Microstation CAD software and covers most of the functions of point cloud data processing. It includes Terra Scan, Terra Modeler, Terra Photo, Terra Match, and other modules. The Terra Scan is used for processing point cloud data; the Terra Modeler is used for building surface models; the Terra Photo is used for producing orthophotos; the Terra Match is used for point cloud aerial strip splicing.

   TerraSolid supports reading multiple point cloud formats, images, digital elevation model (DEM) data, and vector data (dgn, dwg) and supports the display of point cloud and image data, route management, point cloud amplitude and batch processing, profile interaction, contour production, DEM production, terrain analysis, calibration, and coordinate conversion. The integrated point cloud filter algorithm uses the progressive triangulated irregular network (TIN) filtering. Professional applications include power line extraction, forestry analysis, and hydrological analysis. The disadvantage of TerraSolid is that it is based on the secondary development of MicroStation, and users have to install MicroStation before using TerraSolid. Otherwise, some of the software's functions and application extensions are limited, e.g., visualization and human-computer interaction.
2. CloudCompare. The CloudCompare is developed using the C++ programming language and can be compiled on Windows, Linux, and Mac operating systems. It is a 3D point cloud (and triangle mesh) processing software, originally designed to compare two dense 3D point clouds (e.g., those acquired by laser scanner) or to compare point clouds with triangle meshes. The software relies on a specific octree structure and has high computational performance. For example, a dual-core processor laptop can compute

TABLE 1.6
Major LiDAR Data Processing Softwares and Their Functions

Software	3D Display	Classification	Interactive Editing	Batch Processing	Topographic Application	Forest Application	Powerline Application	Building Application
ArcGIS	√	√	√	×	√	×	×	×
CloudCompare	√	×	√	×	×	×	×	×
ENVI LiDAR	√	√	√	×	×	×	√	×
FUSION	×	×	×	×	×	√	×	×
Global Mapper LiDAR Module	√	√	√	×	×	×	×	×
Quick Terrain Modeler	√	×	×	×	×	×	×	×
LiDAR360	√	√	√	√	√	√	√	×
LP360	√	√	√	√	√	×	×	×
PCC (Point Cloud Catalyst)	√	√	√	×	√	√	√	×
PCM (Point Cloud Magic)	√	√	√	√	√	√	√	√
RiALITY	√	×	×	×	×	×	×	×
TerraSolid	√	√	√	√	√	×	×	×
ALiDAR	√	√	√	√	√	×	√	×

3 million points to 14,000 triangle meshes in about 10 s. Subsequently, the software was expanded into a general-purpose point cloud processing software including many advanced algorithms (alignment, resampling, color/normal vectors/scales, statistical computation, sensor management, interactive or automatic segmentation, display enhancement, etc.). Also, some functions, such as normal vector optimization, Poisson mesh construction, and point cloud filtering, can be easily used.

3. ENVI LiDAR. The predecessor of ENVI LiDAR is Environment for 3D Exploitation (E3De) developed by the EXELIS VIS company (original manufacturer of ENVI/IDL). ENVI LiDAR allows users to write a program to implement a specified function by creating an Interactive Data Language (IDL) project file according to the users' needs. This indicates its excellent secondary development capabilities. As highly integrated software, ENVI LiDAR is easy to operate and has low requirements for users. It supports LAS, NITF LAS, ASCII, and LAZ file formats, among others. It has functions for interactive cross-section visualization, visual domain analysis, 3D visualization flight browsing and editing, point cloud feature extraction and classification, and some professional applications of forest resources survey, urban expansion mapping, terrain visualization, and power line survey decision-making.
4. Point Cloud Magic (PCM). PCM is LiDAR data processing and application software developed by the Institute of Aerospace Information Research Institute, Chinese Academy of Sciences. It was first released in October 2015, and version 2.0 was released in November 2020. It has a flat theme style and data management platform. The software functions include point cloud basic tools, point cloud filtering, land classification, mine mapping, forest application, building 3D models, 3D modeling of cultural heritage sites, safety analysis of power lines, 3D reconstruction of transmission corridors, crop monitoring, etc. It also provides customizable workflow settings to further enhance the user experience. Its basic functions include (1) basic platform: support opening point cloud data, model data, image data, and vector data and support rendering point cloud data by elevation, category, RGB, intensity, GPS time, etc.; support profile operation, single-point and multipoint selection, distance measurement; support interactive operations such as point cloud data cropping and attribute change; (2) basic tools: support basic operations such as partitioning, merging, cropping, filtering, format conversion, attribute statistics of point cloud data; (3) machine learning classification: three classifiers with customizable parameters, i.e., random forest, neural network, and Light Gradient Boosting Machine (LightGBM); and (4) other functions: provide up to 20 interface styles to meet the user's visual experience and support the setup of operations according to the user's personal operating habits.
5. LiDAR360. LiDAR360 is a LiDAR point cloud data processing and analysis software independently developed by Beijing Digital Green Earth Technology Co., Ltd. It supports the visualization, classification, analysis, extraction, editing, modeling, and multivariate data exporting of massive

