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# The Square Kilometre Array

## A Science Mega-Project in the Making, 1990-2012

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Composite image showing artist's impressions of the SKA telescope sites in South Africa (SKA-Mid, left) and in Australia (SKA-Low, right). Credit: SKA Observatory

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# Foreword

This is a story of how a grand vision became a reality. The Square Kilometre Array is now under construction and will take its place as one of the great astronomical instruments of the twenty-first century. It will be the world's largest radio telescope, providing a unique view of the very early cosmos. Together with the James Webb Space Telescope, the European Extremely Large Telescope, and other facilities in space and on earth, it promises to transform our understanding of the universe we live in.

The night sky is special. It is the one thing that everyone in the world—and indeed everyone who has ever lived—has in common. It is hard to imagine any human who has not looked up at the stars, galaxies, and planets and wondered what they are, where they came from, and how we fit in. SKA combines this age-old desire to understand our world with the grand engineering vision of building a telescope so large that its collecting area would cover an entire square kilometre—a truly huge instrument, larger than anything ever done before, collecting and processing more data than the entire global Internet.

The story of SKA is undoubtedly a success story. The telescope is now being built and an inter-governmental treaty has been signed guaranteeing its funding and operation. But it's also a story of continuous compromise—not least in that what is currently under construction, while it will indeed be the world's largest telescope, it is considerably less than the original square kilometre in area. A big program of expansion and upgrades will be needed to come anywhere close to the original goals.

While this is a story about science, technology, and engineering, it is also a very human story: one that is intimately woven into the personal and career histories of the actors. SKA could never have gone through its long gestation and eventual realisation without the dedication, even passion, of those involved, sometimes almost verging on the irrational. It is also human in the way the life story of SKA itself almost mirrors that of a child growing up. In particular, there is a recurring theme running through it of a loss of innocence, of youthful enthusiasm confronting the painful realities of adult life, of idealism being trumped by pragmatism.

Idealism, the sense that anything is possible, eventually has to give way to the constraints of money and time, or nothing concrete will ever happen. Surely a real observatory, even one reduced in scale, is to be preferred to a dream, no matter how perfect? Yes, but it still feels a little sad to discover that the price of success is to sacrifice much of one's dreams.

The story is also full of transitions—as SKA moved from a concept to a research program to a project, each new phase brought a transition in management, governance, and funding mechanisms. Seeing all this recounted here, one cannot but remark on the sheer amount of time and effort that was spent organising and re-organising the project and its various committees and boards. This was certainly not wasted effort but makes one realise again the inherent complexities involved in setting out to build a global project with no existing host organisation.

I think everyone understands that this process of compromise—of 'growing up'—is essential. But that doesn't make it easy. Surely all those involved appreciate the necessity of focusing efforts and concentrating on a buildable project that can actually deliver science, even if some of the original vision must be discarded? The answer is a resounding 'yes and no'. The scientists and engineers who designed—no, who *owned*—the vision of SKA were very much human, and it's a natural human instinct to prefer unrealised perfection to a messy compromise. You would expect an architect to want the building they have designed to be built—and they do—but they certainly don't look forward to the loss of their original vision that comes with all the messy adjustments to buildability. SKA may seem like a technical vision rather than an artistic one, but for those who had spent many years working on it the emotional commitment was just as real. Moreover, SKA went through this process not once, but several times, and may well do so again.

It's also a challenge to stop improving the design and freeze the specifications. There are always improvements that can be made, but if the project is ever to be built we need the self-discipline to stop doing this. That too can be quite hard. On one of my other projects, I was accused by the scientists of 'asking them to become engineers and just build something'. It was meant as a criticism, but—aside from the arrogant implication that engineers are lower status than scientists—it was an entirely accurate description of what was needed. Admiral Hyman Rickover, mastermind of the US nuclear navy, once noted that there were two kinds of nuclear reactor: those that offered higher power, lower weight, greater efficiency—and then those that actually ended up powering submarines. No matter how ambitious, no matter how capable, an SKA that exists only on paper isn't going to tell us anything about the universe.

A second related challenge which this book also explores at some length is the engagement with the political domain that becomes essential for a project with the size and international visibility of SKA. This is where I myself was fortunate to be able to play a role in helping to make SKA a reality, both as head of the Science and Technology Facilities Council (STFC, the UK funding agency responsible for particle physics and astronomy) and as chair of the SKA's governing board. The selection of site or sites for the telescope and its headquarters, the governance and funding of the project, and the procurement strategy all attracted the interest not just of scientific funding agencies but of their elected political masters. This was undoubtedly good, because it is hard to see how SKA could have been delivered without it. But it came with its own challenges and its own loss of innocence. The scientific and technical challenges of designing and building SKA, while huge, can be reconciled in an evidence-based way that everyone will, at least in principle, agree with. They map on to key systems engineering requirements. There was naturally a desire among the project team to approach questions like siting and cost in the same way, but this proved simply impossible. By their very nature, government policy questions are not ones with purely right or wrong answers. Nothing happens in government policy, including science policy, without an element of compromise. Many stakeholders need to support a decision for it to pass, and each stakeholder has their own concerns so the only things that ever actually happen involve messy attempts to reconcile slightly differing viewpoints, with all that this entails.

The compromises necessary to secure support and funding for SKA have certainly attracted attention: in particular, was the decision to site elements of the telescope in both South Africa and Australia the right one? I would strongly argue that it was, as it preserved the project as a single enterprise with a global vision when this might easily have been lost. I am also often asked whether SKA should have engaged with governments sooner (or indeed waited to do so later). With the benefit of hindsight, I think the engagement came at roughly the right time, at least as far as the UK was concerned. The project needed to have a pretty clear view of the science it would do, what it wanted to build, and how much this would cost, before the engagement could be fruitful. It also needed an element of luck. As it happened, SKA captured the enthusiasm of the UK science minister David (now Lord) Willetts at just the time when he had a budget for capital investment in research infrastructure available. This was quite a feat, as the prevailing view was that research needed to demonstrate impact, to be relevant to society and the economy, and ‘pure’ fields like astronomy would struggle to do so when competing for funding with medical research, engineering, or the life sciences.

We certainly pitched SKA to some degree as a big data and computing project with astronomy motivations, rather than purely as an astronomy project, in order to help attract the interest of the political stakeholders. SKA definitely caught the attention of other science communities, and I was even complimented, in a backhanded way, by the then head of the Medical Research Council who was surprised to see a ‘pure science’ project like SKA presented as a UK priority.

Of course luck can also run out, and in this case it almost did. I can recall travelling back from a Research Councils’ dinner in Edinburgh where rumours were rife that Willetts was about to be moved out of his post, just at the time when a public announcement to commit funding to SKA was imminent. I was extremely dejected—a new minister would surely revisit all of Willetts’ decisions, months of work would be wasted, and the opportunity might never come again. Fortunately Willetts survived the government reshuffle and made that firm commitment during a visit to Jodrell Bank, thus securing the UK’s role in the project.

We should also remember that there were informal contacts with funding agencies long before the first ‘official’ engagement with SKA at Heathrow in 2005. Any good astronomy program manager will keep an eye on emerging initiatives within the community, and SKA was no exception. It's a mistake to think that funding agencies don't like requests for money—what they don't like is being surprised by requests for money.

When I present seminars on big science projects, one recurring theme in the discussions afterwards—and one that certainly applies to SKA—is the observation that there is almost always a very big escalation in costs from the initial estimate to the final approval. Is it inevitable to overstate the potential and understate the cost of big projects? It's tempting to accuse the initial proponents of 'low-balling' the cost to secure approval and then admitting the truth later. I think things are much more complex than this. Initial estimates are optimistic. Optimism is not a sin—in fact it is probably inevitable. No one would dedicate themselves to a project in its early stages without a high degree of optimism about cost and schedule, including the ability to do things at lower cost and at larger scale than before. Initial estimates rarely include contingency, and they assume that all the needed R&D delivers. There is nothing wrong with an optimistic estimate as long as the underlying assumptions are clearly stated, and, perhaps more importantly, the risks and the resulting uncertainty on the estimate are also communicated.

I've also been asked how one can tell if one is engaging closely enough with the political decision-makers when seeking support and funding for something like SKA. My slightly flippant response is to say that unless you feel a little bit dirty, you're probably not getting close enough. What I mean by this is that unless you, as a scientist, start to feel like you are engaging in a non-scientific way—something that often makes scientists uncomfortable—you're not really engaging. To do this successfully you have to respect the political decision-making process and the right of political decision-makers to do things their way and set aside the idea that you—with your science Ph.D.—obviously know more than they do. In my experience elected politicians are often far smarter than they appear (or choose to appear) and they have a gift of empathy that scientists often lack.

A final question, I suppose, is why the SKA story matters. Who should read and care about the formative phases of a project like this? Obviously, there is an academic interest in documenting the genesis of a project which we fully expect to be one of the most scientifically important observatories of the coming decades. Those who have invested so much of their time, talent, and emotional commitment deserve it to be recorded, in a way that can't be fully captured by the myriad scientific papers that SKA will in time produce. But more importantly there are important lessons here. SKA is one of very few scientific endeavours to have successfully negotiated the often-treacherous path from a bottom-up, community-led concept to the creation of a dedicated international treaty organisation with the goal of making it happen. There are lessons here aplenty, especially as other fields of science become ever-more global and require ever-larger facilities to carry them forward. I don't expect the lessons of SKA to fully apply anywhere else, but I am pretty sure there are lessons here for anyone proposing an international big science—and even a not-so-big science—initiative.

Finally, I would like to express my personal gratitude to the entire team of the SKA for allowing me, as a relative outsider, to feel a part of their family. SKA is the collective work of many hundreds of participants who have dedicated years—sometimes their entire careers—to the project. Like any complicated and challenging endeavour, there were plenty of disagreements along the way, but it was obvious to me from the very beginning that there was something quite special in the way everyone shared a commitment to a consistent overall vision. Without this shared commitment I doubt that the project would have survived, never mind be under construction today. And it was equally obvious that there was an SKA culture—an SKA way of doing things—that valued openness, honesty, and that saw colleagues around the world as friends. It has been one of the highlights of my research career to be a part of this effort and I wish it every success for the future.

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John Womersley

# Preface

Why write a history of the Square Kilometre Array now, before the telescope has been fully built? It is a good question and one we authors debated at some length before taking up the challenge of putting this volume together. In the end, our motivation was quite simple. Telling the story of the formative years of a project that began life as a global ‘grass-roots’ collaboration at individual scientist level and went on to achieve mega-project scale (and funding) and inter-governmental organisation status is a worthwhile endeavour in itself. Having spent many years at the centre of the global project during its formative years and beyond, we felt we were in a good position to write the story. One of the perceived challenges to be overcome was to capture the diverse contributions to the history into a coherent account. Fortunately, comprehensive records have been kept and, just as importantly, almost all the key players involved in making the SKA history are still alive which has allowed us to record some of their thoughts, memories, and reflections through informal discussions, interviews, and a conference in 2019 dedicated to this period of SKA history. Not all the material gathered in this way has made it into the book explicitly, but it remains in the archive at the SKA Observatory for future studies. Of course, having so many knowledgeable colleagues in the potential audience for this book has kept us on our toes.

## Project Overview

The idea for a very large collecting area radio telescope first saw the light of day in the 1970s and 1980s independently in four different places around the globe. It was driven by science and, in the first place, detection of hydrogen, the most abundant element in the universe, in emission from very distant galaxies. The concept of a collecting area of one million square metres, one hundred times more sensitive than the then most powerful telescope in the world, did not come out of the blue; it built on decades of radio telescope development after the Second World War. Not surprisingly, the idea proved attractive for a much wider community and the science case expanded, as did the requirements for innovative supporting technology to make it affordable and to service the other observing frequencies and modes of operation involved. An additional strong underlying theme was, and still is, the discovery of the unknown, spurred on by the realisation that most of the discoveries in observational astronomy (including many Nobel Prizes) have come in fields unknown at the time a project was funded.

Other motivations for a large global project like the SKA also came into play, such as national and regional prestige and return on funding investment measured in terms of industrial contracts and opportunities for education and training of young potential scientists. These factors, as well as the ever-present geopolitical issues, add extra layers of complexity to an already complex multi-institute project aiming to provide a huge scientific step forward. We examine all these aspects and their interactions in varying levels of detail in the book.

In the book title we have designated 1990–2012 as the formative years of the SKA, a time when the project transitioned from a dream to a science mega-project starting its detailed design phase leading to construction. This long formative period is bounded at both ends by major milestones in the life of the project. October 1990 marked the first time the concept of a very large collecting area radio telescope was aired at an international conference, in this case the International Astronomical Union Colloquium 131 held in Socorro, New Mexico, USA. Three almost coincident milestones define the end of the formative years. The first was the transition in project governance from a scientist-led collaboration to a legal entity, the SKA Organisation (the precursor to the current SKA Observatory), at the end of 2011. This also marked the second milestone, the start of the decade-long pre-construction phase. The third milestone followed a few months later in mid-2012—the final decision by the SKA Board to locate the first phases of the low and mid-frequency components of SKA in Australia and South Africa, respectively, the dual-site solution.

Earlier brief accounts of various aspects of the history of the SKA have been given separately by Ron Ekers (2012) and by Jan Noordam (2012),[1] Ken Kellermann, Ellen Bouton, and Sierra Brandt (2020),[2] Kellermann and Bouton (2023),[3] and Jasper Wall, Elizabeth Griffin, and Richard Jarrell (2024).[4]

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[1] Both papers are published in *Resolving The Sky - Radio Interferometry: Past, Present and Future* (Proceedings of Science, http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=163), 2012. Also published in book form by Dolman Scott Ltd for the SKA Organisation, 2013.

[2] See *Open Skies* (Springer, 2020).

[3] See *Star Noise* (Cambridge University Press, 2023).

[4] See *Radio Astronomy in Canada* (Springer 2024).

## Book Plan

The SKA story is one of five intertwined themes running in parallel throughout much of the period. These themes are global collaboration and its evolution from a working group in 1993 to a legal entity in 2011; the evolution of the science case; the evolution of the SKA design and the inevitable confrontation of innovation with reality; the site selection stories for telescope and project headquarters; and engagement with industry. We have chosen not to recount the story in terms of a strict time sequence of events across all the themes; rather we examine each theme separately in terms of its chronological development, both globally and nationally, and discuss the interactions with the other elements as we go along. Preceding these theme-based chapters is an overview of the emergence of the very large collecting area telescope concept in the context of several decades of post-World War II radio astronomy development and, at the end of the book, a concluding chapter reflecting on the SKA project as a whole. We do not provide a detailed timeline table of dates and events for the SKA; rather there are graphical views of the timelines in several of the chapters to help the reader navigate through the many overlapping threads of activity, discussion, and decision taking place in the project.

In writing this history we have had access to a large amount of material available in several forms: unpublished minutes of meetings and associated documents; SKA Memos and SKA Newsletters; project documents; presentation material and discussion transcripts from the 2019 conference on the early history of the SKA; interview transcriptions; and other documents, emails, and personal notes held by the authors. Vast numbers of the formal project documents from 1999 onwards have been compiled and archived electronically at SKAO Headquarters at Jodrell Bank Observatory by Colin Greenwood. We thank Phil Diamond, SKAO Director-General, and Colin Greenwood for providing access to the SKAO Archive. Also archived at SKAO are the minutes of meetings of the Funding Agencies groups involved in the SKA, and we thank Colin Vincent at the Science and Technology Facilities Council in the UK for allowing access to this material.

## Appendices

In Appendix A, readers can find a set of instructions on how to access the online reference documents and supplementary material associated with the book that are held in the SKA Observatory Archive. Appendix B provides a list of online Supplementary Material also held in the SKA Observatory Archive.

## About the Authors

As mentioned earlier, the authors of this book have had a long association with the SKA. *Richard Schilizzi* is a radio astronomer who spent much of his career working with the very-long-baseline interferometry (VLBI) technique particularly in the field of active galactic nuclei. He was actively involved in developing European, global, and space VLBI including the establishment of the Joint Institute for VLBI in Europe (JIVE) where he was the inaugural director from 1993 to 2002. He became involved in the SKA in 1999 as an at-large member of the International SKA Steering Committee (ISSC), the initial governance entity for the project. In January 2003, he was appointed as the first International SKA Director in January 2003, a position he held until December 2011. In the years following, he established an SKA Group in the University of Manchester and eventually took up an Emeritus Professor position at the University in 2018.

*Ronald Ekers* has had an international career involving research and promotion of radio astronomy and radio astronomical techniques. He has worked with some of the largest radio astronomy arrays including Westerbork in the Netherlands and as director of the VLA in the USA and ATCA in Australia. He is a former president of the International Astronomical Union and has been actively involved in the promotion of international scientific research through the IAU, URSI, and OECD. He has been directly involved in the concept of a Square Kilometre Array (SKA) as a global science mega-project since its inception. He was member of the URSI Large Telescope Working Group from 1993 to 1999, he helped establish the IAU Working Group for Future Large-Scale Facilities in 1995, and he became the first chair of the International SKA Steering Committee when it was established in 2000. He has always been interested in the history and philosophy of science and the role of the research environment in innovation and discovery. He promoted the SKA concept as the continuation of the exponential growth found in many other areas of experimental science and technology. His research interests in astronomy are broad including extragalactic astronomy and cosmology, galactic nuclei (the centres of galaxies), ultra-high energy particle physics, and innovative applications of radio astronomical techniques. He is currently a CSIRO fellow and an adjunct professor at Curtin University in Perth, Australia.

*Peter Dewdney* is a researcher who has crossed back and forth between the science and technical sides of radio astronomy and has been associated with the SKA since the idea began to gel globally. After spending much of his research career at the Canadian National Research Council's Dominion Radio Astronomy Observatory with involvement in a variety of radio telescopes, he moved to the University of Manchester in 2008 to take up the role of Project Engineer for the Preparatory Phase of the SKA (PrepSKA). In 2012, he joined the Square Kilometre Array Organisation for its pre-construction phase, where he became the SKA Architect responsible for coalescing the design, based on previous work during PrepSKA. Returning to Canada in 2018, he continues to hold the position of SKA Architect, but acting in an advisory role to the engineering staff as the SKA is being constructed.

*Phil Crosby* entered the world of radio astronomy from a career in aerospace, industrial electronics, and radio engineering. He joined the (then) CSIRO Division of Radiophysics in 2006, bringing a business and commercial facet to the ATNF. He was seconded to the SKA Project Development Office (SPDO) in Manchester in 2009 for two years, developing and delivering the SKA industry engagement strategy which laid the foundation for subsequent industry cooperation and participation. Beyond 2011, Phil's support for SKAO has helped shape global procurement, and he continues to offer specialist expertise in large-scale complex project management.

As insiders in the SKA project, we have taken the 'practitioner' approach[5] to writing this history. We set ourselves the primary task of, from a global perspective, identifying and describing the major issues and events that defined the formative years while at the same time bringing in the parallel national and regional contributing efforts. Each of the authors took responsibility for drafting the various theme-based chapters. Schilizzi wrote Chap. 2 on the emergence of the SKA concept, Chaps. 3 and 4 on the evolving global collaboration in the SKA, Chaps. 7 and 8 on the telescope site selection story, and Chap. 9 on the SKAO Headquarters site selection process; Ekers wrote Chap. 5 on the science case; Dewdney wrote Chap. 6 on the SKA design; and Crosby wrote Chap. 10 on engagement of industry in the SKA. Schilizzi and Ekers wrote the Introduction (Chap. 1). Within the individual chapters, we have complemented the historical narrative with analysis and reflection on the approaches and decisions taken as well as their consequences, and in the final chapter (Chap. 11) to which all authors contributed, we have drawn some conclusions on the project as a whole. We have not attempted to set out prescriptions or lessons learned for other very large projects, but merely describe the route taken through the complex environment faced by the SKA and make some general observations.

## Acknowledgements

We owe a great deal of thanks to our colleagues who wrote meticulous minutes of the Steering Committee meetings: Russ Taylor (August 1999–January 2003), Wim Brouw (January 2004–November 2006), and Colin Greenwood (April 2008–November 2012). In addition, Michelle Cooper wrote similarly detailed minutes of meetings of the Funding Agencies (2005–2011), PrepSKA Board (2008–2012), and Founding Board (2011). These have been an invaluable aid to fallible human memory.

Likewise, thanks to the many colleagues who wrote SKA Memos and other project documents over the years on the science and engineering aspects of the

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[5] An approach defined in the Preface to *Joe Pawsey and the Founding of Australian Radio Astronomy* by W. M. Goss, Claire Hooker, and Ronald D. Ekers (Springer, 2023).

project, again much used in this work. Also, thanks to those around the world who contributed to the twenty-three SKA Newsletters published from 2000 to 2012. These provide detailed snapshots of the project status, both global and national/regional, over more than a decade and are a valuable historical record in themselves.

We extend our special thanks to a large number of people for additional material (documents, photographs, figures, and other information) provided to the authors in the course of writing the various chapters: Rob Adam, Jaap Baars, Ron Beresford, Simon Berry, Rosie Bolton, Wim Brouw, John Bunton, Harvey Butcher, Cassandra Cavallaro, Aaron Chippendale, Michelle Cooper, Joe Diamond, Phil Diamond, Richard Ellis, Christian Fabjan, Mike Garrett, Martin George, Anne Green, Colin Greenwood, Yashwant Gupta, Leonid Gurvits, Anthony Holloway, Hirax Hirabayashi, Gary Hovey, Ken Kellermann, Gordon Lacy, Joe Lazio, Malcolm Longair, Franco Mantovani, Jim Moran, Rob Millenaar, Patricia Kelly, George Nicolson, Jan Noordam, John O'Sullivan, Sarah Pearce, Corrado Perna, Vernon Pankonin, Bo Peng, Ethan Schreier, Giancarlo Setti, Helen Sim, Jill Tarter, Russ Taylor, Steve Tingay, Adrian Tiplady, Tasso Tzioumis, Arnold van Ardenne, Wayne van Citters, Ed van den Heuvel, Richard Wade, Peter Wilkinson, Yihua Yan, and Anton Zensus.

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It was a great privilege to see many of our friends and colleagues at the conference organised on the history of the formative years of the SKA at SKAO Headquarters at Jodrell Bank Observatory (UK) in April 2019. The aim of the conference was to hear and discuss presentations on who was involved, what happened, and why, from individual, institute, national, regional, and global perspectives. Participants were Rob Adam, Paul Alexander, Jaap Baars, Tony Barry, Tony Beasley, Simon Berry, Roy Booth, Justin Bray, Joe Callingham, Chris Carilli, Rebecca Charboneau, Tracy Cheetham, Michelle Cooper, Ian Corbett, Gary Davis, Dave DeBoer, Eloy de Lera Acedo, Marco de Vos, Joe Diamond, Phil Diamond, David Eggleton, Bernie Fanaroff, Andy Faulkner, Yongcheng Fu, Martin Gallagher, William Garnier, Mike Garrett, Nuno Gil, Keith Grainge, Colin Greenwood, Leonid Gurvits, Peter Hall, Simon Haynes, Carole Jackson, Justin Jonas, Ken Kellermann, Joe Lazio, Jingnam Li, Matthew Lilley, Colin Lonsdale, Yu Lu, Peter Mathewson, Joe McMullin, Stefan Michalowski, Khotso Mokhele, Jim Moran, George Nicolson, Jan Noordam, Richard Oberland, Vernon Pankonin, Bo Peng, Elena Righi-Steele, Nigel Rix, Miriam Roelofs, Ethan Schreier, Terry Soame, Jill Tarter, Russ Taylor, Isak Theron, Peter Tindemans, Adrian Tiplady, Arnold van Ardenne, Thijs van der Hulst, Michiel van Haarlem, Tejinder Virdee, Patricia Vogel, Richard Wade, Althea Wilkinson, Peter Wilkinson, John Womersley, and Anton Zensus. Thanks are also due to Joe Diamond, Sarah Lamb, Michelle Hussey, and Claire Taylor in the Local Organising Committee who worked tirelessly behind the scenes to make the conference a success.

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# Contents

# Abbreviations

| | |
|---|---|
| AA | Aperture Array |
| AAD | Aperture Array Demonstrator |
| AAVP | Aperture Array Verification Program |
| AAVS | Aperture Array Verification System |
| ADC | Analogue to Digital Converter |
| AGN | Active Galactic Nucleus |
| AHP | Analytic Hierarchical Process |
| AIP | SKA Advanced Instrumentation Program |
| ALMA | Atacama Large Millimetre-sub millimetre Array |
| ANZ | Australia–New Zealand |
| APERTIF | APERture Tile In Focus, Westerbork Synthesis Radio Telescope (WSRT) upgrade |
| ASG | Agencies SKA Group |
| ASKAC | Australian SKA Committee |
| ASKAIC | Australian SKA Industry Consortium |
| ASKAP | Australian SKA Pathfinder |
| ASTRON | Netherlands Institute for Radio Astronomy |
| ASTRONET | A European Commission planning and advisory network for European Astronomy |
| ATA | Allen Telescope Array |
| ATCA | Australia Telescope Compact Array |
| ATNF | Australia Telescope National Facility |
| AUD | Australian dollars |
| AUI | Associated Universities Inc. |
| AWG | Antenna Working Group |
| BAE | British Aerospace Corporation |
| BAO | Baryonic Acoustic Oscillations |
| BYU | Brigham Young University |
| CALIM | Workshop series on calibration and imaging of astronomical data |
| CASCA | Canadian Astronomical Society |

| | |
|---|---|
| CASPER | Collaboration for Astronomy Signal Processing and Electronics Research |
| CBF | Correlator Beam Former |
| CDIT | (ISPO) Central Design & Integration Team |
| CDR | Critical Design Review |
| CERN | Centre Europeen pour la Recherche Nucleaire |
| CETC | China Electronics Technology group Corporation |
| CFRP | Carbon Fibre Reinforced plastic |
| CHIME | Canadian Hydrogen Intensity Mapping Experiment |
| CHORD | Canadian Hydrogen Observatory and Radio-transient Detector |
| CISCO | Cisco Systems, Inc |
| CISPR | Comité International Spécial des Perturbations Radioélectriques |
| CMB | Cosmic Microwave Background |
| CMOS | Complementary Metal Oxide Semiconductor |
| CNRS | Centre Nationale de la Recherche Scientifique |
| CODR | COnceptual Design Review |
| COST | European organisation for COoperation in Science and Technology |
| COTS | Commercial Off The Shelf |
| CRAF | Committee for Radio Astronomy Frequencies |
| CSIRO | Commonwealth Industrial and Scientific Research Organisation |
| DEST | Department of Education Science and Technology (Australia) |
| DIGESTIF | Prototype for APERTIF |
| DIISR | (Australian) Department of Industry, Innovation, Science & Technology |
| DRAO | Dominion Radio Astronomy Observatory (Canada) |
| DRM | Design Reference Mission |
| DSP | Digital Signal Processing |
| DVA | Digital Verification Antenna |
| DVP | Dish Verification Program |
| EHT | Event Horizon Telescope |
| EIB | European Investment Bank |
| ELT | Extremely Large Telescope at optical wavelengths |
| EMBRACE | Electronic Multi-Beam Radio Astronomy ConcEpt |
| EMI | Electro-magnetic Interference |
| EMSS | EMSS Antennas (South African company) |
| EMT | (SKA) Engineering Management Team |
| ERIC | European Research Infrastructure Consortium |
| ESA | European Space Agency |
| ESFRI | European Strategy Forum on Research Infrastructures |
| ESKAC | European SKA Consortium |
| ESO | European Southern Observatory |
| ESRF | European Synchrotron Radiation Facility |
| EU | European Union |
| EURO-16 | Early Universe Radio Observatory (16 antennas) |

| | |
|---|---|
| EVLA | Extended Very Large Array |
| EVN | European VLBI Network |
| EWG | (SKA) Engineering Working Group |
| FAST | Five-hundred-metre Aperture Spherical radio Telescope |
| FAWG | Funding Agencies Working Group |
| FFT | Fast Fourier Transform |
| FIRST | Faint Images of the Radio Sky at Twenty-centimetres |
| FPA | Focal Plane Array |
| FPGA | Field-Programmable Gate Array |
| FRB | Fast Radio Burst |
| FX | Type of correlator (Fourier transform followed by cross-correlation) |
| GAIA | ESA astrometric Space Mission |
| GERT | Giant Equatorial Radio Telescope |
| GMRT | Giant Metre wavelength Radio Telescope (India) |
| GPS | Global Positioning System |
| GPU | Graphics Processing Unit |
| GSF | (OECD) Global Science Forum |
| GSMT | Giant Segmented Mirror Telescope |
| GURT | Giant Ukrainian Radio Telescope |
| HALCA | Highly Advanced Laboratory for Communications and Astronomy (also VSOP) |
| HEMT | High-electron-mobility transistor |
| HERA | Hydrogen Epoch of Reionisation Array |
| HIA | Herzberg Institute of Astronomy (Canada) |
| HRAO | Hartebeesthoek Radio Astronomy Observatory (South Africa) |
| HST | Hubble Space Telescope |
| IAU | International Astronomical Union |
| ICRAR | International Centre for Radio Astronomy Research (Australia) |
| ICT | Information and Computing Technology |
| IEAC | (SKA) International Engineering Advisory Committee |
| IEEE | Institute of Electrical and Electronics Engineers |
| IEMT | (SKA) International Engineering Management Team |
| IFAG | International Funding Agencies Group |
| IGO | Inter-Governmental Organisation (entity created by treaty) |
| INAF | Istituto Nazionale di Astrofisica (National Institute for Astrophysics - Italy) |
| IP | Intellectual Property |
| IR | Infrared |
| IRAM | Institut de RadioAstronomie Millimétrique |
| ISAC | (SKA) International Science Advisory Committee |
| ISAS | Institute of Space and Aeronautical Science (Japan) |
| ISKAF | International SKA Forum |
| ISM | Interstellar Medium |
| ISPO | International SKA Project Office |

| | |
|---|---|
| ISSAC | International SKA Site Advisory Committee |
| ISSC | International SKA Steering Committee |
| ITER | International Thermonuclear Experimental Reactor |
| ITU | International Telecommunication Union |
| JBO | Jodrell Bank Observatory |
| JCMT | James Clark Maxwell Telescope |
| JDEM | Joint Dark Energy Mission |
| JIVE | Joint Institute for VLBI in Europe |
| JPL | Jet Propulsion Laboratory |
| JVLA | Jansky Very Large Array |
| JWST | James Webb Space Telescope |
| KARST | Kilometre-square Area Radio Synthesis Telescope |
| KAT | Karoo Array Telescope |
| KPMG | KPMG International Limited (Accounting firm) |
| KSP | Key Science Projects |
| KTN | Knowledge Transfer Network (UK) |
| LAR | Large Adaptive Reflector (Canada) |
| LEO | Low Earth Orbit |
| LFAA | Low Frequency Aperture Array |
| LFST | Largest Feasible Steerable Telescope |
| LIGO | Laser Interferometer Gravitational Wave Observatory |
| LISA | Laser Interferometer Space Antenna |
| LL | Luneburg Lens |
| LNA | Low-Noise Amplifier |
| LNSD | Large Number-Small Diameter (dishes) |
| LOFAR | LOw Frequency ARray |
| LPDA | Log Periodic Dipole Array |
| LRP | (Canadian) Long Range Plan |
| LSST | Large Synoptic Survey Telescope |
| LTWG | Large Telescope Working Group, URSI |
| LWA | Long Wavelength Array (USA) |
| MERLIN | Multi-Element Radio Linked Interferometer Network (UK) |
| MIRA | Mileura International Radio Array (Australia) |
| MIRANdA | MIRA-NdA—large-N, small-d Array |
| MIT | Massachusetts Institute of Technology |
| MMA | Millimetre Array |
| MMIC | Monolithic Microwave Integrated Circuit |
| MOST | Molonglo Observatory Synthesis Telescope (Australia) |
| MOU | Memorandum of Understanding |
| MRO | Murchison Radioastronomy Observatory (Australia) |
| MSF | Mega Science Forum of OECD |
| MWA | Murchison Widefield Array |
| NAIC | National Astronomy and Ionosphere Centre (Arecibo radio telescope) |

| | |
|---|---|
| NAOC | National Astronomical Observatory of China |
| NAOJ | National Astronomical Observatory of Japan |
| NASA | National Astronautical and Space Administration (USA) |
| NCRA | National Centre for Radio Astrophysics (India) |
| NCRIS | National Collaborative Research Infrastructure Strategy (Australia) |
| NDA | Non-Disclosure Agreement |
| NEP | Network Enabled Platform |
| NFRA | Netherlands Foundation for Radio Astronomy |
| NGST | Next Generation Space Telescope |
| ngVLA | new generation VLA |
| NPV | Net Present Value |
| NRAO | National Radio Astronomy Observatory (USA) |
| NRC | National Research Council (Canada) |
| NREN | National Research and Education Network |
| NRF | National Research Foundation (South Africa) |
| NRL | Naval Research Laboratory (USA) |
| NSERC | Natural Sciences and Engineering Research Council of Canada |
| NSF | National Science Foundation (USA) |
| NTD | New Technology Demonstrator |
| NWO | Netherlands Organisation for Scientific Research |
| NXP | NXP Semiconductors N.V. (Manufacturer) |
| OECD | Organisation for Economic Co-operation and Development |
| OPTICON | OPTical Infrared COordination Network for Astronomy |
| OSMA | One Square Metre Array |
| OSU | Ohio State University |
| OVRO | Owens Valley Radio Observatory |
| OWG | Operations Working Group |
| 2-PAD | 2-Polarisation All Digital |
| PAF | Phased Array Feed |
| PAFSKA | A formal collaboration to develop the SKA PAF design |
| PAPER | Precision Array for Probing the Epoch of Reionisation |
| PDR | Preliminary Design Review |
| PEP | Project Execution Plan |
| PHAD | PHased Array Demonstrator |
| PITF | Power Investigation Task Force |
| PPARC | Particle Physics and Astronomy Research Council (UK) |
| PPD | Preloaded Parabolic Dish (India) |
| PPP | Program Prioritization Panels (USA ASTRO2010 survey) |
| PrepSKA | Preparatory Phase Study for the Square Kilometre Array |
| PSF | Point Spread Function |
| PSFRMS | Point spread function root mean square |
| RAS | Royal Astronomical Society |
| RATAN | Russian Academy of Sciences Radio Telescope |
| RF | Radio Frequency |

| | |
|---|---|
| RFI | Radio Frequency Interference |
| RfI | Request for Information |
| RFP | Request for Proposal |
| ROACH | Reconfigurable Open Architecture Computing Hardware |
| RQZ | Radio Quiet Zone |
| RRI | Raman Research Institute (India) |
| RSM | Reference Science Mission |
| RST | Radio Schmidt Telescope (Canada) |
| RUG | University of Groningen (Netherlands) |
| SALT | Southern African Large Telescope |
| SAO | Special Astrophysical Observatory, Russia |
| SARAO | South African Radio Astronomy Observatory |
| SCWG | Site Characterisation Working Group |
| SDR | Spatial Dynamic range |
| SDS | System Design Studies |
| SELEX | Selex ES (Italian technology company) |
| SESC | Site Evaluation and Selection Committee |
| SETI | Search for Extra Terrestrial Intelligence |
| SEWG | Site Evaluation Working Group |
| SIKTN | Sensors and Instrumentation Knowledge Transfer Network (UK) |
| SIRTF | Space InfraRed Telescope Facility, renamed Spitzer Space Telescope |
| SKA | Square Kilometre Array |
| SKADC | SKA Dish Consortium |
| SKADS | Square Kilometre Array Design Studies |
| SKAMP | Square Kilometre Array Molonglo Prototype (Australia) |
| SKAO | Square Kilometre Array Organisation (2011–2021); SKA Observatory (2021→) |
| SKT | Square Kilometre Telescope (Russia) |
| SMART | Stretch Mesh Attached to Rope Trusses (India) |
| SME | Small and Medium Enterprises |
| SNLD | Small Number-Large Diameter (dishes) |
| SOFIA | Stratospheric Observatory For Infrared Astronomy |
| SOW | Statement of Work |
| SOWG | Site Options Working Group |
| SPDO | SKA Program Development Office |
| SPF | Single Pixel Feed |
| SPO | SKA Project Office |
| SRC | SKA Regional Centre |
| SSAC | SKA Site Advisory Committee |
| SSEC | SKA Science and Engineering Committee |
| SSG | SKA Siting Group |
| SSRC | SKA Specifications Review Committee |
| STFC | Science and Technology Facilities Council (UK) |

| | |
|---|---|
| SWG | Science Working Group |
| SWOT | Strengths, Weaknesses, Opportunities, and Threats analysis |
| TDP | US SKA Technology Development Program |
| TEC | Total Electron Content |
| THEA | THousand Element Array (tile) |
| TID | Travelling Ionospheric Disturbance |
| TIFR | Tata Institute for Fundamental Research (India) |
| TMT | Thirty Metre (optical)Telescope |
| TUE | Eindhoven University of Technology (Netherlands) |
| UC | University of California |
| UCAL | University of Calgary |
| UCAM | University of Cambridge |
| UKTI | United Kingdom Trade and Industry, government department |
| UMAN | University of Manchester |
| UNESCO | United Nations Educational, Scientific and Cultural Organisation |
| UOXF | University of Oxford |
| URSI | Union Radio-Scientifique Internationale (International Union of Radio Science) |
| USD | United States Dollar |
| USSKAC | US SKA Consortium |
| USSR | Union of Soviet Socialist Republics |
| UT | Universal time |
| UTR | UTR-2 radio telescope (Ukraine) |
| VIRGO | Gravitational wave observatory in Italy |
| VLA | Very Large Array (USA) |
| VLBA | Very Long Baseline Array (USA) |
| VLBI | Very-Long-Baseline Interferometry |
| VLT | ESO Very Large (optical) Telescope |
| VSOP | VLBI Space Observatory Program (Japan) |
| WBS | Work Breakdown Structure |
| WBSPF | Wide Band single Pixel Feeds |
| WG | Working Group |
| WP | Work Package |
| WPC | Work Package Consortia |
| WSRT | Westerbork Synthesis Radio Telescope |
| XC | Executive Committee (ISSC, SSEC) |
| XDM | 15 m diameter prototype dish in South Africa |
| XFEL | European X-Ray Free-Electron Laser Facility |
| WG | Working Group |
| XMM | X-ray Multi-Mirror Mission-Newton |

# Chapter 1
# Introduction

This is a book about a grand vision radio telescope project called the Square Kilometre Array (SKA) and its transition from a global grass-roots collaboration among astronomers and engineers in the early 1990s to a formal legal entity two decades later, on the path towards an Inter-Governmental Organisation constructing a science mega-project.

The story of the SKA's development is one of ground-breaking science ideas, innovative engineering, and global collaboration. It is one of the few examples of a community-driven global project that has demonstrated the perseverance and clarity of purpose needed to develop into a treaty-based science mega-project without the benefit of an existing large organisation to act as host in its formative years. There are striking similarities to the formation of the European Southern Observatory (ESO) which started as an astronomer-driven vision in 1953 to build a large optical telescope in the Southern Hemisphere and, a decade later, became a treaty organisation based on a Convention among governments largely modelled on the European Organisation for Nuclear Research (CERN) (Blaauw, 1991).

The development of the SKA has been a long and complex story, reflecting the many issues faced in creating a scientifically ground-breaking but affordable design, choosing a site, and creating a viable global organisation starting from a simple working group established by the International Union of Radio Science (URSI) in 1993. When complete, the SKA will take its place as one of the Great Observatories of the mid twenty-first century alongside the Atacama Large Millimetre/submillimetre Array (ALMA), the James Webb Space Telescope, the Cerenkov Telescope Array (CTA), the large optical telescopes under construction (ELT, TMT, and GMT), and the gravitational wave observatories (LIGO, VIRGO, KAGRA).

This historical account will take the reader from the emergence of the SKA concept through to the decision on where to locate the telescope, in 2012. A number of brief overviews of the SKA history, or elements of it, have already been published by Ekers (2012), Noordam (2012), Butcher (2015), Kellermann et al. (2020), and Kellermann and Bouton (2023). At the time of writing in 2023, construction of the

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first phase of the SKA has now started after a further decade of design and development involving hundreds of scientists, engineers and administrators around the world.

Like any big idea, the SKA did not emerge *ex nihilo*. As radio astronomy flourished and matured as a scientific discipline after World War II using technology pioneered in the war period,[1] many different concepts for radio telescopes were discussed, and some were built. In the process a rich legacy of radio astronomy projects, large and small, was created (see Chap. 2), several of which had direct influence on the SKA in terms of its design and ambition. Others had a more indirect influence in terms of defining the state of the art of what could be built at any particular epoch, or they were unfunded visionary proposals that provided a more distant goal for the community to strive towards.

It is beyond the scope of this book to describe the development of radio astronomy around the world, and the scientific insights generated, in the years before the emergence of the SKA. The reader is referred to a number of books that cover parts of the history, some from national perspectives—(Sullivan, 2009) covering all radio astronomy pre-1953; (Edge & Mulkay, 1976) primarily on UK radio astronomy; (Raimond & Genee, 2011) on The Netherlands; (Kellermann et al., 2020) on the USA; (Goss et al., 2023) on Australia; and (Baars, 2021) on global radio astronomy history from the perspective of the International Union of Radio Science (URSI).

In this Introduction, we will provide the context in which the SKA was born as a science mega-project.

## 1.1 SKA: A Global Science Mega-Project Is Born

The proposed giant step in collecting area of the SKA compared to existing national telescopes operating in the same region of the electro-magnetic spectrum immediately put it in the class of "very large project". Its size led directly to cost estimates well beyond those of any radio telescope built to that point (in 1990), costs that looked to be beyond the funding available for radio astronomy in any single nation. However, this was never seen as a problem. The telescope would be a global endeavour, building on the long tradition in radio astronomy of sharing ideas with colleagues, allowing open access to observatories by users from different institutes and countries (called "Open Skies"), and collaborating in observations involving national radio telescopes working in concert as a single telescope spanning the world

---

[1] World War II (WW II) radar developments in Australia and the UK led to the emergence of radio astronomy in Sydney (Goss et al., 2023) and in Cambridge (Edge & Mulkay, 1976). It is also worth noting that after WW II, several radio telescopes in the USA (Haystack, Naval Research Laboratory and Arecibo) were justified on military grounds while, in the UK, Cold-War tensions helped solve the financial problems surrounding the construction of the Mk I Telescope at Jodrell Bank Observatory (see Kellermann & Bouton, 2023—Chap. 11). Similar justifications were applied to radio telescope funding in the Soviet Union (see Sect. 2.4.1.4).

(Very-Long-Baseline Interferometry, VLBI). The scale of the project dictated that in addition to a strong science case, innovative technologies would need to be developed to keep costs down, and national and international sources of design and construction funds would need to be sought. As the project progressed, its large scale brought science and governmental political aspects to the fore including its long-term governance structure, the location of the telescope itself and its headquarters, and the accommodation of differing national motivations for joining the project including the engagement of industry. In addition, the political, sociological and cultural differences across the global partnership were not always as easy to accommodate in more formal structures as had been the case in earlier simpler projects. We trace the paths taken in solving these many concurrent issues as well as the successes and failures along the way and reflect on SKA as an enterprise through the lens of hindsight.

## 1.2 The Initial Motivation for the SKA

### *1.2.1 Science Drivers*

The SKA was initially conceived as an interferometer array providing a major advance in sensitivity of nearly a factor of 100 compared with the world's most powerful radio telescope at the time, the Very Large Array (VLA) in New Mexico. Driving this desire for a very large collecting area was the goal of detecting the very faint neutral hydrogen emission in distant galaxies using the 21 cm spectral line (see Chaps. 2 and 5). Hydrogen is the most abundant element and its study is fundamental to our understanding of the formation and evolution of galaxies and their large-scale structure in the early universe. The large increase in sensitivity was to be achieved by pushing the boundaries of instrumental parameter space via a combination of much larger collecting area and developments in technology.