point clouds. It supports multiple data formats of point cloud, images, DEM data, vector data (shp/dxf), and other customized data formats (LiData, LiModel). It can automatically match aerial strips with different flight paths to generate a highly precise point cloud. It provides automatic or semi-automatic classification and quickly classifies ground, vegetation, buildings, and powerlines. It supports the interactive editing of point clouds through the profiling tool. Its terrain application module includes generation of a high-precision digital terrain model; interactive editing of DEM; generation of maps of slope, aspect, contour lines, and surface roughness; and generation of orthophoto models. Its powerline application module includes classification, fitting of power lines, and monitoring of hazardous points. It also supports 3D reconstruction of buildings and forest statistical variable extraction.

1.3 LiDAR REMOTE SENSING APPLICATIONS

LiDAR technology was mainly used in the military field in the early stage, and then it was popularized in the civil field. Its application scope not only includes the land and ocean on the Earth but also covers the atmosphere and the surface of the Moon, Mercury, and Mars. This book focuses on LiDAR land applications, including most of the land features and many aspects of the national economy and social development. The following briefly describes several representative applications. More detailed introductions are provided in Chapter 5.

1.3.1 Topographic Mapping

The major advantage of LiDAR is its ability to directly obtain high-precision 3D spatial information. For example, spaceborne LiDAR can carry out sub-meter-level elevation measurements on a global scale, which provides support for the production of global high-precision control points. The high-density and high-precision point cloud acquired by airborne LiDAR can be classified into the ground point cloud by filtering. Then DEM, digital line graphic (DLG), and contour lines are generated by constructing a TIN from ground point clouds. These topographic products provide the surveying and mapping data for many applications.

1.3.2 Forest Resource Investigation

High-frequency laser pulses can penetrate forest canopy gaps to reach the ground, which acquire data not only on the fine canopy vertical structure but also the understory topography. The LiDAR signal can be used to accurately retrieve forest structural parameters, such as tree height, biomass, crown size, and Leaf Area Index (LAI). LiDAR overcomes the problem of vegetation index saturation of optical imagery in forest LAI inversion and significantly improves the accuracy of forest LAI inversion. In addition, terrestrial LiDAR can acquire the diameter at breast height (DBH) and height under branches of trees, which provides efficient and accurate data support for forest resource investigation.

1.3.3 Digital Cities

Building 3D models is an important part of digital city construction; especially in a real 3D world, the demand for 3D spatial information is unprecedented. Airborne and terrestrial LiDAR systems can perform multiangle and all-around rapid scanning of urban buildings and the surrounding environment. The acquired 3D point cloud data of buildings can be reconstructed to provide high-precision and measurable true 3D digital models required in digital city construction through data processing and 3D modeling. In addition, these 3D models can be published on the Internet, achieving real-time and interactive presentation of the urban scene, as well as an immersive user experience.

1.3.4 Digital Power Grid

The application of LiDAR in the digital power grid covers the whole process of power grid construction, such as power line design and planning, 3D digitization of the power infrastructure, hazard detection, and early warning analysis. For the power line design, 3D point cloud data can intuitively show the topography and surface coverage of the entire power transmission area, providing a scientific basis for power line selection and design, survey and positioning, 3D simulation, and construction volume estimation. For the power line safety inspection, LiDAR can accurately detect the 3D position of power lines and power towers; intuitively display the 3D spatial position relationship between the power lines and the other objects in the power transmission channel; and help analyze the safety distance between the power lines and the ground, the power line span distance, and the safety distance between the power lines and the vegetation. In addition, combined with other parameters (temperature, wind speed, etc.) acquired by monitoring equipment installed on the power tower, the power line arc sag changes under different working conditions can be simulated to conduct hazard analysis and provide an early warning. A comparative analysis of multiperiod LiDAR point cloud data can also analyze the changes (e.g., tree growth, illegal building construction) in the power transmission corridors and the possible dangers to the safe operation of power lines.

1.3.5 Crop Monitoring

LiDAR returns can accurately characterize light penetration into the canopy and provide fine canopy structure information in the vertical direction. This makes its application in low vegetation such as crops possible. For example, the airborne and terrestrial LiDAR data can achieve accurate estimation of crop parameters, such as crop plant height, LAI, leaf angle distribution, fraction of absorbed photosynthetically active radiation (FPAR), and aboveground biomass. In addition, the LiDAR and hyperspectral data can be integrated for classifying crops and mapping various crop parameters.