### *1.2.2 Exploration of the Unknown*

In a study of scientific advances, Derek de Solla Price (1963) reached the conclusion that most advances follow laboratory experiments rather than theoretical predictions. Subsequently, Martin Harwit (1981) applied a similar analysis to astronomy and showed that most important discoveries result from technical innovation, in other words, technology leads discovery. The discoveries peak soon after new technology becomes accessible, usually within 5 years.

Throughout the history of radio astronomy new instruments utilised then state-of-the-art technologies to push the boundaries of instrumental parameter space and have made many fundamental discoveries about the universe (Sullivan, 2009; Kellermann & Bouton, 2023). The key instrumental parameters, then and now, were and remain the sensitivity set by collecting area and the system electronics, as well as the imaging quality and the frequency and time resolution.

There are many examples of unexpected discoveries from radio astronomy including Quasars, Pulsars, and the Cosmic Microwave Background. These are summarised in a book on the discoveries in radio astronomy called "Star Noise" (Kellermann & Bouton, 2023). They note that in almost all cases, the discovery had not been predicted before the observations. This has been called the "discovery of the unknown" and has been a key component of the science case for the SKA from its inception, illustrating the importance attached to 'blue-sky' research. It reflects the fact that a very large fraction of the discoveries made by radio telescopes were not anticipated at the time when the telescope construction was funded. The prominence given to this point by the SKA was not always seen by funding agencies and peer-review committees as being as strong an argument in justifying the expense of a science mega-project as having a set of key science projects with quantified improvements in performance supported as being important by a large fraction of the science community. However, quantifying the costs and outcomes of the exploration of the unknown is not straightforward. Successful telescopes that push the state-of-the-art are built by visionaries but often for reasons that turn out to be lower scientific priorities by the time the telescope begins operation.

### *1.2.3 Exponential Growth in Sensitivity*

Between 1939[2] when Grote Reber made the first successful observations with the first purpose-built radio telescope and the early 1990s when the VLA had been in full operation for almost a decade, radio astronomy sensitivity increased by a factor of about one hundred thousand. Further upgrades to the VLA in the following decade took this increase to 1 million (see Sect. 2.2.2.3). Over the 65-year period from Reber's first telescope, sensitivity increased exponentially with a three-year doubling time. The SKA's proposed major advance in sensitivity by another factor of about 100 compared with the VLA in 1990 would have enabled it to stay on the same exponential curve for sensitivity assuming the telescope was operational by 2015 (see Fig. 1.1).

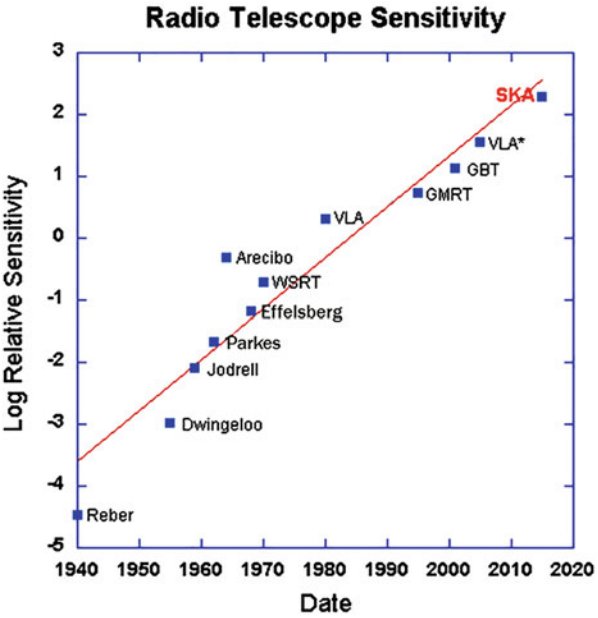
## 1.3 How to Achieve the Sensitivity

Such a 100-fold increase in sensitivity would also be a significant step forward in capability and potential for discovery compared with the state of the art, as would be expected for such an expensive project. The increased sensitivity was to come from a

---

[2] See Chap. 1 in Kellermann et al. (2020).

**Fig. 1.1** A log-linear plot made in 2001 showing the relative sensitivity as a function of year for a selection of radio telescopes. Boxes indicate the sensitivity attained when the systems were first commissioned. Acronyms: WSRT—Westerbork Synthesis Radio Telescope; VLA—Very Large Array, VLA*—Extended VLA upgrade; GMRT—Giant Metre-wave Radio Telescope; and GBT—Green Bank Telescope. The SKA point was the expectation at the time when the plot was first made in 2001



combination of greatly increased collecting area (from 13,000 to 1 million square metres) and the exploitation of developments in low-noise wide-bandwidth detector technology. Innovation in all areas was thought to be the key factor in continuing the sensitivity increase (see Fig. 1.1). This exponential improvement in sensitivity would follow the experience in high energy physics with accelerator beam energies. Starting in 1930, each new particle accelerator technology provided exponential growth in energy and reduced unit costs up to a ceiling when the technology capability saturated, and a new technology emerged. The envelope of the exponential curves for each technology is also an exponential, and these are known as Livingston Curves.[3] A factor of $10^{10}$ increase in energy was achieved in the 60 years to 1990 and the exponential envelope continued until the Large Hadron Collider became operational around 2010, after which it became impossible to sustain this rate of growth with the current technology (Riesselmann, 2009). The evolution of radio astronomy sensitivity is also a form of Livingston Curve. We return to the subject of innovation in the SKA in Sect. 11.4.3.

Two major classes of radio telescope emerged early on to exploit various combinations of these parameters. These were *single dishes* and *arrays* of dishes. As shown in Fig. 1.1, radio telescope sensitivity grew dramatically over time, initially as the collecting area of single dishes became much larger with increasing dish diameter. But by 1970 dish size reached a limit set by the effects of earth's gravity, and single dishes were succeeded by the coherent combination of many

---

[3] See hba.skao.int/SKASUP1-1, *Exponential Growth and the Livingston Curves.*

smaller dishes that use aperture synthesis or beam-forming techniques[4] to create a telescope whose total collecting area can be much larger than a single dish. The much larger array sizes possible also allowed much higher angular resolution than afforded by a single dish. In subsequent decades the number and size of elements in arrays also became larger, improving image quality as well as sensitivity. This time period also saw very substantial improvements in detector (receiver) technology which reduced instrumental noise, and in high-speed digital signal processing.

When the SKA emerged as a concept, substantially increasing the collecting area was the most obvious performance enhancement option available for a telescope whose main goal was the detection of the faint neutral hydrogen spectral line. This is why the collecting area envisaged, a square kilometre, provides the name of the telescope. In subsequent years several innovative concepts for the antenna elements were pursued in an effort to substantially reduce the cost per square metre of the collecting area. As we describe in Chap. 6, these initial options included arrays of about 50 very large diameter dishes or 3000 small diameter dishes, arrays of many tens of thousands of antenna elements fixed on the ground but steered electronically, lens antennas, and cylindrical paraboloid reflecting structures. A decision was made in 2005 on which avenues to follow and this was further refined in 2010 (see Chaps. 4 and 6). The first phase of the SKA now being built is only a tenth of the area of the original concept so cannot match the original science expectations, but the full SKA remains the long-term goal.

## 1.4 Big Science

The SKA was conceived to do “Big Science”. Derek De Solla Price (1963, 1986) introduced the terms ‘Little Science’ and ‘Big Science’ in his discussion of the pervasive presence of exponential growth in all areas of developing science. He was the first to apply quantitative measurement to the progress of science (scientometrics).

It is clear that very large-scale facilities are having an increasing impact on science. One measure of this is the award of Nobel Prizes. To demonstrate the value of large facilities in astronomy (Ekers, 2010) plotted the scale of Nobel prize winning discoveries in astronomy as a function of time (see Fig. 1.2). This provides an independent way of assessing the increasing importance of the scale of the facility used to make the discovery. Large facilities like Hubble Space Telescope and the Laser Interferometer Gravitational-Wave Observatory (LIGO) are the ones that currently dominate Nobel Prize discoveries.

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[4] This technique creates a telescope whose effective size is as large as the largest separation of individual array elements thereby increasing the angular resolution compared with a single dish. Aperture synthesis is used to create 2D spatial images while “beam-forming” is used to measure the time series for transient phenomena. See Thompson et al. (2017) and Chap. 37 in Goss et al. (2023) for the historical development of aperture synthesis.

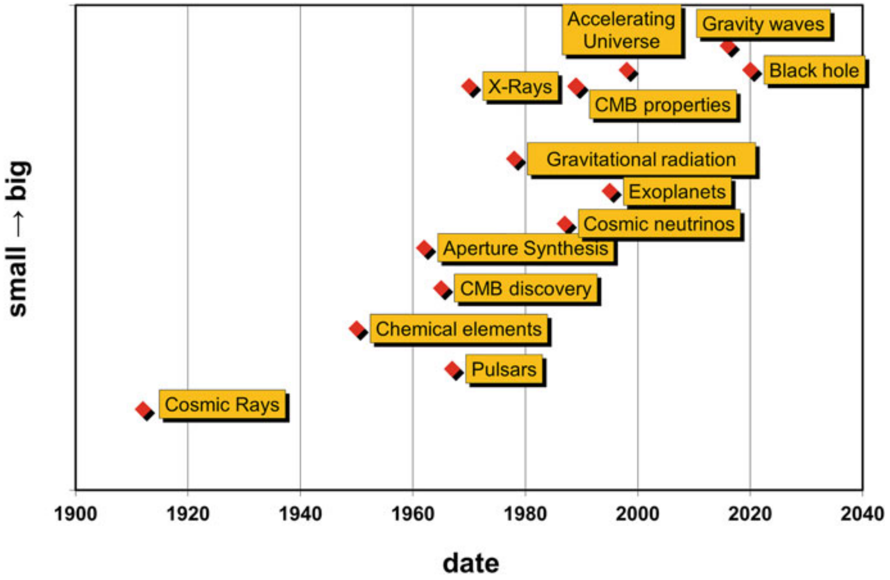

**Fig. 1.2** Scale of Nobel Prize projects in experimental astronomy as a function of discovery date. The vertical axis is a logarithmic estimate of the project scale in arbitrary units. Updated by the authors from Ekers (2010)

Innovation in technology and growth in its capabilities led to the continuous stream of new discoveries. However, exponential growth in the capability of a new technology, with "Moore's Law" as applied to semi-conductor devices as the classic example, cannot continue indefinitely and will plateau when a ceiling is reached, usually due to physical limitations, but sometimes due to finite funding or human resources. At this time either a new technology will be needed to continue the exponential and enable a new instrument or telescope, or an evolution from "little" to "big" science will be required to increase the resources to pay for increased instrument/telescope capability. This entails resources moving from local research institutes to national facilities and finally to global big science. Ekers (2010) shows how the development of astronomical facilities has followed this same trend from 'Little Science' to 'Big Science' as a field matures, but there are significant differences between the 'Big Science' culture in Physics and in Astronomy as we discuss briefly later in this Introduction.

As the scale of the projects developed to exploit the new technologies grew, the term "Mega-Science Project" was coined to categorise them. A more apt term is "Science Mega-Project" to emphasise the large-scale nature of the project required to carry out the desired science research. In recent years in astronomy, an additional descriptive term "Transformational Science" has been added to categorise what Big Science and Science Mega-Projects are expected to contribute to human understanding. A common phrase now used to promote a new, large telescope concept such as the SKA, is that it will “transform our understanding of the universe”. While such a slogan may appear trite, it does accurately capture the aspiration of such projects and their scientific user communities.

## 1.5 Complexities of Science Mega-Projects

Global science mega-projects are particularly complex to deliver, especially in cases where no single partner is dominant as is the case for SKA. They involve multiple nations and multiple players including large and small research organisations and universities, large and small industrial organisations, and governments and funding agencies, and they can involve inter-disciplinary research with different scientific requirements on the instrument. The various national and regional motivations for participating in the SKA project are discussed in Sect. 11.3.8.

Many challenges face a global science project, and in the SKA case not all the challenges were fully recognised by the early proponents. In the various countries taking part there are different funding cycles, different prior investment histories, different scientific interests, different levels of competence in technology development, different decision-making cultures, and different cultures of interaction between science and government. National and regional funding may be contingent on “juste retour/fair return” regarding industrial spin-off or location of the main or supporting facilities. Political considerations also influence some decisions on concept and location.

Holding a global collaboration together in the face of these challenges and complexity requires a clear and shared vision of the final goal, and good governance. While scientific questions are borderless, funding and legal frameworks are not. Experience shows that a lasting collaboration is based on mutual advantage, and good governance will seek to optimise that advantage for all parties. At the project management level, leaders need to understand and respect the agendas of the individuals and institutions involved.

## 1.6 Historical Funding Environment

When proposals for future radio astronomy developments were included on the agendas of the OECD Mega Science (Global Science) Forum meetings starting in 1996, science policy advisors in a number of governments in the OECD member countries were interested in information on the global level of funding on astronomy, and in particular in radio astronomy infrastructure. This interest continued throughout the following decade.

Figure 1.3 was compiled in 2005 to illustrate the capital funding levels for all ground- and space-based research facilities in astronomy. This does not include any estimate of the total funding support for research in astronomy, merely the

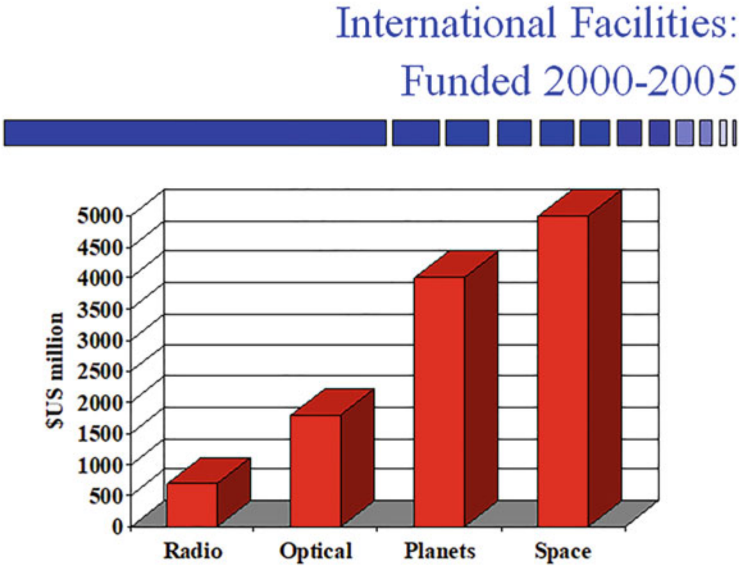

**Fig. 1.3** The international funding environment for astronomy facilities from 2000–2005

investment in infrastructure. For the space-based category the funding is divided into the two distinctly different components, one focussing on exploration of the planets in the solar system, the other on observations of objects outside the solar system at wavelengths not accessible from Earth (X-ray, ultraviolet and infra-red). By 2020 funding commitments over the previous 15 years for the construction of the SKA Precursor and Pathfinder telescopes and the first phase of the SKA was roughly about €1.5 billion (in 2005 units). This indicates a fairly flat funding rate over the past two decades of about €100 million per year.

## 1.7 The Culture of Radio Astronomy

Astronomy is a technique-oriented observational science. (Sullivan, 2009) in Chap. 17.4 discusses the significance of this distinction and calls radio astronomy a "techno-science".

Astronomers cannot, in general, carry out experiments following the traditional scientific method. There is only one universe to observe. They can only observe it, and then interpret these observations, using a variety of instruments at 'observatories'; these often have longer lifetimes than the individual instruments they host. We return to the observatory concept in Sect. 11.6. Compared to particle physics, for example, where recent mega-science facilities are used by large teams brought together by the desire to address a small number of key questions, one of the distinguishing characteristics of the astronomy culture is that multiple groups of astronomers use flexible instruments for a diverse range of experiments. As discussed in Chap. 5 and Sect. 11.4.2, this difference generated some tension in the radio astronomy community because the notion of an SKA with a few well-defined and focussed science cases was not consistent with a more general-purpose instrument that would support a diverse range of science, including exploration of the unknown. There were also tensions arising from the engineering design compromises needed for different science cases (see Sect. 5.7).

This cultural difference with respect to high energy physics was significant, because in the minds of many governments and funders, high energy physics was the archetypal field of big science. It was seen as a natural example to follow when areas like radio astronomy moved into the same scale of investments. This difference has also impacted the way the SKA concept developed at low frequencies. The main scientific and technical driver of the low frequency component of the SKA is the detection of the Epoch of Reionisation in the early universe (see Chap. 5) which is a classic-style scientific experiment rather than being one of the programs for a low-frequency observatory. In radio astronomy, input on telescope design and data handling from collaborating organisations in many countries is taken for granted. There are even sets of observations such as those with the highest angular resolution Very Long Baseline Interferometers including the Event Horizon Telescope (see Sect. 2.3) or the International Pulsar Timing Array (Manchester, 2013) which are only possible through international collaboration among diverse groups with instruments straddling the globe. Sharing of ideas, staff exchanges, and the open skies policies mentioned below, are the norm. It was natural for the radioastronomy groups from around the world to be thinking of an international collaboration to jointly build a very large telescope like the SKA, rather than competing.

Another important aspect of the radio astronomy culture is the close interactions between scientists and engineers. These interactions were a critical element for the development of the SKA as design tradeoffs had to be made between scientific opportunities and practical solutions. This has always been part of the culture in radio astronomy which itself was born from the engineering innovations of the early pioneers.

Open access to radio astronomy facilities for scientists with good projects independent of institutional or national affiliation has always been part of the radio astronomy culture and is seen as the most effective way to make scientific progress. This concept has become known as “Open Skies” and is employed in many radio observatories around the world (see Sect. 4.2).

## 1.8 This Book

With the context sketched above in mind, subsequent chapters go on to examine the instrumental heritage of the SKA and the emergence of the SKA concept, the global collaboration and governance structures put in place during the journey from working group in 1993 to legal entity in 2011, the evolution of the science case and its presentation, the twists and turns of telescope design, the decade-long story of telescope site selection from 2001 to 2012, the two SKA headquarters selection rounds in 2007 and 2011, and efforts to engage industry in the SKA. It concludes with some thoughts on SKA as a science mega-project, reflections on key issues that arose, and decisions made.

At the time of writing (2023), a decade after the end of the period covered in this book, the first phase of SKA construction by the SKA Observatory, a new Inter-Governmental Organisation, is underway. This is the culmination of the decades of global collaboration at government, institute and personal levels on SKA research and development and planning by hundreds of scientists, engineers and administrators in many countries.

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# Chapter 2
# Large Radio Telescopes and the Emergence of the SKA, 1957–1993

## 2.1 Introduction

As Chap. 1 outlined, the SKA will be a radio interferometer with 100 times the collecting area of the Very Large Array (VLA), initially conceived as the instrumental answer to the quest to detect neutral hydrogen spectral-line emission from distant galaxies in the universe. This was the primary goal motivating the people recognised as the originators of the SKA—Govind Swarup in India, Peter Wilkinson in the UK, and Robert Braun, Ger de Bruyn and Jan Noordam in The Netherlands—to explore, independently, over a decade-long period from 1978 to 1990 very large radio telescope concepts capable of satisfying this aim. In addition to these ideas, Yuri Pariiskii and colleagues in the Soviet Union began to develop a 1 km$^2$ telescope concept in 1982 with a variety of scientific aims including neutral hydrogen. Later in the chapter, we describe how these pioneering ideas were developed, how they first came to the attention of an international audience in October 1990 at IAU Colloquium 131,[1] and the creation three years later in 1993 of the first formal international working group to take these ideas further.

A radio telescope with a large collecting area (where "large" is arbitrarily defined as $>$10,000 m$^2$) has a long heritage going back to at least 1957 when the 600-foot (183 m) diameter Sugar Grove antenna was proposed and funding secured through the US Naval Research Laboratory, but never finished. In the 1960s, several large collecting area telescopes *were* built including the first very large diameter dish, the Arecibo 1000-foot (305 m) fixed spherical antenna, as well as large Mills Cross-type telescopes based on long cylindrical paraboloids, and dipole arrays at low frequencies ($<$200 MHz) where larger collecting areas are much easier to design and fund compared to instruments operating at higher frequencies ($>$1 GHz). Large radio telescope construction has continued since then, at a rate of one per decade or so,

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[1] IAU Colloquium 131 on Radio Interferometry: Theory, Techniques and Applications held in Socorro, New Mexico (USA) to celebrate 10 years of operation of the Very Large Array (VLA).

R. T. Schilizzi et al., *The Square Kilometre Array*, Historical & Cultural Astronomy,
https://doi.org/10.1007/978-3-031-51374-9_2

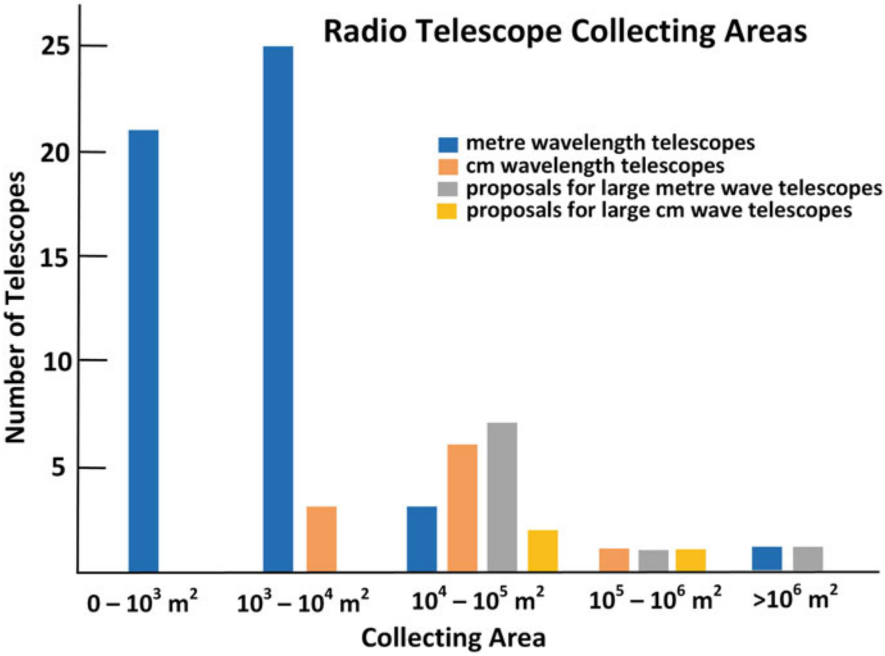

**Fig. 2.1** Histogram of the distribution of geometric collecting area radio telescopes listed in Ekers and Wilson (2013). Metre wavelength telescopes are shown in blue and centimetre wavelength telescopes in orange. Also shown are entries for large (>10,000 $m^2$) radio telescope concepts proposed but not constructed with metre wavelength telescopes in grey, and centimetre wavelength telescopes in yellow

exemplified by the Very Large Array (VLA, later the Jansky VLA) built in the 1970s in the USA, the Giant Metrewave Radio Telescope (GMRT) built in the late 1980s–1990s in India and, in the 2000–2010s, the Low Frequency Array (LOFAR) in The Netherlands and the European-US-East-Asian Atacama Large Millimetre/submillimetre Array (ALMA) in Chile.

The telescopes built by the time the SKA concept first emerged in 1990 had geometric areas ranging from a few tens of square metres to 150,000 $m^2$ (at lower frequencies). Ekers and Wilson (2013) provide a list (in their Table A2) of operational centimetre and metre wavelength telescopes (anno 2012) with diameter greater than 25 m or equivalent area. Figure 2.1 shows a histogram of the distribution of the geometric collecting area of the radio telescopes listed in Ekers and Wilson (2013). Included in Fig. 2.1 are eleven large telescopes with collecting areas >10,000 $m^2$ that were built as well as nine not included in Ekers and Wilson (2013) which were proposed but never built. One of the latter group, the Cyclops array, has an entry in two columns in Fig. 2.1 one for the 750,000 $m^2$ version and the other for the 7.5 $km^2$ version. Cyclops had a major impact on thinking about the

SKA concept. Note the entry (in blue on the right-hand side of the figure) for the first *working* square kilometre array, built in 1961–1962 by Grote Reber to operate at 2.085 MHz (see Sect. 2.2.3).

A number of these telescopes influenced the early SKA concepts in direct and indirect ways particularly the "large" (>10,000 m$^2$) telescopes and the somewhat smaller "work-horses" of radio astronomy—the 100 m diameter telescope at Effelsberg (Germany), the 100 m Richard C. Byrd III telescope at Green Bank (USA), the 76 m Lovell telescope at Jodrell Bank (UK), the 64 m Parkes dish (Australia), the RATAN-600 array (USSR), the Westerbork Radio Synthesis Telescope (The Netherlands), the Australia Telescope Compact Array, e-MERLIN (UK), the Very Long Baseline Array (USA), and the European VLBI Network. These provided hands-on experience for many of the engineers who designed the SKA and its principal Precursors and Pathfinders—MeerKAT, ASKAP, LOFAR and MWA.

In the decade leading up to the IAU Colloquium in 1990, there were thought to be several ways to create a collecting area of 1 million m$^2$ at frequencies above 300 MHz[2] including two-dimensional arrays of cylindrical paraboloids and arrays of small or large (up to 100 m diameter) parabolic dishes. Reflector arrays are preferable to a monolithic structure with a collecting area of 1 million m$^2$ even if the latter was feasible technically and from a cost point of view. The ability to spread the reflector elements out in an array of much larger dimensions than a monolithic structure provides far higher angular resolution observations. We briefly survey the concepts and constructions of arrays of cylinders and arrays of dishes in the next section to provide the context for the emergence of ideas for what became the SKA project. More comprehensive histories of many of these telescopes can be found elsewhere e.g. Leverington (2016) and Thompson et al. (2017).

One final comment in this introduction—in the early 1990s the range of SKA concepts expanded to include arrays of very large (>300 m) spherical dishes.[3] This was stimulated by the existence of many suitable geological depressions in southern China (see Sects. 3.2.6.2, 3.3.3.3, and 7.2.1) similar to the Arecibo location in Puerto Rico. As the design process for the SKA developed further in the 1990s and 2000s and the potential scientific scope expanded, several other completely new, innovative concepts for the SKA that expanded radio astronomy parameter space came into contention for the selection of the SKA "reference design" in late 2005. These were dense aperture arrays, arrays of Large Adaptive Reflectors,[4] and arrays of Luneberg Lens antennas.[5] Also in contention in 2005 were low frequency dipole arrays primarily for the detection of the Epoch of Re-ionisation in the early universe (see Sect. 5.5.20). Brief descriptions of the heritage instruments for very large diameter

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[2] 300 MHz was the lowest frequency thought feasible in 1990 for the detection of Doppler-shifted neutral hydrogen emission for distant galaxies.

[3] The large fixed spherical dish concept was pioneered by the Arecibo Telescope (see hba.skao.int/SKASUP2-1, *Other Large Radio Telescope Concepts and Constructions, 1957-1990*).

[4] See hba.skao.int/SKASUP6-28, The Large Adaptive Reflector (LAR).

[5] See hba.skao.int/SKASUP6-30, Luneburg Lenses.

**Fig. 2.2** Sketch of an array of parabolic cylinders, 900 m × 900 m, with a collecting area of ~0.8 $km^2$ (Credit: Bracewell et al. (1962), reproduced with permission of Springer Nature)

(parabolic and spherical) dish arrays and dipole arrays are given in on-line supplementary material.[6]

## 2.2 Cylinder and Dish Array Concepts and Constructions: The SKA Instrumental Heritage in 1990

### *2.2.1 Parabolic Cylinder Arrays*

Large collecting area parabolic cylinder arrays were in contention for the SKA antenna element design down select in 2005. Here we describe the extensive heritage of this concept.

#### 2.2.1.1 A Concept Array of Parabolic Cylinders, 1962

Bracewell et al. (1962) published a paper on “Future large telescopes” in which they described an array of parabolic cylinders arranged like a square venetian blind with dimensions of 900 m × 900 m and a collecting area of about 800,000 $m^2$ (see Fig. 2.2). The large area cylinder concept was a natural extension of the earlier work by Bernard Mills (see below) but the Nature paper was not a proposal for a specific project and was never funded as such. Bracewell et al. contended this would be a more feasible way than large dishes to achieve a goal set by a US National Science Foundation Panel on Radio Telescopes (Keller, 1961) of 1 arcminute angular resolution at an observing wavelength of 21 cm thereby enabling studies of cosmology and the evolution of galaxies. However much smaller arrays of cylinders arranged like the Bracewell et al. concept were built as the north-south arm of the

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[6] See hba.skao.int/SKASUP2-1, *Other Large Radio Telescope Concepts and Constructions, 1957-1990.*

**Fig. 2.3** **Left**: Aerial view of the Molonglo Cross Radio Telescope. The more visible arm in the picture is the 1.6 km east-west arm which intersects the north-south arm, also 1.6 km long, in the centre of the picture. (Courtesy of the University of Sydney Archives). **Right**: Aerial view of the Northern Cross Radio Telescope at Medicina comprising a single cylinder E-W arm 564 m long in the background, and a 640 m long array of 64 shorter cylinders as the N-S arm in the foreground. (Courtesy of INAF-Institute of Radio Astronomy)

Northern Cross Telescope, Italy (see below), and as the Canadian Hydrogen Intensity Mapping Experiment (CHIME).[7]

#### 2.2.1.2 Molonglo Cross Radio Telescope, Australia (Operational 1965–2023)

The Molonglo Cross Radio Telescope, a one by two cylinder array in a cross configuration, located at Bungendore, New South Wales (near Canberra), Australia, was proposed by Bernard Mills (University of Sydney) in 1960 and received seed funding the same year from the University of Sydney and from the US National Science Foundation in 1962 and 1964 (McAdam, 2008). At the time these were the largest grants made by the NSF to any science project outside the USA. It came into operation in 1965. The cross concept was conceived by Mills in 1953 while at CSIRO in Australia and earlier versions were built at Potts Hill and Fleurs near Sydney. The Molonglo Cross was formed by two intersecting 778 m × 12 m parabolic cylinders (see Fig. 2.3 left), one a fixed continuous structure north-south that could be steered electronically and separated east and west arms that were steered by mechanical rotation around their long axis. The total collecting area was 19,000 $m^2$ and the telescope operated at 408 MHz. For the first 11 years of operation, the primary scientific goals were all-sky surveys and searches for the then newly discovered pulsars. In 1978, it was converted to an Earth-rotation synthesis instrument at 843 MHz called MOST (Molonglo Observatory Synthesis Telescope) using the east and west arms only and a new deep survey of the whole southern sky was made. From 2013–2021 a super-computer backend was installed as part of a

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[7] Canadian Hydrogen Intensity Mapping Experiment (CHIME). https://chime-experiment.ca, accessed February 2022.

further upgrade of instrumentation for a project to detect Fast Radio Bursts. It ceased operation in 2023.

#### 2.2.1.3 Northern Cross Radio Telescope (Operational 1967)

The Northern Cross Radio Telescope, a one by sixty-four cylinder array in a cross configuration, at the Medicina Observatory near Bologna in Italy was constructed from 1960 to 1967[8] (Fig. 2.3 right). Like the Molonglo Cross, it was a meridian transit telescope but with a different configuration composed of a single cylindrical reflector 564 m × 35 m forming the east-west arm, and an array of 64 cylindrical reflectors each 23.5 m long and 8 m wide forming a north-south arm with dimensions of 640 m × 23.5 m. The total useable collecting area is 27,000 $m^2$. Also, like the Molonglo Cross in the southern hemisphere, it observed at 408 MHz and carried out high sensitivity sky surveys yielding large radio source catalogues as well as pulsar research and spectrometric studies.

The Northern Cross has undergone several major upgrades of its instrumentation over the decades; most recently, the N-S arm has been converted into a sensitive Fast Radio Burst detector.

#### 2.2.1.4 Pushchino DKR-1000, Russia (Operational 1964)

The DKR 1000 is a cross-type antenna[9] is a one by one cylinder array in a T-configuration with cylindrical parabolic E-W and N-S arms each 1000 m long by 40 m wide providing a collecting area of 70,000 m (see Fig. 2.4 left). DKR stands for Wide-band Cross-type Radio telescope (in Russian—*Diapazonnyi Krestoobraznyi Radioteleskop*). It is located at Pushchino near Moscow and was brought into operation in 1964 in the 30–120 MHz frequency range. It was originally built to carry out counts of radio sources and is now known for its work on pulsar investigations, observations of spectral radio lines corresponding to transitions between levels with high principal quantum numbers, and studies of flux density variations in radio sources.

#### 2.2.1.5 Ooty Radio Telescope, India (Operational 1970)

Govind Swarup (Tata Institute for Fundamental Research, India) followed up the Bracewell et al. (1962) Nature paper referred to above with the design and

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[8] Northern Cross Radio Telescope. https://www.med.ira.inaf.it/crocedelnord.html, accessed February 2022.

[9] DKR-1000 Cross-type Telescope. https://www.craf.eu/radio-observatories-in-europe/pushchino, accessed February 2022.

**Fig. 2.4** **Left:** The East-West arm of DKR-1000 meridian radio telescope at Pushchino Radio Observatory in Russia (Credit: Rustam Dagkesamansky). **Right:** The single cylinder Ooty Radio Telescope in India (Credit: National Centre for Radio Astrophysics, Tata Institute of Fundamental Research)

construction of the Ooty Radio Telescope (ORT) near Udhagamandalam in India (Swarup et al., 1971), a single North-South cylinder 530 m long, and 30 m wide, with collecting area 16,000 $m^2$. Explaining what he wanted to do, Swarup (2006) said "the plan was to construct a large cylindrical radio telescope on a suitably-inclined hill in southern India so as to make its axis parallel to the Earth's axis, and thus taking advantage of India's close proximity to the Equator". It is located on a hill whose natural slope, 11°, is the same as the latitude of the ORT (see Fig. 2.4 right). This makes it possible to track celestial objects for about 10 h continuously as the Earth rotates only by rotating the antenna mechanically along its long axis. As with the Molonglo Cross, the antenna beam can be steered in the north-south direction electronically. It operates at 327 MHz and is known[10] for its work on radio galaxies, quasars, supernovae, pulsars, the interstellar and interplanetary media. One of the most successful observational programs carried out for many years at Ooty was to determine the angular structures of hundreds of distant radio galaxies and quasars by the technique of lunar occultation.

### 2.2.1.6 Giant Equatorial Radio Telescope (GERT), Proposal, 1978–1983, India-Africa

In 1978, following several years of successful ORT operation, Swarup led an international African-Indian proposal for a large array of parabolic cylinders comprising one long cylinder +14 shorter cylinder segments with collecting area of ~200,000 $m^2$. This was to be located on the equator in Africa where no hill was necessary to enable simple tracking of the radio sources (Swarup, 1981). It was to be composed of one 2 km long × 50 m wide cylinder + fourteen 50 m × 15 m wide

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[10] Ooty Radio Telescope. http://rac.ncra.tifr.res.in/research, accessed on 19 October 2022.

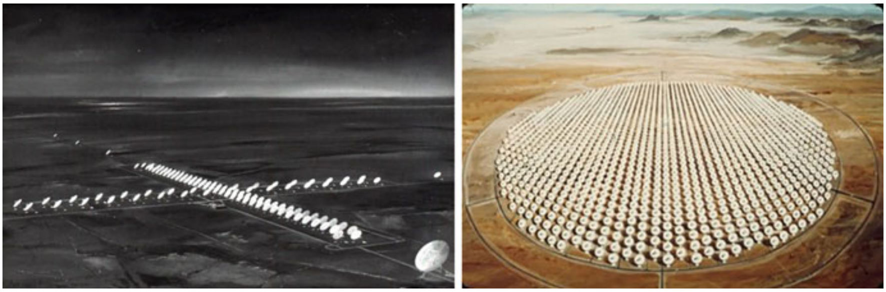

**Fig. 2.5** Artist's renditions of (*left*) the Benelux Cross Antenna (credit Herman Kleibrink, courtesy Netherlands Foundation for Research in Astronomy/ASTRON) and (*right*) the Cyclops array containing 1000 × 100 m diameter dishes (credit: Project Cyclops Report, prepared under Stanford/NASA/Ames Research Centre 1971 Summer Faculty Fellowship Program in Engineering Systems Design)

cylinder segments spread over an area of 14 × 12 km, operating at 325 and 38 MHz simultaneously. However, by the end of 1983, it was clear that GERT would not be funded and Swarup turned his attention to the GMRT, as described below.

## *2.2.2 Arrays of Dishes*

### 2.2.2.1 The Benelux Cross Project Proposal, The Netherlands - Belgium, 1958–1964

Once the 25 m Dwingeloo telescope began operation in 1957 in the Netherlands, Jan Oort (Leiden University, The Netherlands) began thinking about a large telescope project that became known as the Benelux Cross (Christiansen & Högbom, 1961). Originally an advanced version of a Mills cross antenna (Sect. 2.2.1.2), it started life with two orthogonal parabolic cylinder arms each 5 km long by 30 m wide operating at 408 MHz and sited close to the border between The Netherlands and Belgium. The collecting area would have been 300,000 $m^2$. But prompted by the initial high costs of realising this design and the advent of computers providing the possibility of a smaller dish-based interferometer that could track individual radio sources for long periods of time to compensate for lower instantaneous collecting area, the design changed from cylinders to 100 or more 30 m diameter dishes (collecting area $>$ 75,000 $m^2$, see Fig. 2.5 left,[11] (Raimond, 1996)). In addition, digital correlators had come onto the scene able to perform the pairwise combinations of the many dishes required and simulate an analogue instrument like a cylinder (W. N. Brouw, priv. comm.). The concept became a cross configuration but with

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[11] Figure 2.5 left appeared in Raimond (1996) but was probably first published by Christiansen, W. N., and Högbom, J. A., BCAP *Tech. Rep.* No. 3 (1961). The latter document is no longer extant.

1.5 km arms and operating at 1.4 GHz to allow observations of the neutral hydrogen line. In 1962, the proposal went to both governments for approval, but political complications led to The Netherlands going it alone in 1964 with a linear E-W array of twelve 25 m dishes over 1.6 km. This was the Westerbork Synthesis Radio Telescope that started operation in 1970.

#### 2.2.2.2 Project Cyclops Study, USA, 1971

In 1960, motivated by a suggestion by Cocconi and Morrison (1959) that interstellar signalling using radio might be feasible, Frank Drake (then at the National Radio Astronomy Observatory, USA) used the 85-foot telescope at Green Bank in the first attempt to detect interstellar radio signals from extra-terrestrial intelligence. His targets were two relatively nearby stars, and the frequency used was 1.4 GHz, the hydrogen line. After a decade of increasingly more sensitive, but unsuccessful, observations by Drake and collaborators, the National Aeronautics and Space Administration (NASA) commissioned a report in 1971 from an external panel led by Bernard (Barney) Oliver[12] (Hewlett-Packard Corp., USA) and John Billingham (NASA Ames Research Center, USA) to investigate what technology would be required to carry out an effective search for what Drake's experience now showed would be extremely weak radio signals if they existed at all. In their comprehensive report (NASA, 1971), the panel concluded it would be feasible to start with a 3 km diameter array of 100 × 100 m dishes (collecting area 750,000 $m^2$) operating between 1 and 3 GHz as a phased array forming a single beam (a one pixel image).[13] In the light of the large uncertainty in the average distance between 'communicative civilisations' in the galaxy, they argued for an expandable search system, growing perhaps to 1000 × 100 m dishes (see Fig. 2.5, right, collecting area 7.5 $km^2$), and only stopping once an Extra-Terrestrial Intelligence signal had been detected. The interesting concept of building a large telescope which can be incrementally expanded is possible for a radio array and this has influenced the final SKA design. This was the first proposal for a radio telescope with more than a square kilometre of collecting area at cm wavelengths. Estimated overall costs in 1971 were 6–10 billion USD. This cost tag made it impossible to fund, but its legacy influenced the SKA design requirements.

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[12] Barney Oliver (1916–1995) was Director of Research & Development at the Hewlett Packard (HP) Company from 1952–1981. He led the development of the HP hand-held calculator and was co-inventor of Pulse-code modulation (PCM), a method used to digitally represent sampled analogue signals. He became interested in SETI in 1960 when he visited Frank Drake at the NRAO Green Bank Observatory (https://www.seti.org). John Billingham (1930–2013) was Chief of the Biotechnology Division at NASA Ames Research Center and intrigued by the idea of searching for extraterrestrial intelligence. He initiated the NASA SETI program, heading that effort from its inception in the 1970s until its cancellation by Congress in 1993 (https://www.seti.org).

[13] hba.skao.int/SKAHB-1, *SKA-Early US Science Interest*, J. Tarter, presentation at SKAHistory2019 Conference, 2019.

**Fig. 2.6** The 27 antennas of the VLA in its most compact configuration (credit: US National Radio Astronomy Observatory)

Project Cyclops became well-known in radio astronomy circles, setting a benchmark for “blue-sky” thinking in terms of number of antenna elements, total collecting area and estimated cost. It influenced several key “early players” in the SKA (see “Revisiting the Project Cyclops” by Jill Tarter (SETI Institute, USA) in Ekers et al. (2002)).

#### 2.2.2.3 Very Large Array (VLA), New Mexico, USA (Operational 1980)

In 1961 in parallel with the Largest Feasible Steerable Telescope (LFST) Study,[14] NRAO scientists began to design a radio telescope that could make images with comparable angular resolution to the best optical telescopes. By 1967, NRAO submitted a proposal to the US National Science Foundation (NSF) for the construction of the Very Large Array (VLA, see Fig. 2.6). The original proposal was for 36, later 27, fully steerable 25-m diameter antennas in a “Y” configuration spread over an area 35 km in diameter. The antennas can be moved along rail tracks to form four configurations. The total collecting area was to be 13,000 m$^2$, making it the most sensitive interferometer at cm wavelengths. Intense competition for the VLA came from a Caltech proposal for an 8-element array of 130-foot dishes and the

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[14] See hba.skao.int/SKASUP2-1, Other Large Radio Telescope Concepts and Constructions, 1957–1990.

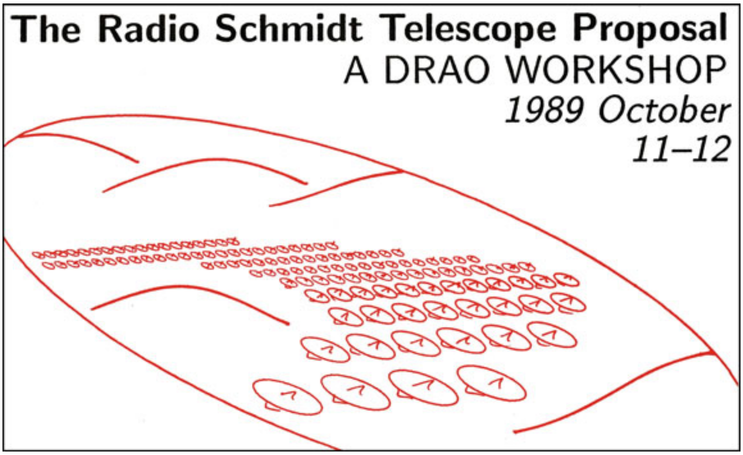

Fig. 2.7 An artist's impression of the Radio Schmidt Telescope concept

440-foot radome-enclosed antenna proposed by the North-East Radio Observatory Corporation described earlier. Eventually, support of the VLA by the 1970 National Academy Decadal Review of Astronomy led to approval of its construction; it was completed in 1980 (Kellermann et al., 2020, Chap. 8).