1.3.6 Cultural Heritage Digitization and Preservation

Stone carvings, grottoes, ancient buildings, and other cultural heritage sites are valuable treasures left to us by the ancients. Their digitized 3D models are not only formally displayed in an all-round way but also of great significance for their protection, 3D digital archiving, and permanent preservation and dissemination. LiDAR technology can directly and quickly acquire high-precision, high-density 3D spatial information on the surface of these heritage sites. Also, the high-resolution digital camera carried by LiDAR systems can acquire the fine feature information of objects. By combining the LiDAR point cloud and camera photos, the real 3D digital model of cultural heritage sites can be constructed. In addition, the terrestrial 3D laser scanning technology can digitally record and preserve the archaeological site, such as the 3D measurement of cultural relics and analysis of the erosion of the site surface, to achieve the dynamic display of the archaeological process, digital record, and analysis of the changes. The airborne LiDAR can obtain the understory topographic information, providing basic data support for understory archaeology.

1.3.7 Unmanned Driving

LiDAR calculates the distance to the obstacle based on the round-trip time between the laser to the obstacle. In the driverless field, LiDAR helps cars autonomously sense the road environment and automatically plan driving routes to reach the intended destination. LiDAR can also accurately measure the relative distance between the object's contour edge in the field of view and the LiDAR. By using the contour point cloud, a 3D environment map can be drawn through 3D modeling, with an accuracy of up to centimeters.

1.3.8 Transportation Route Planning

Fine road modeling is very important in road engineering design, pavement inspection, and 3D visualization. Traditional methods, such as single-point measurement by GNSS or total station, only obtain discrete data and are affected by road vehicles, which makes it difficult to know the road situation completely and accurately. Different from the single-point measurement method, LiDAR can obtain high-precision 3D coordinates of the road through scanning and does not require a control point network to be established. After data processing, a high-precision 3D digital model of the road panorama is obtained. In addition, LiDAR technology is used as an important detection means in railroad tunnel construction, such as monitoring and sampling in the tunnel construction process, generation of high-precision cross-section maps, blasting area and volume analysis, excavation earthwork volume calculation, flatness analysis of the excavated tunnel wall, over- or under-digging analysis, and check and calibration of the tunnel boring direction. In recent years, high-speed railroads have been developing rapidly over the world, and LiDAR plays an important role in the rapid detection of track micro-changes.

1.3.9 Mine Monitoring

There are more and more large and super-large mines. In particular, the open-pit mines are facing the problem of expanding mining scale and deepening mining depth gradually, which brings threats to the stability of mine slope rocks and soil bodies. LiDAR technology extends the point measurement to the surface measurement to a large extent. It can be used for mapping open-pit mine slopes and other complex fields and reconstructing 3D models of the mine scene. Through multitemporal LiDAR data, the users can extract the deformation information of the slopes and ore body to provide data support for the mine safety monitoring.

1.3.10 Other Applications

In addition to the previous applications, LiDAR is used in near-coastal topographic mapping, river surveying, flood assessment, dam deformation monitoring, and other fields. This section does not describe such applications in detail. Interested readers can refer to the relevant literature for more information.

1.4 SUMMARY

This chapter first briefly introduces the origin, characteristics, classification, and development history of LiDAR, as well as the LiDAR system composition. Then, the current mainstream commercial LiDAR equipment and data processing software products are summarized. Finally, several representative applications of LiDAR remote sensing are briefly introduced.

EXERCISES

1. Briefly describe the characteristics of LiDAR.
2. What are the components of a LiDAR system? Explain the role of each component.
3. List five ways to categorize LiDAR.
4. What are the LiDAR point cloud data formats? Please introduce one of the data formats in detail.

NOTES

1 IEC 60825-1:2007 Safety of laser products — Part 1: Equipment classification and requirements.
2 Theodore Harold (Ted) Maiman, an American physicist produced a collimated, monochromatic, coherent beam of light by amplifying a line of optical radiation at a narrow-amplitude frequency through stimulated radiation amplification and necessary feedback resonance on July 8, 1960. Since then, the world's first ruby laser has been introduced.
3 Friedrich Ackermann, a very prominent leader in the field of photogrammetry worldwide, is known for his outstanding achievements in photogrammetric research.

REFERENCES

He, Y., Hu, S., Chen, W., Zhu, X., Wang, Y., Yang, Z., Zhu, X., Lv, D., Huang, T., Xi, X., Qu, S., & Yao, B. (2018). Research progress of domestic airborne dual-frequency LiDAR detection technology (in Chinese). *Laser & Optoelectronics Progress*, *55*(8), 082801.

Li, M., Zuo, J., Zhu, J., & Meng, T. (2013). Research on dual-channel 3D imaging LiDAR technology (in Chinese). *Science of Surveying and Mapping*, *38*(3), 49–51.