Once in operation, it took centre-stage in radio astronomy and has impacted most areas of astronomy and astrophysics and telescope design ever since.

#### 2.2.2.4 The Radio Schmidt Telescope Proposal, Canada, 1986–1991

The Radio Schmidt Telescope (RST), a dish array in a compact configuration covering 2 × 3 km, was conceived by Peter Dewdney during an extended visit to the VLA in 1986. It was to be a future aperture-synthesis telescope comprising 100 × 12-m antennas (collecting area 11,300 m$^2$) covering an area 2 km E-W by 3 km N-S (see Fig. 2.7), and capable of wide-field imaging of low surface-brightness, complex, extended continuum radio emission and distributed spectral line emission, at frequencies between 408 MHz and 22 GHz (Dewdney & Landecker, 1991a).

Dewdney's goal was to build a telescope with capabilities that was complementary to the VLA for low surface brightness extended radio emission particularly for the interstellar medium in our own galaxy and for neutral hydrogen (HI) in nearby spiral and irregular galaxies. The telescope would operate as a high-speed wide-field radio camera and with its high sensitivity it could observe HI in other galaxies to a modest redshift (~0.2).

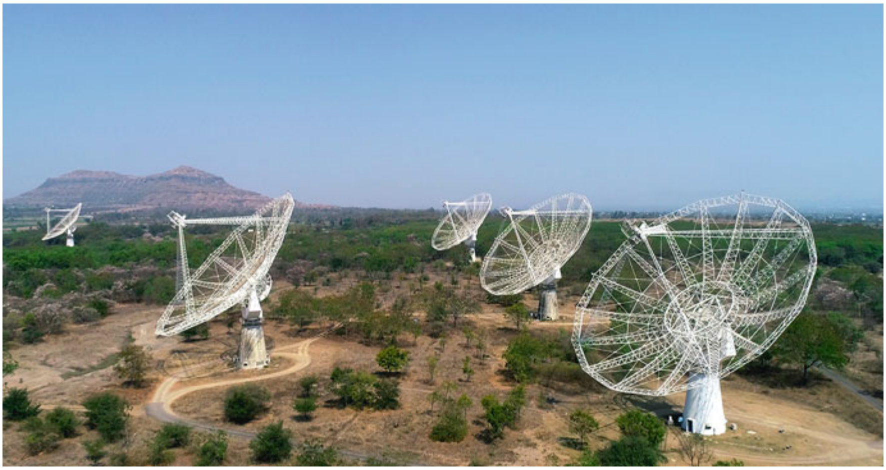

**Fig. 2.8** Part of the Giant Metre-wave Radio Telescope, near Pune, India. (Credit: National Centre for Radio Astrophysics, Tata Institute of Fundamental Research)

This was the first design study of what, later, became known as the Large Number-Small Diameter (LNSD) dish array concept now adopted for the mid-frequencies for the SKA, as we discuss in Sect. 6.4.

Despite widespread community support including an international workshop in 1989[15] as well as numerous presentations by Dewdney including one at IAU Colloquium 131 in 1990 (see below), it was "tough sledding" in Canada, and the concept did not achieve sufficient traction to be funded.

#### 2.2.2.5 Giant Metre-Wave Radio Telescope (GMRT), Pune, India (Operational 1995)

The GMRT was proposed by Govind Swarup in 1984, funded nationally in 1989, and came into operation in 1995 (Swarup et al., 1991). It has thirty 45-m diameter dishes (total collecting area ~ 50,000 $m^2$) in fixed positions in a "Y" configuration with largest separation of antennas of 25 km (Fig. 2.8). It operates at frequencies from 100 MHz to 1.42 GHz and provides sensitivity at high angular resolution as well as the ability to image radio emission from diffuse extended regions. After the recently completed upgrade (Gupta et al., 2017), the GMRT will remain the most sensitive low frequency interferometer in the world until the first phase of the SKA

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[15] hba.skao.int/SKAHB-81, *Proceedings of a Workshop on the Radio Schmidt Telescope* in 1989, Dominion Radio Astrophysical Observatory, Dewdney, P. E. F., and Landecker, T. (1991), Herzberg Institute of Astrophysics, National Research Council of Canada.

**Fig. 2.9** An aerial view of the 2 MHz array taken in 1965, showing a significant portion of the array (courtesy Estate of Grote Reber, supplied by Dr. Martin George)

comes into operation. As with its higher frequency counterpart, the VLA, the GMRT is used for the study of a wide range of astrophysical questions.

Of particular note are the low-cost antennas based on an imaginative design by Swarup and colleagues called the SMART concept—**S**tretch **M**esh **A**ttached to **R**ope **T**russes (Swarup et al., 1991). This concept returned to prominence a decade later in 2005 as one of the possible telescope designs for the SKA described in Sect. 6.4.4.3.

### 2.2.3 *The First Square Kilometre Array: Grote Reber's 2 MHz Array in Tasmania, Australia*

It is worth remembering in this historical survey that the first extremely large collecting area telescope was designed and constructed near Bothwell in Tasmania in the early 1960s by one of the pioneers of radio astronomy, Grote Reber (George et al., 2015).

Reber set up a large array of dipoles (see Fig. 2.9), and over the period 1963–1967, mapped the sky at a frequency of 2.085 MHz. The array comprised 192 wire dipole antennas suspended on wooden poles spread at regular intervals over an area of approximately 1 km × 1 km, making it a 1 $\text{km}^2$ filled aperture array (George et al., 2015).

## 2.3 Global Collaboration in Radio Astronomy Pre-SKA

Astronomy is a global science with a long tradition of inter-institute and international collaboration, particularly in radio astronomy. One of the main motivations for this was very-long-baseline interferometry (VLBI) , a technique that combines telescopes separated by hundreds to thousands to tens of thousands of km—in the case of an Earth-orbiting element—into a single instrument to achieve the highest possible angular resolution. Initial experiments in 1967 involved pairs of telescopes in the US and Canada (Kellermann et al., 2020) (Chap. 7), and in 1968 in the UK (Lovell, 1970). But this expanded in scope to trans-Atlantic experiments (US-Sweden in 1968, and US-USSR and UK-Puerto Rico[16] in 1969) and, by 1980, multi-station networks, operating part-time, had been established in the USA (1976) and in Europe (1980) making use of the existing telescopes (e.g. Thompson et al. (2017), Chap. 7 in Kellermann et al. (2020), Porcas (2010)). Trans-Atlantic networks became a regular mode of operation from the early 1980s.

Collaboration across institute and country borders lies at the heart of VLBI. In the early stages, agreements, initially at scientist level and later at institute level, were set up that enabled the required coordination to take place before and during observations. This ensured all participating telescopes observed the same point in the sky at the same time with the same band of frequencies. Operational management structures were set up to select proposals for observing time, provide the stations with detailed schedules and operational instructions for the observations, and transport the data from the telescopes to the central data processor. In addition, upgrades to VLBI-specific instrumentation at the telescopes were also carried out in a coordinated manner.

The US Network gave way to the 10-station NRAO Very Long Baseline Array (Fig. 2.10 left) in 1995 which operated mostly in self-contained mode but also in part-time network-mode with the VLA, Arecibo and Effelsberg, as well as with the European VLBI Network (EVN)). The EVN (Fig. 2.10 right) continued to grow beyond Europe to the east and west, encompassing 23 telescopes in 10 countries at the time of writing.

Other networks have been established in Australia, China, Russia, and east Asia, as well as global networks for geodetic measurements and for even higher angular resolution at millimetre wavelengths, the “Event Horizon Telescope” (EHT[17]). Radio telescopes were launched into earth orbit on two separate occasions, VSOP-HALCA (VLBI Space Observatory Program—Highly Advanced Laboratory for

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[16] Not mentioned in Chap. 1 of Thompson et al. (2017) or Chap. 7 of Kellermann et al. (2020) are two Jodrell Bank Observatory to Arecibo Observatory VLBI experiments carried out successfully in 1969 and 1970 using analogue equipment designed by Bryan Anderson. The experiments were mentioned by Lovell (1971, 1972) in annual reports on activities at the Nuffield Radio Astronomy Laboratories at Jodrell Bank, but the astronomical results were never published.

[17] The EHT became famous in 2019 for its first published image, that of the shadow of the massive black-hole at the centre of the galaxy M87 (EHTCollaboration, 2019).

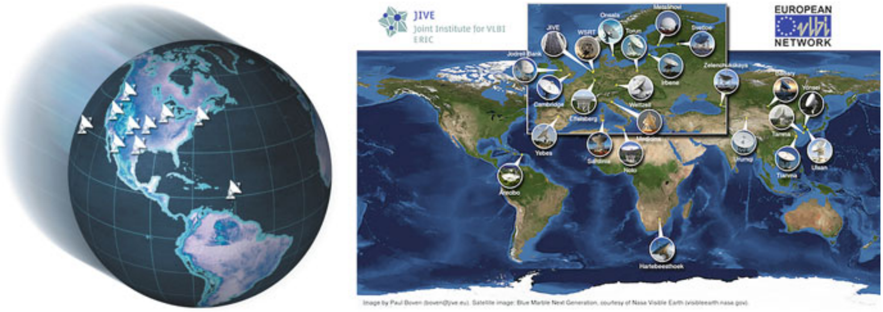

Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

**Fig. 2.10** **Left:** The US Very Long Baseline Array (credit: U.S. National Radio Astronomy Observatory). **Right:** The European VLBI Network (credit: NASA Earth Observatory, and Paul Boven, Joint Institute for VLBI-ERIC)

Communications and Astronomy) by Japan in 1997 (Hirabayashi et al., 1998), and RadioAstron by Russia in 2011 (Kardashev et al., 2011) to carry out observations together with the ground arrays to increase the angular resolution. Both these 'space-VLBI' missions had their origins in the 1980s and, in each case, were partnerships of the national space agencies and the global radio astronomy community. The HALCA-ground-based array observations were coordinated by the Global VLBI Working Group formed under the auspices of Commission J on Radio Astronomy in the International Union for Radio Science (URSI) (Gurvits et al., in preparation).

As time went on, those involved in VLBI gained an understanding of the different social and work cultures as well as the different scientific points of view in parts of the world other than their own. They also gained a belief that, with clearly stated scientific objectives and mutual benefit for all participants, supra-national projects could be undertaken successfully.

But even before the advent of VLBI, radio astronomers and engineers spent time visiting each other's institutes, observatories and engineering laboratories, to learn from, and in turn give advice to, colleagues in the general interests of advancing science. Just as importantly, astronomers from anywhere in the world could obtain observing time on any radio telescope by writing proposals in regular open competitions. This "open skies" policy is an embodiment of the collaborative spirit, and is still a common dominator in many, but not all, radio observatories.

## 2.4 The SKA: First Ideas

The preceding pages make it clear that, in the 40 years after World War II, radio astronomers had not been averse to thinking on big scales, both in terms of individual telescopes and array sizes. With VLBI, they had also made international collaboration part of their scientific way of life. Blue-sky thinking about radio astronomy instrumentation and its impact on astrophysics and cosmology was also part of the culture. Lower frequency telescopes were easier to construct, so large versions of dipole arrays[18] and parabolic cylinders saw the light of day earlier than larger dish telescopes for higher frequency work, with the exception of Arecibo. The arrival of the VLA in 1980 as the largest and most versatile dish array on the planet was a major step forward at higher frequencies, but that did not stifle continued thinking about even larger telescopes. In fact, the early ideas that eventually led to the emergence of the SKA in the early 1990s arose for the most part in the 1980s during informal coffee-time discussions at a number of institutes and observatories around the world, and developed in bursts throughout the decade, finally merging in the 1990–1993 period into the global effort to create what became the SKA.

A number of names can be associated with the crystallisation of the 1 $km^2$ collecting area concept in 1990—Govind Swarup in India, Yuri Pariiskii in the USSR, Peter Wilkinson in the UK, and Robert Braun, Ger de Bruyn and Jan Noordam in The Netherlands. Peter Dewdney in Canada led the first proposal for an array design that is now the basis of SKA-mid, but its use for a much larger collecting area than the VLA was not part of Dewdney's thinking at this time (see Sect. 2.2.2.4). For Wilkinson, Braun and Dewdney, the initial "coffee table" was located at the newly operational VLA site where visiting astronomers from around the world were assured of a receptive audience from local scientists, other visiting scientists, and the inaugural Director (one of the present authors, Ron Ekers). Wilkinson, Braun and Dewdney were at the VLA at different times, and all three came away with ideas on how to improve on what was the world's most powerful radio telescope.

In the US itself, the VLA was still too new for any energy to be spent thinking about a major upgrade, and with the Very Long Baseline Array under construction and the Atacama Large Millimetre and sub-millimetre Array (ALMA) on the horizon, no funds could be expected for the more minor VLA upgrades that were already under discussion—the short-baseline E-array to provide the low brightness sensitivity of the Radio Schmidt Telescope and the supercomputer processing capability to enable full spectral line observing.

### 2.4.1 Separate Bubbles of Activity

The early development of ideas on the SKA took place independently in India, the Soviet Union, the UK and The Netherlands, and occurred without any explicit interactions among the main players until Wilkinson (Jodrell bank Observatory, UK) and Noordam (ASTRON, The Netherlands) discussed the large collecting area concept at a coffee break during IAU Colloquium 131 held in Socorro, New Mexico

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[18] See hba.skao.int/SKASUP2-1, Other Large Radio Telescope Concepts and Constructions, 1957–1990.

**Fig. 2.11** Govind Swarup (Credit: National Centre for Radio Astrophysics, Tata Institute of Fundamental Research)

in 1990—see Sect. 2.4.2. This conversation led to Wilkinson presenting a paper on "The Hydrogen Array" (Wilkinson, 1991a, b) in the last session on future visions for radio astronomy, a paper that is generally seen as the "light bulb" moment for the SKA.

Swarup, Pariiskii (Pulkovo Observatory, USSR) and Dewdney also took part in the conference, but it appears that little specific interaction on the large collecting area topic took place with Noordam and Wilkinson. However, Ekers recalls that the talks by Wilkinson and Pariiskii were the trigger for the radio astronomy community to start thinking about a future of a next generation telescope that might even be beyond what a single nation could achieve. This laid the ground for the collective action on a global scale which began to be taken only a few months later, as we describe in Sects. 2.4.2 and 2.4.3.

In the following four sections we describe what did these individuals brought to the table in Socorro in 1990?[19]

#### 2.4.1.1 Govind Swarup, India, GERT (1978), GMRT (1984)

By the time the IAU Colloquium took place, Govind Swarup (see Fig. 2.11) had been a world leader in radio astronomy and in innovative radio telescope design for many years (Swarup, 2021). From the early 1960s, his main focus had been on the use of relatively cheap cylindrical paraboloids as a means of achieving a large collecting area (see Sect. 2.2.1). The Ooty Radio Telescope (ORT, Sect. 2.2.1.5) came into operation in 1971 as the centre-piece of Indian astronomy, and this led in

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[19] The scientific motivations are discussed in more detail in Chap. 5 on the Evolution of the SKA Science Case.

1978 to the Giant Equatorial Radio Telescope (GERT) proposal (see Sect. 2.2.1.6) for a telescope with at least ten times the collecting area of the ORT.

GERT was to be a project designed and developed by a group of “non-aligned” countries[20] led by India and envisaged not only a telescope, but also an associated new international institute (see also Orchiston & Pharkatkar, 2019). One of the key aspects of the GERT science case was the potential provided by a large collecting area for detecting neutral hydrogen in emission in the distant universe at an epoch before the formation of galaxies. This was the first formulation of what became the initial main scientific driver for the SKA.

The proposal was given support by a Resolution of the International Astronomical Union[21] and was considered for several years by UNESCO and potential funding nations until the end of 1983 when, in exasperation, Swarup radically changed the concept into what became the dish-based Giant Metre-wave Radio Telescope (see Sect. 2.2.2.5), a second nationally funded telescope for India. Swarup (priv. comm. to R. Schilizzi, see also Orchiston and Pharkatkar (2019)) tells the story that he came up with the idea of transforming GERT into the GMRT while seeing in the New Year with a shot of whisky early in the morning of 1 January 1984. The trigger was a Christmas letter from Alec Little (ex-Molonglo Telescope Director and famed instrumentalist) on his investigation of the use of optical fibre for connecting the Australia Telescope antennas. The original idea for the GMRT was 34 cylinders of ~60 m × 50 m, in a 14 km Y-shaped array connected by optical fibre. The cylinders gave way to dishes in 1986 when he conceived the SMART concept for cheap parabolic antennas. As was the case for GERT, detecting neutral hydrogen in emission in the distant universe became a key scientific driver for the GMRT.

In 1987, the GMRT was approved, and the design completed in 1989. But even in this busy period, much larger telescopes were never far from Swarup’s mind. In 1991 he published an article on a concept for a 700,000 $m^2$ telescope comprising 160 × 75 m diameter SMART dishes (Swarup, 1991b), and in 1992, he wrote a paper on the use of 1000 GMRT 45 m diameter antennas (1 million $m^2$) for SETI observations (Swarup, 1992). And in 1993 he played a key role, with Ekers, in setting the course for the global collaboration that became the SKA.

However, it was the GMRT success that he came to Socorro in 1990 to describe in his presentation at the IAU Colloquium.

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[20] The Non-Aligned Movement (NAM) is a forum of 120 developing world states that are not formally aligned with or against any major power bloc. It was formed in 1961. NAM policy on science and technology is: (i) Promotion of mutually beneficial collaboration among scientists and technologists and scientific organisations from the non-aligned and other developing countries, (ii) Establishment of links between national and regional S&T centres, and (iii) Stimulating and promoting joint R&D projects, workshops, etc. Reference: Wikipedia, and http://www.namstct.org/ (accessed February 2022).

[21] Resolution no. 2 on the Giant Equatorial Radio Telescope (GERT) at the 17th General Assembly of the International Astronomical Union, Montreal, Canada 1979, https://www.iau.org/static/resolutions/IAU1979_French.pdf

**Fig. 2.12** Peter Wilkinson (credit: Peter Wilkinson)

#### 2.4.1.2 Peter Wilkinson, UK, Hydrogen Array, 1985, 1990

Peter Wilkinson (see Fig. 2.12) was a staff member at the Jodrell Bank Observatory (JBO) when he visited Socorro and the VLA for 3 months from July to September 1984 at the end of a one-year sabbatical at NRAO as a visiting scientist. He remembers a day when Leo Blitz from UC Berkeley showed him a state-of-the-art VLA image of neutral hydrogen in the nearby galaxy M51. Wilkinson's immediate reaction was that it would be even better with ten times the angular resolution to match typical optical images. Discussing the day's highlights with his wife, Althea Wilkinson, also an astronomer, during the drive back to Socorro later that day, he came to the conclusion that the VLA collecting area needed to be 100 times larger. This would provide images of HI in other galaxies with the same sensitivity per pixel as in current observations, but with ten-times smaller sized pixels matching optical observations.[22]

**Study Group for the Priorities for Astronomy in the United Kingdom for the Period 1990–2000: The Wilkinson Note, 1985**

Wilkinson came back to this conclusion a year later in 1985 in connection with a study of the Priorities for Astronomy in the United Kingdom commissioned by the Royal Astronomical Society (RAS) and the Royal Society (RS) in 1985. The study

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[22] hba.skao.int/SKAHB-2, *What stuck in my memory…*, Peter Wilkinson, presentation at SKAHistory2019 Conference, 2019.

was chaired by the then Astronomer Royal and JBO Director, Sir Francis Graham-Smith.[23]

As input to discussions on radio astronomy priorities at Jodrell Bank, Wilkinson composed a Note on 5 July 1985 on his conclusions on a large collecting area telescope made the previous year while visiting the VLA. The two-page note was handwritten and has never been published before now.[24]

Two key passages went on to motivate thinking on the SKA in later years: (1) "The evident success of Arecibo in astronomical terms, despite its restricted pointing capability, is a testament to the fact that its collecting area is roughly ten times that of the largest steerable paraboloids. If we could construct a radio telescope with ten times larger collecting area still, we could confidently expect to garner a rich harvest of new, and unexpected, discoveries; and (2) "Its primary goal would be imaging/detecting and hence determining the velocity and column density of atomic neutral hydrogen, which comprises ~90% of the (observable) matter in the universe."

The original Note also includes annotations by Wilkinson, made during IAU Symposium 119 on Quasars in Bangalore in December 1985, following discussions with Subramaniam Ananthakrishnan from the Tata Institute for Radioastronomy about plans for the GMRT, plans that Wilkinson previously had not heard about.[25] In the annotation, Wilkinson notes that the GMRT decision to use dishes rather than cylinders ("dishes not dashes") made him realise this would be a more flexible and simpler approach for the much larger array he had in mind. This was largely because a circular beam would mean simpler software and greater ease of handling confusing sources as a function of hour angle.

The final report by the RAS-RS Study Group in November 1986 included the Large Radio Flux Collector concept in a section on lower priority projects. The wording of this entry makes it clear that elements of the submissions by Wilkinson and other Jodrell Bank staff had been taken up by the Study Group, including the goal of detecting HI in emission, the possible use of cylindrical paraboloids, and the necessity of international collaboration for a project of this size. However, the idea of the very large collecting area of 20 hectares or more was a step too far, and a figure of 'several hectares' was all that was mentioned, equivalent to the GMRT which was mentioned in the report as a similar project.

Following the lack of any support for his proposal, Wilkinson transferred his attention to the higher Jodrell Bank priority of the extension of e-MERLIN interferometer to Cambridge. It was this that he came to Socorro in October 1990 to present at IAU Colloquium 131.

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[23] For further details see hba.skao.int/SKASUP2-2. (i) *The Royal Astronomical Society—Royal Society Study Group on UK Priorities for Astronomy for 1990–2000.*

[24] See hba.skao.int/SKASUP2-2 (ii) *The Wilkinson Note and its transcription*, for the note and transcription.

[25] It is interesting to speculate whether a meeting with Govind Swarup at this time would have led to earlier more widespread recognition of the very large collecting area telescope idea.

**Fig. 2.13** Contemporaneous photographs of Robert Braun (left, credit: Robert Braun), Ger de Bruyn (centre, credit: Jan Noordam) and Jan Noordam (right, credit: Jan Noordam)

#### 2.4.1.3 Robert Braun, Ger de Bruyn and Jan Noordam, the Netherlands, Large Telescope, 1989–1993

Robert Braun (Fig. 2.13 left) was a research associate and assistant scientist at NRAO stationed at the VLA from 1985 to 1989 before moving to ASTRON in The Netherlands as a staff scientist. He went to the VLA as a newly minted PhD graduate from Leiden University with the aim of extending his work on neutral hydrogen in our Galaxy to nearby galaxies. His experience using the Westerbork Synthesis Radio Telescope (WSRT) for galactic HI had shown that a spatial resolution of a few parsecs (~10 light years) was the goal to aim for in nearby galaxies. But the VLA did not have the surface brightness sensitivity to achieve that spatial resolution goal for HI emission, even though that was possible in principle with the interferometer baselines available [R. Braun, priv. Comm.]. This was the same conclusion Wilkinson had arrived at a year earlier, although Braun was unaware of this. Braun discussed this problem with Ekers in his role as VLA Director, as a number of other HI astronomers such as Leo Blitz and Carl Heiles had done, but there was little to be done to upgrade VLA capabilities at that relatively early stage of VLA operations, as noted earlier in this section. This was due in part to computer limitations restricting the number of line channels for HI observations, which meant improvement of image processing capacity had the highest priority in NRAO. However, the lack of pressure for increasing the sensitivity from the user community as a whole was a factor. Most users were very satisfied with the vastly improved continuum sensitivity, resolutions and image quality provided by the VLA, and there was no demand for more collecting area.

When Braun returned to The Netherlands in 1989, he encountered a small group at ASTRON including Ger de Bruyn (Fig. 2.13 centre) on the astronomical side and Jan Noordam (Fig. 2.13 right) on the engineering side who were thinking, mostly during coffee breaks, about a North-South extension to the Westerbork array to improve its imaging quality. As related by Noordam (2012), Braun thought increasing the collecting area of radio telescopes, perhaps as far as a million m$^2$, was far more important than the N-S extension. It did not take long for Braun's idea to take off, underpinned by the results of a computer program for "rudimentary cosmology"

**Fig. 2.14** Yuri Pariiskii (photo taken in 1970, Credit: Pariiskii Family Archive)

written by de Bruyn that calculated the collecting area needed to detect the neutral hydrogen line in emission in distant galaxies assuming plausible masses of HI [R. Braun, priv. comm.]. This showed that 1 km$^2$ was needed for galaxies at redshifts of two. Initial thoughts on potential antenna elements for such a telescope focused on an array of a relatively small number of large diameter antenna elements.

Braun made a presentation on the Large Array in a talk on “Imaging the known universe in HI and CO” to a Dutch National Brainstorm on Radio Astronomy on 27 September 1990, just before the IAU Colloquium in Socorro the following month. [No copy of this presentation can be found.] Noordam went to the Socorro conference to present results on polarisation purity using the Westerbork Synthesis Radio Telescope, but also armed with these initial thoughts on large collecting areas in case an opportunity arose to debate them with the assembled experts on radio interferometry in Socorro. In this he was successful.

#### 2.4.1.4 Yuri Pariiskii and Large Telescope Studies in the USSR, 1960–1991

In the USSR, first discussions of a 1 million m$^2$ collecting area telescope were initiated by Semyon Khaikin and Yuri Pariiskii (Fig. 2.14) in 1960 at the Pulkovo Observatory.[26] As a first step towards this, design and construction of a novel circular parabolic telescope concept 600 m in diameter and a few thousand m$^2$ collecting area, called RATAN-600, began early in the 1960s in the Caucasus under Pariiskii’s leadership. In 1964, a Super-RATAN project was proposed, 20 km across with 2 million m$^2$ collecting area (Pariiskii, 1992). This had potential as an early-warning system for Western missiles as well as for radio astronomy

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[26] hba.skao.int/SKAHB-3, SKA behind the Iron Curtain, Gurvits, L. I., presentation at SKAHistory2019 Conference, 2019.

(L. I. Gurvits, priv. comm.) which is an interesting, but unsurprising, parallel with the US Sugar Grove 600-foot antenna, described in Kellermann et al. (2020), Chap. 9.[27] In the Super-RATAN case, astronomers were involved from the start whereas, for Sugar Grove, astronomers only became involved very late in the process.

In parallel with the Pulkovo activities in the 1960s and 1970s, other groups in the USSR in Pushchino and Kharkov took up the challenge of designing and constructing large, but not 1 km$^2$, telescopes at low frequencies, see Braude et al. (2012)—the DKR-1000 (see Sect. 2.2.1.4), BSA and UTR.[28]

By the early 1980s, these and other facilities had reached their technical limits, and in 1982 Pariiskii used the moment to initiate the formation of a Working Group on the Square Kilometre Telescope (WG-SKT) (Gurvits, 2019) under the auspices of the Radio Astronomy Council of the USSR Academy of Sciences (see Fig. 2.15). Members of the WG were drawn from the main radio astronomy institutes/observatories in the USSR in Pulkovo, Pushchino, Kharkov and Gorky.

The main science cases for the SKT included studies of the statistics of extragalactic sources (log $N$–log $S$), pulsars, and cosmological radio recombination lines. Neutral hydrogen in our own Galaxy and in other galaxies and the search for extraterrestrial intelligence were also part of the science case. The SKT was one of the national large-scale radio astronomy initiatives, alongside a space-based interferometric array and a 70-m radio telescope for dm-mm radio astronomy on the Suffa plateau in Uzbekistan, both led by Nikolai Kardashev, Pariiskii's colleague from the Space Research Institute in Moscow and a close friend since their study years at the Moscow University (Gurvits et al., in preparation).

The design of the SKT drew on the experience forged in the earlier telescopes as well as other non-astronomical installations such as low frequency phased arrays for over the horizon radar reception, and mid-frequency Luneburg lenses. (The latter re-emerged in the early 2000s as one of the contenders for the SKA reception element.[29]) The most important output from the WG-SKT was a Council of Radio Astronomy White Paper in 1986 entitled "Radio Astronomy Aperture System for Metre Wavelengths: Design Study Notes" authored by Valery Bovkun et al. (in Russian) at the Radio Astronomical Institute in Kharkov. This described a 1 km$^2$ telescope operating from 30 to 330 MHz whose elements were somewhat similar to the present SKA-Low design and the Giant Ukrainian Radio Telescope (GURT, see Konovalenko et al. (2016)). At the time of writing, the GURT is in operation near Kharkiv as an extension to the UTR-2 telescope.

In 1990, at the 22nd and the last "All-Union" conference on Radio Telescopes and Interferometers in Yerevan, Armenia, three of the four groups represented in the

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[27] See also hba.skao.int/SKASUP2-1, Other Large Radio Telescope Concepts and Constructions, 1957–1990.

[28] See hba.skao.int/SKASUP2-1, Other Large Radio Telescope Concepts and Constructions, 1957–1990.

[29] See hba.skao.int/SKASUP6-30, Luneberg Lenses.

**Fig. 2.15** Plenary session of the Radio Astronomy Council of the USSR Academy of Sciences in Pushchino, 1981. Front-row nearest the camera are: Nikolai Kardashev (astrophysicist and initiator of the RadioAstron Space VLBI mission) and Yuri Pariiskii. The astrophysicist, Iosif Shklovsky, one of the radio astronomy pioneers in the USSR, is the 3rd from the right in the second row. Both Pariiskii and Kardashev were Shklovky's students. (credit: Pushchino Radio Astronomy Observatory)

SKT-WG published a paper on the activities towards the SKT (Bovkun et al., 1990). Pariiskii and his colleagues at Pulkovo were not among the authors despite Pariiskii's leadership of the WG. According to Gurvits (2019), the Pariiskii group was more concerned with a proposal to upgrade the RATAN-600 telescope at that time. However, Pariiskii did show a diagram at the conference (Fig. 2.16) displaying the exponential increase in collecting area of radio telescopes as a function of year since 1955 and projections into the future. He concluded that it was inevitable that the largest radio telescopes would reach 1 million m$^2$ collecting area by 2000 if the trend from the first five decades of radio astronomy continued. Pariiskii also showed this diagram and related projections at the URSI General Assembly in Prague in August 1990 at the same meeting where Ekers gave a General Lecture on "The Invisible Universe" that included a plot of the evolution of radio telescope angular resolution with time and linked such plots to Livingston curves (see Sect. 1.2.3). This was based on analysis done in 1989–1990 as part of the Australian Decadal Review of Astronomy. Finally, Pariiskii showed the plot in a talk in the final session on visions for the future at IAU Colloquium 131 two months later in Socorro, the same session where Peter Wilkinson presented ideas on a 1 km$^2$ Hydrogen Array. However, no mention of the SKT project was made in either of Pariiskii's talks in Prague or Socorro, and his IAU Colloquium talk was not published in the

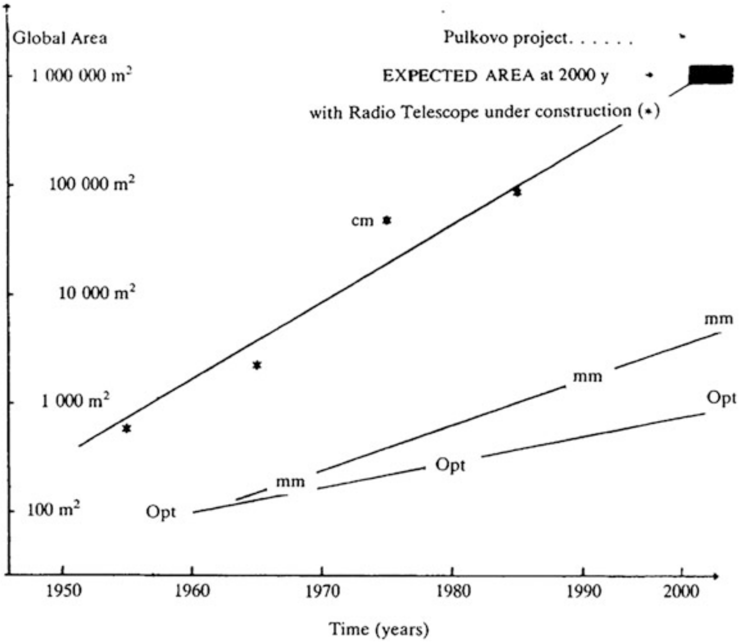

**Fig. 2.16** The figure shows the collecting area of individual radio telescopes as a function of year from 1950 to 2000 on a log-linear scale showing that the collecting area of the largest telescope constructed In 2000 could be expected to be 1 km$^2$. (Credit: Fig. 3 from Pariiskii, Y. (1992), Radio astronomy of the next century". *Astronomical and Astrophysical Tronsactions,* 1(2). 85–106. Reprinted with permission from the Eurasian Astronomical Society)

Conference Proceedings, so the rest of the world remained unaware of this long-standing intellectual effort taking place in the USSR.[30] Interestingly, VLBI observations between the US and the USSR Crimean antenna began in 1969 in the depths of the Cold War and continued with many other telescopes in global arrays throughout the period under review in this chapter, and beyond, see Kellermann et al. (2020), Chap. 7.

The non-publication of Pariiskii's paper in the IAU Colloquium Proceedings was most likely for a simpler reason, to avoid the many months of tedious paperwork required for publication in a non-Soviet journal. It was submitted in January 1991 to Astrophysical and Astronomical Transactions: the Journal of the Soviet Astronomical Society (Pariiskii, 1992). Perhaps a more fundamental reason for Pariiskii's reticence concerning details of ongoing and future radio astronomy plans in the USSR was the prevailing political system which prevented him from talking openly

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[30] Pariiskii's avoiding mention of the SKT project may have been related to the lack of Soviet Academy support for updated versions of the Super-RATAN concept and consequent reduction in his personal interest in the SKT.

to western colleagues on this topic, and so avoid drawing outside attention to the potential for application of radio astronomy techniques and technology for other (military) objectives (L. I. Gurvits, priv. comm.).

The final activity related to the SKT project was a wide-ranging discussion of its SKT science case led by Pariiskii and Gurvits (then at the Space Research Institute, USSR) at the last "All-Union" Radio Astronomy Conference ever held, in Ashkhabad (Turkmenistan) in September 1991, and plans were laid for a focused SKT conference in 1993. This never came to pass as scientific activity slowed down considerably post-1991 following the dissolution of the Soviet Union, and the SKT did not regain any of the momentum it once had.

### 2.4.2 Lighting the SKA Torch in October 1990: IAU Colloquium 131 on Radio-Interferometry—Theory, Techniques and Applications

The first decade of VLA operation firmly established it as one of the key instruments for world astronomy. Its state-of-the-art engineering as well as its "open skies" policy of selecting the best proposals for observing time no matter where they originated, contributed to its success. The IAU Colloquium was held to celebrate the first 10 years of VLA operation and to show-case the astronomy results and the technical developments making them possible. A substantial number of papers in the formal program were on new concepts for telescopes and techniques or major upgrades of existing telescopes, including those by Govind Swarup on GMRT (Swarup, 1991b), Peter Dewdney on the Radio Schmidt Telescope (Dewdney & Landecker, 1991b), Peter Wilkinson on Phase 2 of the Jodrell Bank MERLIN interferometer (Wilkinson, 1991b), and Jan Noordam on High Accuracy Polarisation Measurements with the WSRT (Noordam, 1991).

At the meeting, there was a general feeling of great satisfaction with the progress made in radio interferometry over the previous 10 years, both in terms of the science and the development of new software and hardware techniques. There was no shortage of ideas for the new projects for the next decade. As noted above, only Jan Noordam and Yuri Pariiskii came armed with even more innovative ideas than those on the conference program. Noordam (2012) describes the meeting, somewhat tongue-in-cheek, as "suitably self-congratulatory", but he felt there was a "hovering consensus that, after a dizzy ride, the heyday of radio astronomy was more or less over, and the next great strides would be made in other wavelength areas." Whether that was a view widely-held at the conference is unlikely in the light of subsequent developments in the discipline, but it galvanised Noordam to float the recent ASTRON ideas on large collecting area telescopes to various people at the meeting.

In Peter Wilkinson he found a very positive reception,[31] over the inevitable cup of coffee. As Wilkinson describes it, being in Socorro again had brought back his earlier thoughts on the need for 100 times the VLA collecting area especially for HI imaging in distant galaxies, but it needed Noordam's prodding to bring that to the fore. They approached Ekers and the other coordinators of the conference to include a talk by Wilkinson in the final special session on the future of radio astronomy at the end of the meeting. On the basis of Pariiskii's URSI General Assembly talk 2 months before, Ekers also invited him to make a presentation in the session.

A few handwritten plastic overhead sheets sufficed for Wilkinson to lay out the general idea for "The Hydrogen Array". As recalled by Bryan Gaensler (2012), then a final-year high-school student in Sydney but 17 years later SKA Project Scientist, Wilkinson's first words were 'The time is ripe for planning an array with a collecting area of 1 km$^2$'. In the published paper (Wilkinson, 1991a), Wilkinson sketched possible scientific goals, foremost of these being neutral hydrogen imaging, and various technical considerations. On the scientific goals, he came up with a memorable statement:

> The first task is to establish a clear set of goals. To my mind one goal stands out—a volume of the 'Encylopedia of the Universe' is written in 21 cm typescript. Unfortunately the printing is rather faint and we need a large 'lens' to read the text!

On technical considerations, he suggested 100 × 113 m diameter dishes, using the GMRT SMART design as a starting point. This was reminiscent of Barney Oliver's Project Cyclops Project Cyclops of which Wilkinson was aware (priv. comm.), although no mention was made in the Proceedings paper.

His final comment was a call to interested parties to contact him so that these issues could be taken further. Only one comment after the talk was recorded in the Conference Proceedings, from Swarup, who said that the major question for such an array was to identify the outstanding science objectives since that would drive the antenna design and cost. It is worth noting that Wilkinson did not refer to his 1985 handwritten note in the Conference Proceedings since it had not been published (P. N. Wilkinson, priv. comm.)

Pariiskii presented the Livingston curve-like plots he had shown in 1990 at the "All-Union" conference on Radio Telescopes and Interferometers in Yerevan, Armenia and 2 months earlier at the URSI General Assembly in Prague (see Fig. 2.16) which were similar to those shown by Ekers in his General Lecture at the same meeting. As mentioned earlier, Pariiskii did not publish a paper in the Conference Proceedings and no questions or comments were recorded.

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[31] hba.skao.int/SKAHB-4, *The Dawn of the SKAI (a.k.a. SKA, the prequel),* J. Noordam, presentation at the SKAHistory2019 Conference, 2019.

### 2.4.3 October 1990–August 1993, Interim Activities

Following IAU Colloquium 131, no direct heed was paid to Wilkinson's call for collaboration. The time may have been ripe for a square kilometre array, but it certainly did not dominate the discussion at the Socorro meeting or internationally in the immediate years following. There was too much in the way of new and exciting data coming in from the VLA, the Australia Telescope Compact Array and VLBI, as well as other plans for new telescopes or upgrades. However, collective action on the large telescope concept did take place on a smaller scale within a few months of the Socorro meeting including publication of a number of papers.

Wilkinson published the Hydrogen Array paper in the Conference Proceedings but had no further involvement in large telescope ideas for the next 3 years as he continued working on e-MERLIN. Swarup was fully occupied with GMRT but found time to publish his Conference paper as well as papers on the International Telescope for Radio Astronomy (ITRA) and a proposal for an array of 1000 GMRT SMART antennas for the Search for Extra-Terrestrial Intelligence mentioned in Sect. 2.4.1.1. Pariiskii published his paper on "Radio Astronomy of the Next Century" in 1992 (Pariiskii, 1992), while the ASTRON group and others in The Netherlands continued to engage in thinking about antenna design for a large collecting area radio telescope and attempting to enthuse the Dutch astronomical community about the concept via presentations and proposals to national committees and an external visiting committee (the Foreign Advisors). This was the start of a decade-long dominance of the very large telescope landscape by the group at ASTRON.

In September 1991, Noordam, Braun and de Bruyn published an internal NFRA (Netherlands Foundation for Research in Astronomy) Note 585 on their thinking about large telescope concepts.[32] This summarised the case for the wider Dutch astronomy community in the following words:

> The next big step forward in radio astronomy will require a massive increase in collecting area. Ultimately, 1 km$^2$ will be needed for the imaging of individual galaxies in HI at high redshifts.

As an interim step, they proposed the EURO-16 array of 16 telescopes of 100 m diameter in The Netherlands, a maximum baseline of 15–20 km, and operating up to frequencies of 1.4 GHz to enable studies of neutral hydrogen in our own and more distant galaxies. 'EURO' stood for Early Universe Radio Observatory and was planned to carry out HI work but also studies of pulsars, variability in stars, supernova remnants and galactic nuclei, as well as non-thermal continuum emission from normal galaxies. Interesting to see in this Note is the considerable innovative thinking that had already gone into possible antenna types for the individual elements: a fixed spherical dish with movable focal point along a circular trajectory

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[32] hba.skao.int/SKAHB-5, *EURO16: Proposal for an Array of Low Cost 100 Meter Radio Telescopes,* J. E. Noordam, R. Braun and A. G. De Bruyn, Netherlands Foundation for Radio Astronomy, Internal Note 585, 1991.

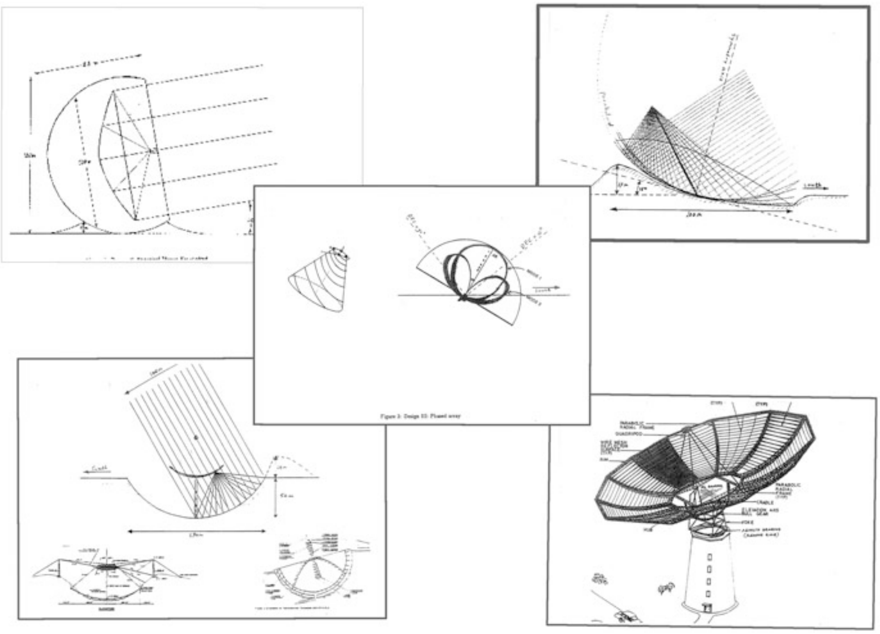

**Fig. 2.17** Compendium of possible antenna concepts for EURO-16 (Credit: Jan Noordam])

to enable source tracking; a fixed active-surface parabolic dish with a movable receiver location on a tiltable pole; a phased array; a scaled-up GMRT-type antenna; and a paraboloid suspended in a spherical shell suspended on a liquid or roller bearing and acting as an omni-directional mount (Fig. 2.17). The last of these concepts is reminiscent of the 600-foot Largest Feasible Steerable Telescope (LFST[33]). All but the LFST analogue returned later in the SKA story in one guise or another, and sometimes in combination (see Chap. 6).

An exchange of letters between de Bruyn, Braun and Noordam and Swarup in August 1991[34] shows that the Dutch contingent were eager to engage Swarup in a feasibility study of the EURO-16 concept. He in turn was interested but said he preferred 24 × 80 m SMART design antennas. In the event, the feasibility study was not pursued.

Discussion of the EURO-16 proposal in the Dutch National Brainstorm on Radio Astronomy in August 1991 and by the ASTRON Foreign Advisors in October 1991 led to "honourable mentions" in both cases. The Foreign Advisors Committee, chaired by Ekers, recommended that work should begin as soon as possible on "a

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[33] See hba.skao.int/SKASUP2-1, Other Large Radio Telescope Concepts and Constructions, 1957–1990.

[34] hba.skao.int/SKAHB-120, Letter to A.G de Bruyn, R Braun and J.E Noordam from G. Swarup, August 1991.

new large project" to follow the ongoing upgrade of the WSRT with the new multi-frequency suite of receivers. Other contenders for the new large project were a large infra-red/optical telescope, a large array operating at mm/sub-mm wavelengths and a north-south extension to the Westerbork Telescope to enable useful observations to be made in the southern hemisphere and overlap with the new ESO Very Large Telescopes (VLT) in the optical domain.

Continued discussion of these options was followed up a year later with a proposal by Ed van den Heuvel and Jan van Paradijs (University of Amsterdam, The Netherlands) for a "Square Kilometre Radio Telescope"[35] for the study of the Sun and Stars, and in May 1993 by a paper by Robert Braun on 'A concept for a new generation radio telescope for the frequency interval 150–1500'.[36] Braun's paper discussed the range of science that would be possible and also focused on a technical concept of arrays of small (6–20 m diameter) dishes configured in groups of 200–300 m diameter spread over a region 30 × 50 km. Like the Radio Schmidt telescope proposal (see Sect. 2.2.1.4) this was a forerunner of the LNSD concept later adopted for the SKA.

As described in Sect. 3.2.6.1, in 2004, under the overall leadership of the ASTRON Director, Harvey Butcher, and project leadership of Arnold van Ardenne as Head of Research and Development, ASTRON began the development of the phased array concept for the large radio telescope mentioned in the EURO-16 proposal. A year later in 1995, the Dutch Government made the first substantial grant anywhere in the world (4.5 million guilders) for innovative technology research leading to a square kilometre array. We return to the Dutch story in Sect. 3.2.6.1 on national SKA efforts around the world and their integration into the developing formal international collaboration.

From 1992 onwards, Ekers gave several presentations at national and international meetings on the future of radio astronomy with emphasis on the new technologies that could continue the exponential increase in radio telescope sensitivity over time discussed in Sect. 1.2.3. This involved new technology for signal processing and receiver sensitivity as well as a progressive increase in collecting area. However, it was an intervention by Swarup and Ekers in 1993 that set the future course of the SKA as a global radio astronomy project from the outset.

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[35] hba.skao.int/SKAHB-121, *Proposal on behalf of the Working Group on the Sun and Stars for a very large radio telescope for the study of a wide range of astrophysical problems in stellar and solar astrophysics*, van den Heuvel, E. P. J., and van Paradijs, J. A.

[36] hba.skao.int/SKAHB-122, *Concept for a next generation radio telescope for the frequency interval 150–1500 MHz,* Braun, R.

## 2.5 SKA Is Born Global, August 1993

In May 1993, the European Space Agency convened a meeting on the Frontiers of Astronomy at the European Space Technology Centre (ESTEC) with an Organising Committee chaired by Malcolm Longair, then Director of the Royal Observatory Edinburgh, and including Ekers as a member. Swarup also attended the meeting. Ekers gave a talk on future developments in radio astronomy including the planned space-borne elements, VSOP-HALCA and RadioAstron, and the benefits of a ground station with an area of a square kilometre. Swarup was keen to discuss his proposal for the International Telescope for Radio Astronomy (ITRA, (Swarup, 1991a) with Ekers and they decided that the time was indeed now ripe to start collective action to realise a large collecting area radio telescope as an international effort.

Formation of a Working Group and finding a home for it in an international entity was the obvious first step. Equally obvious was the choice of the International Union for Radio Science (URSI) as WG home since URSI had a very active Radio Astronomy Commission (J) of which Ekers was Chair, and the WG activities would fit neatly into the Commission's remit. As senior members of Commission J and URSI as a whole, both Ekers and Swarup felt it would be relatively straightforward to establish the WG at the next General Assembly of URSI in Kyoto, Japan in September 1993 to begin a worldwide effort to develop the scientific goals and technical specifications for a next generation radio observatory.

Neither Ekers nor Swarup wished to initiate the WG since their current institute activities did not allow sufficient time, and in Ekers' case, he was also conflicted by his current position as Commission J chair and his future membership of URSI's Long Range Planning Committee following the General Assembly. This led them to invite Robert Braun to prepare the case and chair the WG. At the General Assembly, all went according to plan, and the Large Telescope WG was duly formed with nine members—Robert Braun (NFRA, Netherlands, chair), Ron Ekers (CSIRO ATNF, Australia), Lloyd Higgs (DRAO, Canada), Yuri Pariiskii (SAO, Russia), Wolfgang Reich (MPIfR, Germany), Wu Shengyin (Beijing Astronomical Observatory, China), Govind Swarup (Tata Institute for Radio Astronomy, India), Dick Thompson (NRAO, USA), and Peter Wilkinson (Jodrell Bank Observatory, UK). Francois Viallefond (Meudon Observatory, France) was later added as a member. The WG remit is reproduced in Box 2.1.

Subsequent meetings of the working group provided a forum for discussing the technical research required and for mobilising a broad scientific community to cooperate in achieving this common goal.

August 1993 is regarded as the formal start of the SKA as a global project.

**Box 2.1 Remit of the URSI Large Telescope Working Group, 1993**

At the URSI General Assembly in Kyoto in September 1993, Commission J resolved to form a Large Telescope Working Group to consider:

(a) The strong scientific case for a new, internationally accessible radio telescope with one or two orders of magnitude greater sensitivity than that of any existing or planned facility;
(b) The need for innovative technical developments to realise such a facility at an affordable price;
(c) The likely need for international collaboration to allow realisation of this facility.

And resolved to appoint a working group with the following terms of reference:

(1) To explore the range of scientific problems to be addressed by the instrument.
(2) To discuss the technical specifications and general design considerations needed to maximise the scientific return of such a facility.
(3) To identify and, in so far as possible, resolve the major technical challenges to realisation of an affordable radio telescope with the required sensitivity.

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# Chapter 3
# Global Collaboration on Science and Technology, 1993–2006

## 3.1 Introduction

The long journey from concept to SKA construction can be separated into four distinct phases corresponding to an increasing level of global collaboration and sophisticated governance (Fig. 3.1).

The first is the "Grass-roots" Phase from 1993 to early 2006 that began with the International Union of Radio Science (URSI) Large Telescope Working Group (LTWG) and various national design efforts working in conjunction. A significant effort also began in the first few years to raise the profile of the SKA by embedding it within other international entities like the International Astronomical Union (IAU) and the Organisation for Economic Cooperation and Development (OECD) Megascience Forum. By 1999, interest around the world had grown to the point where a global Steering Committee was formed comprising institute directors in the collaboration who oversaw the generation of a comprehensive science case, initiated the site selection process and selected a short-list, and coordinated the development of possible design concepts. This scientist-only-led governance structure ended when the national and regional (e.g. European Commission) funding agencies collectively began to be involved in 2005.

A "Transition" Phase of governance (2006–2011) followed when three governance entities operated in conjunction—(i) the International SKA Steering Committee (ISSC), (ii) the informal group of Funding Agencies which operated under a number of names, best known of which was the Agencies SKA Group (ASG), and (iii) the SKA Preparatory Phase (PrepSKA) Board. Each had their own specific responsibilities within an envelope of common interest. The PrepSKA Board was responsible for the oversight of a €5.5 million grant from the European Commission to take the project from its conceptual state to a "signature-ready" agreement to start construction in 2011.

The third phase of governance, the "Pre-construction" Phase, followed establishment of the SKA Organisation as a UK Company at the end of 2011, with

R. T. Schilizzi et al., *The Square Kilometre Array*, Historical & Cultural Astronomy,
https://doi.org/10.1007/978-3-031-51374-9_3

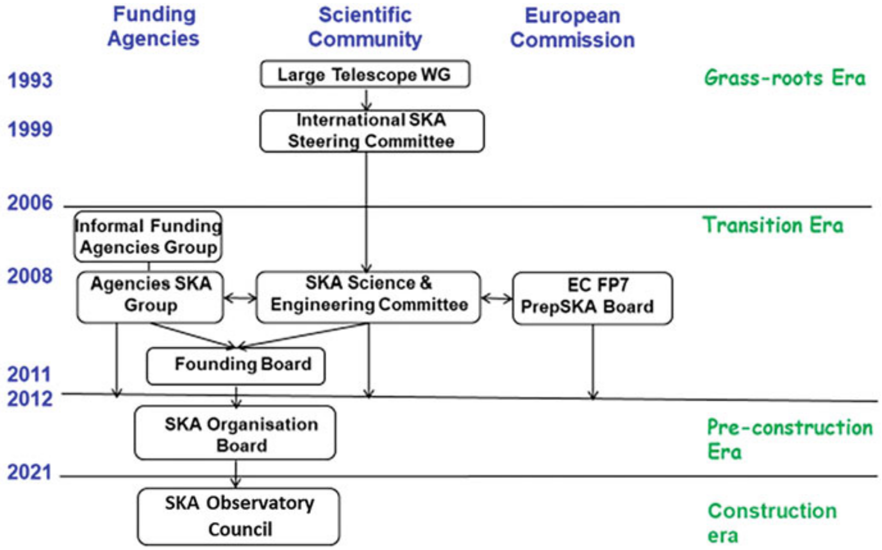

**Fig. 3.1** The evolution of SKA governance from 1993–2021. Note that the terms “Era” and “Phase” are used interchangeably in this chapter

governance solely vested in the company. Its first major decision, in mid-2012, was to decide where the SKA would be located. Subsequent activity focused on the refinement and review of the design to achieve construction readiness and solving the project and collaboration difficulties engendered by challenges to budget projections along the way.

This phase lasted until January 2021 when a new governance arrangement, an Inter-Governmental Organisation, came into force for the construction and operation of the SKA. In becoming an IGO, SKA joined other major science facilities like the European Organisation for Nuclear Research (CERN) and the European Southern Observatory (ESO) .

This and the following chapter trace the evolution of the governance structures from the first to the third phase and discuss the triggers that led to the changes. Chapter 3 also outlines the main activities and issues faced by the governing entities in the first phase, while Chap. 4 covers the same topics for the Transition Phase. The long-running story of the site selection culminating in the final site decision in the first year of the Pre-construction Phase (2012) is covered in Chaps. 7 and 8. It is beyond the scope of this history to analyse the Pre-construction Phase in its entirety from 2012–2020, or the project’s transition to a Treaty Organisation and the Construction Phase in 2021.

To provide a framework for the reader in this chapter, Table 3.1 lists the key decisions and events that characterised the 1993-early 2006 period.

**Table 3.1** Key decisions and events in the 1993–early 2006 period

| | |
|---|---|
| 1993 | URSI Large telescope WG established in August 1993. Now recognised as the formal start of SKA. |
| 1996 | First funding for innovative SKA engineering design in The Netherlands; MoU to cooperate in a technology study program leading to a future very large radio telescope (8 institutes/6 countries) |
| 1996 | First international engineering meeting in Delft, The Netherlands |
| 1999 | International SKA Steering Committee (ISSC) formed |
| 2002 | Site selection begins |
| 2003 | International SKA Project Office (ISPO) established<br>Key-science projects identified to drive engineering development |
| 2004 | ISSC decision to stage SKA construction as phase 1, phase 2 and phase 3[a] |
| 2005 | Funding agencies first discuss the SKA<br>Technology down-select, leading to the reference design for the SKA |
| 2006 | Final site selection in 2006 became site short-listing following an intervention by the Funding Agencies at their first formal meeting on SKA in February 2006 |

[a] These phases are defined in Sect. 4.5.1

## 3.2 The Global Collaboration Takes Shape, 1993–1999: The Seeds of International Collaboration Are Sown, and Major Players Begin to Emerge

The international context for the SKA created by the Large Telescope Working Group (LTWG) provided a framework within which national efforts could be accommodated. Both aspects are described in turn, with the national efforts outlined in chronological order of when the first formal steps towards a role in the SKA were taken.

### *3.2.1 URSI Large Telescope Working Group activities*

As described in Chap. 2, Govind Swarup (Tata Institute for Fundamental Research, India) and Ron Ekers proposed the establishment of a Large Telescope Working Group in 1993 under the auspices of Commission J (Radio Astronomy) of the International Union of Radio Science (URSI). Formal URSI recognition was important as it lent the still vaguely defined project the support of the technically minded members of the radio astronomy community and raised the profile and respectability for the national funding agencies and governments. The subsequent development of the Large Telescope concept through the three phases sketched in the introduction to this chapter became a permanent item on the Commission J program at the triennial General Assemblies from 1996 onwards and has remained the case at the time of writing.

The first meeting of the LTWG was held at Jodrell Bank Observatory in March 1994. The goals set out by the WG chair, Robert Braun, were ambitious—a concrete proposal supported by a well-defined scientific case for a fully specified instrument including reasonable cost estimates within the next 2–3 years.[1] WG members described national priorities and resources potentially available, from which it was clear that large capital investments in a large radio telescope were unlikely anywhere in the world on the short term due to commitments in optical and mm-sub-mm astronomical instrumentation. The most opportune time for a Large Telescope proposal in most countries appeared to be in 1996–1997. This first meeting also went through a comprehensive review of the science drivers, instrumental options and site requirements, and so laid a solid basis for further work on concept definition in the years thereafter.

A number of the subsequent meetings were of note, in particular the third meeting in Guizhou in southern China in October 1995, and the fifth meeting in Sydney, Australia in 1997. Two other brief meetings were held at the IAU General Assembly in The Hague in 1994, and at the URSI General Assembly in Lille, France in 1996.

The Guiyang conference combined an LTWG meeting and a workshop on Large Spherical Reflector Telescopes. It made the international community aware of the Chinese telescope design concept based on spherical reflectors (see later in this chapter) and its ambitions to host the Large Telescope, amply reinforced by visits to potential sites in the local region (see Fig. 7.1 left). It was the first large international meeting held in the city, and the first LTWG meeting outside Europe. Thirty Chinese astronomers and engineers and 11 international participants from seven countries (Netherlands, Canada, USA, Poland, Ukraine, France and Chinese Taipei) attended (see Fig. 3.2). Key science drivers for the SKA were again reviewed, and the technical sessions focused on design issues for the spherical reflector.

### *3.2.2 First Steps Towards Global Governance, 1994–1996*

Following the meeting in Guizhou, Ron Ekers (Director of the CSIRO Division of Radiophysics) and Harvey Butcher (Director of the Netherlands Foundation for Research in Astronomy, NFRA) took the initiative later in the year to set up an informal group of Directors of institutes that already had funding to work on SKA science and engineering issues to discuss strategic issues and coordinate efforts globally. The institutes involved were NFRA in The Netherlands, CSIRO Division of Radiophysics in Australia, National Astronomical Observatory in China, and the Herzberg Institute of Astrophysics in Canada.

In parallel, efforts in Canada in 1994 and 1995 to establish priorities for future development (see Sect. 3.2.6.4) by Peter Dewdney (DRAO, Canada) and Russ

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[1] hba.skao.int/SKAHB-123, Minutes of the 1st meeting of the LTWG, Robert Braun, March 1994.

**Fig. 3.2** Participants in the 3rd LTWG Meeting in Guiyang, China, October 1995 (Credit: National Astronomical Observatory of China)

Taylor (University of Calgary, Canada) led to an international meeting in February 1996 to discuss directions for the future of international radio astronomy in Penticton, British Columbia, hosted by the Radio Astronomy Committee of the Canadian Astronomical Society chaired by Taylor. It was clear that a number of institutes around the world were embarking on innovative research into antenna concepts for the large telescope, and that the development of such facilities in radio astronomy was beyond the capabilities of most individual countries. The value of sharing ideas through international collaboration was now the driving force for a global effort.

At the Penticton meeting, Butcher led a discussion[2] on a formal Memorandum of Agreement (MoA) to ‘Cooperate in a Technology Study Program Leading to a Future Very Large Radio Telescope’,[3] using the Joint Institute for VLBI in Europe governance as an example (see Sect. 2.3). This led to the establishment of a Working Group led by Butcher and Donald Morton (Director-General of the Herzberg Institute of Astrophysics, National Research Council of Canada) to identify appropriate procedures and identify countries to be included. The MoA was signed in August 1996 in Lille at the URSI General Assembly by the Directors of six institutes

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[2] *Notes on the February 1996 Meeting in Penticton, Canada, on Future Directions for International Radio Astronomy*, Ekers, R. D., Personal Archives.

[3] hba.skao.int/SKAHB-6, *Memorandum of an Agreement to Cooperate in a Technology Study Program Leading to a Future Very Large Radio Telescope*, 1996.

in six countries (Australia, Canada, China, Netherlands, India, and the USA), and by a further two US institutes later in the year. It was a practical decision to keep the Agreement at institute level rather than involve national funding agencies. Signatories were: the Australia Telescope National Facility (ATNF), Herzberg Institute of Astrophysics (HIA, Canada), Beijing Astronomical Observatory (BAO, China), National Centre for Radio Astrophysics (NCRA, India), Netherlands Foundation for Research in Astronomy (NFRA), SETI Institute (USA), National Astronomy and Ionospheric Centre (NAIC, Arecibo, USA), and the Ohio State University Radio Observatory (OSU, USA).

The specific goals and study program set out in the MoA (see Box 3.1) remained valid for many years, however the proposed year for completing the work (2000) proved optimistic. From this point onwards, this MoA effectively superseded the remit of the LTWG as far as technical cooperation was concerned.

**Box 3.1 Edited Excerpts from the 1996 Memorandum of Agreement to Cooperate on Technology Development for a Very Large Radio Telescope**

*Specific goals of the program*

- Select a conceptual design for a new, very large telescope by 2000.
- Define an organisational framework within which a telescope project can be carried out.

*Study Program*

- The institutes will jointly compile an inventory of the scientific case.
- Technical studies will be undertaken of antenna design and of detection strategies
- Detailed siting criteria will be formulated jointly and potential locations will be identified.
- Preliminary cost estimates for construction and operations will be developed.

*Institute programs*

- NFRA and ATNF: investigate broad band phased array antennas
- BAO and HIA: investigate designs that divide the total collecting area into several tens of large diameter element telescopes
- NCRA and SETI Institute: investigate designs that divide the total collecting area up into many (1000) small, fully steerable, parabolic dish telescopes operating at low and mid-frequencies (NCRA) and high frequencies (SETI Institute).
- NAIC: consider the constraints imposed on the technical specifications by radar studies of solar system bodies

(continued)

**Fig. 3.3** LTWG meeting in Sydney in 1997. (Credit: CSIRO Radio Astronomy Image Archive CRAIA-SKA001)

**Box 3.1** (continued)

- OSU: investigate wide-band, array designs with beams covering the entire sky simultaneously, and novel interference rejection techniques made possible by this approach.

### *3.2.3 LTWG Meeting in Sydney, December 1997*

By the time of the Sydney meeting of the LTWG at the end of 1997, the project had grown substantially with 70 participants from 10 countries (see Fig. 3.3). The format changed to include a half-day meeting of the LTWG itself, primarily on the science drivers, followed by 2 days of presentations and discussion on national progress reports and issues affecting potential engineering solutions.[4] The latter aspect of the meeting reflected the mandate of the 1996 MoU (see Box 3.1).

On the global collaboration side of things, Ekers and Butcher presented thoughts on how to organise and manage the required international collaboration, how to raise its profile via contacts with the OECD, project timescales, and financing. It was clear the Large Telescope project had attracted worldwide interest but there was no national government or existing international organisation equivalent to the European Southern Observatory to act as SKA "project champion".

Being aware of international decision-making processes such as the next US Decadal Survey in 2000 was crucial, as was the potential availability of finance for astronomy projects across the spectrum and where a large radio telescope project

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[4] *Compilation of presentations at the December 1997 LTWG meeting in Sydney*, (Ed. Brouw, W. N.), 1997, http://www.atnf.csiro.au/research/conferences/SKA1997/index.html

might fit into a phased funding process. In 1997, it looked like the optical telescopes under construction (e.g. VLT) would be ready in 2000 or so, the mm arrays in 2005, which left a window for the large radio telescope project in 2005/2006. Obvious concrete steps to take in the near term were to establish an international project definition team to document the science case, assess the feasibility and cost of design options, and define the site criteria and oversee site surveys.

An overview of conclusions from the meeting by the convenor, Wim Brouw (CSIRO Division of Radiophysics), noted that worldwide cooperation was required to implement the facility in view of its likely cost ($600 million). The extensive range of its science goals demanded a general and versatile instrument operating from 20 MHz to 20 GHz, and the complexity of the technology and software that demanded the best ideas from around the planet be applied to its design and implementation. A strong scientific case was required, as well as a well-structured cooperative arrangement. The meeting also marked the first time that a system-wide analysis of design issues was presented by Arnold van Ardenne[5] from ASTRON[6] in the Netherlands. The meeting participants addressed a recommendation to Butcher and the other institute directors who had signed the Memorandum of Understanding on Technical Cooperation a year earlier (see above) that a more formal organisation than currently provided in the MoU was required, as well as a full-time consortium secretary/project scientist and a number of technical sub-committees.

This was the last meeting of the LTWG and set the stage for the creation of the International SKA Steering Committee just over a year later in early 1999. The LTWG mandate had effectively been superseded by the 1996 MoA, which in turn was superseded by the International SKA Steering Committee in 1999.

### *3.2.4 International Science and Engineering Meetings in 1998 and 1999*

#### 3.2.4.1 Calgary, Canada, July 1998: The First SKA Science Book, and SKA Gets a Name

The SKA science case was reviewed in detail in Calgary and published as a Proceedings of the meeting[7] (see Fig. 3.4). This was the first compendium of the many research areas that SKA would enable (see Chap. 5) and was used to support

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[5] *System Integration—An Overview*, Presentation at the LTWG meeting in Sydney, van Ardenne, A., 1997. http://www.atnf.csiro.au/research/conferences/SKA1997/index.html

[6] ASTRON was the new name given to the Netherlands Foundation for Research in Astronomy (NFRA) at the end of the 1980s following a reorganisation of institutes under the umbrella of the Netherlands Organisation for Scientific Research (NWO).

[7] hba.skao.int/SKAHB-7, *Proceedings of a Conference on Science with the Square Kilometre Array held in Calgary in July 1998*, Eds. Taylor, A. R., and Braun, R., published in March 1999.

**Fig. 3.4** Three of the participants at the Calgary meeting during an excursion to Lake Louise near Banff in 1998. *Left to right:* Arnold van Ardenne, Wim Brouw, and Bernard Burke

proposals to include the large radio telescope in the Canadian Long Range Plan 2000–2010 and the US Decadal Survey for the same period.

The meeting participants agreed to adopt a single name for the project. The various prototypes under planning or construction would keep their own distinct names determined by local priorities, but it was agreed that everyone, worldwide, would use the same name in referring to the international project. A vote by those present at the meeting, and in a follow-up electronic discussion, chose the name Square Kilometre Array, SKA, over the many others that had been suggested, and used, including[8]: OSKAR, 1kT, SKAI, ITRA, KARST, SLA, VLRT, SKIRT, ARGO, NGRO, NGAT. The European spelling of “Kilometre” was adopted for the SKA.[9] For convenience in the following sections of the book, we use “SKA” as the national and international name of the Large Telescope project in the years before the formal choice in 1998.

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[8] OSKAR—One Square Kilometre ARray; 1kT—one kilometre Telescope; SKAI—Square Kilometre Array Interferometer; ITRA—International Telescope for Radio Astronomy; KARST—Kilometre-square Aperture Radio Synthesis Telescope; VLRT—Very Large Radio Telescope; SKIRT—Square Kilometre Interferometer Radio Telescope; NGRO—New Generation Radio Observatory; NGAT—New Generation Array Telescope.

[9] The fact that the acronym, SKA, was also the name given to a style of urban-pop music emanating from Jamaica was lost on most of the global radio astronomy community. Schilizzi was reminded of this connection years later in 2006 when he received a compact disc from a Luxemburg SKA Punk band, ToxKapp, obviously in search of like-minded souls.

#### 3.2.4.2 Amsterdam, March 1999, and Dwingeloo, April 1999

As the final two activities under the 1996 MoA on Coordination, two major international meetings focused on the SKA were held in The Netherlands: “Perspectives on Radio Astronomy: Science with Large Antenna Arrays”, in Amsterdam (van Haarlem, 1999) and “Perspectives on Radio Astronomy: Technologies for Large Antenna Arrays, in Dwingeloo (Smolders & van Haarlem, 1999). These two meetings had the effect of substantially raising awareness of the SKA in the wider astrophysics and astronomy and astronomical-engineering communities.

### *3.2.5 Embedding the Large Telescope Project Within Other International Entities*

#### 3.2.5.1 International Astronomical Union (IAU)

The year after establishment of the LTWG at the 1993 URSI General Assembly, discussions on Future Large-Scale Facilities (FLSF) took place at the General Assembly of the International Astronomical Union (IAU) in The Hague in 1994. Harvey Butcher, Wim Brouw and Ron Ekers organised these discussions on policy issues and specific projects with the general aim of creating interest in forming a working group to monitor progress on potential large instruments across the entire electromagnetic spectrum, and the specific aim of embedding the SKA concept in the consciousness of astronomers of all persuasions. A summary of the IAU session on Large Scale Facilities by Virginia Trimble (University of California, USA) and Ron Ekers was published in the “Sidereal Times”, a newspaper published for IAU General Assembly participants.[10] Speakers included representatives of government organisations, people operating collaborative organisations, and colleagues with plans for large scale facilities that no one country could afford. Francoise Praderie described the Mega-Science Forum (MSF) of Organisation for Economic Cooperation and Development (OECD) which had already produced one report on the future of astronomy in the industrialised nations. Following the IAU session, Butcher, Ekers, Masoto Ishiguro (Nobeyama Radio Observatory, Japan), and Praderie submitted a proposal to the IAU Executive Committee to organise a working group.[11] This was established in 1994 with Butcher as first chair. The WG provided a forum for updating the community on the various large projects at subsequent General Assemblies. Radio astronomers kept a firm grip on the management and agenda of the WG in its early years; subsequent chairs were Ron Ekers (1997–2000) and

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[10] hba.skao.int/SKAHB-8, *Summary of Meeting on Large Scale Facilities*, Trimble, V., and Ekers, R. D., Sidereal Times, No 9, p1, August 1994.

[11] hba.skao.int/SKAHB-9, *Proposal to establish an IAU Working Group on Future Large Scale Facilities*, Butcher, H., R., Ekers, R., D., Ishiguro, M., Praderie, F., 1993.

Richard Schilizzi (2000–2003). Not surprisingly, the SKA remained one of the major topics of discussion in meetings of the WG at each of the General Assemblies up to and including the 2006 Assembly in Prague. By then, the SKA was firmly embedded in the consciousness of astronomers and was beginning to make inroads on the thinking of funding agencies, as we discuss later in this chapter and in Chap. 4.

Interesting to note is that Robert Braun (LTWG chair; ASTRON, The Netherlands) gave a 10-minute talk at the first FLSF meeting in 1994 in The Hague on the “Square Kilometre Array”.[12] This marks the first time this name was used for the large telescope concept in a talk for an international audience.[13]

#### 3.2.5.2 Organisation for Economic Co-operation and Development (OECD): Mega-Science Forum/Global Science Forum

The OECD is an intergovernmental organisation that, in the 1990s, had 31 member governments from Europe, North America, Asia, Australia and New Zealand. The Mega-science Forum (MSF) was one of its committees originally formed in 1992 in the wake of the fiasco of the Superconducting Super Collider to provide a forum for funding agency officials to talk about future large projects in a timely manner, and potentially prevent projects collapsing due to, among other things, a lack of adequate internationalisation. The MSF mandate was revised significantly in 1995, with the goal to study and promote scientific collaboration and basic research in big projects, but not specific projects or specific scientific fields.

The MSF, and its successor in 1998, the Global Science Forum (GSF), played a role in SKA affairs for 15 years. The relationship began in June 1993 when Francoise Praderie, then Scientific Head of the MSF, wrote to Ron Ekers after his presentation on IMT (International Mega-Telescope) at the Frontiers of Astronomy conference a month earlier in The Netherlands,[14] the same conference at which Swarup and Ekers decided to form the URSI LTWG (see above and Sect. 2.5). Her intention was to inform Ekers of the OECD ministerial mandate to foster international cooperation in big science, and to offer help by providing framework documents for global cooperation on world-class mega-projects such as Ekers had been talking about. From this point onwards, the Large Telescope/SKA concept was included in OECD discussions on mega-projects in astronomy.

It took 3 years and a re-purposing of the MSF before radio astronomy and the Large Telescope concept took advantage of this opportunity. From Butcher and

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[12] hba.skao.int/SKAHB-10, *The Square Kilometer Array*, in a list of presentations at an IAU meeting on Future Large Scale Facilities in Astronomy, Braun, R., Sidereal Times, No 5, p 18, August 1994.

[13] The name was used a year earlier in the Netherlands during a National Brainstorm meeting on future directions for astronomy (see Sect. 3.2.6.1).

[14] hba.skao.int/SKAHB-125, Letter from Francosie Praderie to Ekers, 7 June 1993.

Ekers' point of view, the OECD and MSF opened the way to benefit from previous experience in global projects and, since the OECD operated at government level, there was the potential to create a political dimension for the project by bringing it to the attention of governments. And in the charismatic MSF/GSF Secretary-General, Stefan Michalowski, they found a willing and knowledgeable partner. Following a proposal by The Netherlands government in 1996 instigated by Butcher, the MSF convened a Working Group on Radio Astronomy (1997–1998) chaired by Butcher, which was followed by a Task Force on Radio Astronomy and the Radio Spectrum (1999–2004) chaired by Mike Goddard from the UK Radiocommunications Agency.

The Working Group meetings were attended by 35 delegates from 17 countries, each delegation including a representative from a government funding-agency and a government-designated scientist. The Working Group met on three occasions: in Paris (June and December 1997) and Washington DC (June 1998). It also co-sponsored a meeting of radio observatory directors and radio spectrum management experts during the August 1997 General Assembly of the International Astronomical Union in Kyoto. In November 1998 a report was prepared specifically for use by science policy makers which noted that "Since the signals received at [radio] telescopes are the only source of information for astronomers, terrestrial contamination of these signals is a very serious concern." More detail is given in Sect. 5.8.2.

The initial 1997–1998 project was well received by those countries with radio astronomy programs, excepting only the USA. According to Butcher,[15] this was for several reasons:

> a. The US government looked to NRAO for advice, but NRAO was looking for Millimetre Array/ALMA funding and made clear SKA was not a priority at that time.
>
> b. The post of President's Science Advisor (Director, Office of Science and Technology Policy) was effectively vacant, so there was no one to talk to at upper government level who was willing to enter into a discussion of longer-term international collaboration. That issue was felt to be essential given the 10-year window for planning in the Decadal Survey.
>
> c. The US Forum delegates made abundantly clear in informal discussions that the US would likely embrace SKA only if the US would take on the leading role in the international project. Their formal remarks made evident that they saw the scientific importance of the project, but its lack of status in the US made significant funding for development unlikely. Their words clearly signaled an intention to lobby to delay progress internationally until the project was granted real priority in the USA.
>
> d. Discussions with NASA at the level of Associate Administrator Space Science found interest in the technology because of a projected serious shortfall in Deep Space Network capability at the time. The strong involvement of the SETI Institute then was a show-stopper, however, given the US government's ban on funding for anything connected to SETI.

From 2003 onwards, the GSF began to take a pro-active role in including the SKA in meetings and discussions on future large scientific instruments. In his second month in office as SKA director in February 2003, Schilizzi gave a talk on the SKA at a workshop on Best Practices in International Scientific Cooperation in Tokyo that brought the project to the attention of a wide range of scientists and administrators. A

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[15] hba.skao.int/SKAHB-11, Email from H. R. Butcher to R. T. Schilizzi, 4 September 2018.

further three Workshops were held in 2003 and 2004 (in Munich, Washington and Chicago, see Sect. 4.3.1) that included talks on the SKA, an effort that paved the way for the further substantial funding in subsequent years described in Chap. 4.

At the Washington meeting, Michalowski suggested the OECD could set up an international, generic project office to act as banker and auditing institute and use the knowledge of the OECD to aid internationalisation of new initiatives. The thought was that the SKA could be the first client, and act as an example. This idea did not go as far as a generic project office, but it did lead to the GSF providing a temporary no-cost banking service for countries contributing to the central SKA Project Office from 2005 to 2008. At the conference on the History of the SKA held in 2019, Michalowski[16] recalled that since the International SKA Steering Committee did not have the legal status to accept funds from governments, the OECD stepped in. It was not straightforward to arrange this as "the OECD was going through one of its periodic funding crises, and the financial administrators said "Yes, we can probably do this, but we'll take a bite out of the sausage. We'll take some of that money for ourselves." He was happy to say that did not happen, and the money was transferred as instructed by the SKA central office, and at the end of the arrangement, the unspent funds went to the SKA "without a bite being taken".

Michalowski continued his involvement in SKA in meetings of the Funding Agency Working Group in 2007 and 2008 (see Chap. 4) and was also a member of the SKA Site Advisory Committee in 2011–2012 (see Chap. 8).

These contributions to SKA had the effect of raising the profile of the SKA at high political levels and are discussed both in the following section as far as Australia is concerned, and in Sect. 4.3.1.

### 3.2.6 *National SKA Activities 1993–1999*

#### 3.2.6.1 The Netherlands

Following the establishment of the LTWG in August 1993 at the URSI General Assembly, The Netherlands was first out of the blocks with a national SKA program as part of LTWG activities.

Fortuitously, a National Discussion Day on future large research infrastructures had been scheduled to take place in September 1993 to provide national decision-makers with advice on priorities and strategies. Fuelling discussion were three key input documents: (i) optical instruments for the Keck, ESO Very Large Telescope and other telescopes by George Miley (Leiden University) and colleagues, (ii) (sub)-mm wave instrumentation for the James Clerk Maxwell Telescope, Owens Valley Radio Observatory, Large Southern Array, and others by Frank Israel (Leiden

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[16] hba.skao.int/SKAHB-12, *OECD Mega-Science Forum and the SKA*, presentation at the SKAHistory2019 Conference, Michalowski, S., 2019.

University) and colleagues, and (iii) a dish-based “Square Kilometre Array” by Ed van den Heuvel (University of Amsterdam), and Harvey Butcher and Robert Braun at ASTRON.[17,18] All three possible future directions had been under discussion for several years with the university astronomers backing the optical and (sub)mm instrumentation, and ASTRON as a national research institute and centre of radio astronomy backing the large radio telescope concept. It was a period of some internal tension in Dutch astronomy, blurred somewhat by the transfer of the optical instrumentation group at the Kapteyn Observatory, previously led by Butcher, to ASTRON Headquarters in Dwingeloo, thus expanding ASTRON’s instrumental responsibilities to the optical as well as the radio.

But it was now crunch-time. A decision needed to be made.

After intensive deliberations, the ASTRON Board in October 1993 approved a Pre-Study into the feasibility of an international very large radio telescope starting in early 1994, a study that was to look into the technical and political feasibility, budget, realistic timescales, and international partners. Initially this focused on a much larger version of the EURO-16 concept of many 100 m diameter dishes,[19] but quickly moved on to phased arrays rather than dishes for their promise of a Moore’s Law-like reduction in cost per square metre of collecting area, as well as their flexibility and innovation potential. In large part, this change in direction was due to Arnold van Ardenne’s return to ASTRON from industry in September 1994 as Head of Research and Development. He had worked on phased arrays for military radar before joining ASTRON for the first time in 1975, and for sub-mm multi-beam arrays for astronomy in a joint ASTRON-Dutch Space Research Institute project in the 3 years before he left for Ericsson in 1989. But it should also be noted that Jan Noordam and Lodie Voute had also explored a “tile” concept for a large telescope as a thought experiment in an unpublished note in 1994 which led van Ardenne to adopt the “tile” nomenclature for the aggregation of aperture array elements.

A year later in 1995, the Dutch Government made the first substantial grant anywhere in the world (4.5 million guilders, USD 2.75M) for innovative technology research leading to a square kilometre array. This led to a sequence of prototype phased arrays starting with AAD (Aperture Array Demonstrator) and followed by OSMA (One Square Metre Array) and THEA (Thousand Element Array).[20]

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[17] hba.skao.int/SKAHB-13, *A Next Generation Radio Observatory: The Square KM Array*, van den Heuvel, E., Butcher, H. R., Braun, R., 1993.

[18] hba.skao.int/SKAHB-14, *Preparing for SKA*, Presentation at the SKAHistory2019 Conference, van Ardenne, A., 2019.

[19] hba.skao.int/SKAHB-15, *Euro-16: Proposal for a low-cost array of 100-m radio telescopes*, Netherlands Foundation for Radio Astronomy, Note 585, Noordam, J. E., Braun, R., and de Bruyn, A. G., 1991.

[20] hba.skao.int/SKAHB-14, *Preparing for SKA*, Presentation at the SKAHistory2019 Conference, van Ardenne, A., 2019, and Chap. 6.

An international meeting on Antennas and Architectures in September 1996 in Delft kicked off the Aperture Array project.[21] Topics covered engineering design and project definition issues. The engineering topics included beam forming and architectures, antennas and calibration, and interference rejection.

Another major Dutch initiative with substantial impact on the development of the SKA, the low-frequency array LOFAR, had its origins in this period. In 1997, George Miley, then Chair of the Leiden Observatory, observed that interest in radio astronomy in a number of Dutch universities including Leiden was beginning to wane as new opportunities in sub-millimetre and optical/infra-red astronomy were emerging, something he contended was also the case world-wide. In his view, the timescale to SKA operation was more like 2020 than the then current estimates of 2010 (Miley, 2010).

With this in mind, Miley took advantage of the opportunity afforded by a workshop at the Leiden Observatory in 1997 with the aim of brainstorming ideas for a next generation radio telescope covering a broad range of options. This had been initiated by Ron Ekers as Oort Visiting Professor at the Observatory. It was in this context that Miley advocated a low frequency array on an intermediate timescale in which the Netherlands would play a leading role.[22] This would be a way of bridging the gap to the SKA and using phased array technology already under development at ASTRON at the time (van Haarlem, 2013). This led to a proposal for a feasibility study led by ASTRON in 1998 and the creation in the following year of an international consortium involving ASTRON, the Naval Research Laboratory and Haystack Observatory in the USA, which CSIRO in Australia joined in 2002.

All three countries involved were contenders for hosting the LOFAR site. A formal site selection process completed in August 2003 ranked the sites in the following order—Australia, US, Netherlands—with all three sites regarded as viable but Australia as the best site based on its scientific and technical merits. However, later in 2003, €52M funding for LOFAR was granted in The Netherlands from a Knowledge Infrastructure Fund, ICES/KIS-3. This came with organisational boundary conditions including the expectation that part, if not all, of the resulting telescope infrastructure would be sited locally. These boundary conditions were a surprise to the international partners and led to the disintegration of the collaboration. The whole experience served as a cautionary tale for the SKA site selection process described in Chaps. 7 and 8, in particular the need for transparency among partners. It was also a lesson in the priorities of national funding agencies.

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[21] hba.skao.int/SKAHB-136, Summary of the meeting in Delft, The Netherlands, on Antennas and Architectures, September 1996.

[22] hba.skao.int/SKAHB-137, *LOFAR: Origins and Hopes*, George Miley, International SKA Forum, Assen, The Netherlands, June 2010, Proceedings of Science, http://pos.sissa.it, ISKAF2010 Science Meeting.

#### 3.2.6.2 China

In the early 1990s, the Chinese radio astronomy community was not large and the radio astronomy facilities comprised the Miyun array near Beijing, the 25 m VLBI dish near Shanghai, a 10 m dish in Yunnan, and a 14 m mm-wave telescope at Delingxa. A further 25 m dish was under construction near Urumqi. However, within 5 years of the formation of the LTWG in 1993 China had become a major player in SKA.[23] This was the result of the vision and leadership of Rendong Nan (then Large Telescope Group Leader, and later Deputy Director of the Beijing Astronomical Observatory) and Bo Peng (then Deputy Large Telescope Group Leader, later Group Leader and at the time of writing, FAST Telescope Director).

With the blessing of the “Father” of Radio Astronomy in China, Shouguan Wang, and the encouragement of Richard Strom, visiting scholar at the Beijing Astronomical Observatory (BAO) from ASTRON, Nan, Peng, Yuhai Qiu, and Shengyin Wu formed a research group at BAO in 1994 to initiate and promote the Chinese Large Telescope concept KARST (Kilometre Area Radio Synthesis Telescope)—an array of large aperture spherical antennas in Guizhou Province in southern China. An early task for Nan and Wu was to enlist the support of the Provincial Governor for a prestigious involvement in a high-profile international project. This was secured during a fine dinner.

In addition to the site investigations noted in Sect. 7.2.1, the group organised the third meeting of the LTWG and the associated Workshop on Spherical Radio Telescopes in October 1995 in Guiyang, the nearest city to the karst geological region (see Sect. 3.2.1). This was the first LTWG meeting outside Europe and helped put China firmly on the SKA map.

In 1997–1998, the FAST (Five-hundred-metre Aperture Spherical radio Telescope) concept was initiated as the KARST forerunner. Nan played the key role in directing the Chinese efforts for the SKA and then the R&D for the FAST project as Chief Scientist and Chief Engineer. At this point, Nan and Peng went public with their plans and visited the UK for a Royal Astronomical Society meeting followed by visits to Cambridge and Jodrell Bank and ASTRON in The Netherlands to establish collaborations. SKA-KARST continued to be developed as one of the options until the site short-listing process in 2006 decided in favour of Australia and South Africa (see Sects. 3.3.3.3 and 7.4).

#### 3.2.6.3 Australia

Australia had maintained a very strong national radio astronomy infrastructure since the pioneering days after World War II, so that in the early 1990s it could boast the

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[23] hba.skao.int/SKAHB-16, SKA Forerunner - *FAST,* Presentation at SKA History2019 Conference, Peng, B., 2019.

Australia Telescope National Facility, the Parkes Dish and the Molonglo Cross Radio Telescope (Sim, 2021). The SKA was seen as the next big step for Australia. Optical astronomers were also highly motivated to keep their facilities at the state of the art. The desire to present a unified front to government funding agencies led Ron Ekers and Lawrence Cram (Australian National University) to make use of the National Committee for Astronomy (NCA), the Australian Academy of Science's highest level body for astronomy, to establish an astronomy decadal review process in Australia. Both Cram and Ekers had come back to Australia from the USA and based the Australian decadal review on the very successful US model with the aim of setting priorities for future funding for both major branches of astronomy. This was carried out by the NCA chaired by Harry Hyland, which, before this, had only functioned as the corresponding body for Australian membership of the International Astronomical Union. The first report,[24] "Australian astronomy: Beyond 2000—Astronomy decadal plan, 1996-2005" issued in 1995, was submitted to the Australian Government by the Australian Research Council. It gave top priority to Australia joining the European Southern Observatory (ESO) and also endorsed a "one kilometre aperture cm-wave radio telescope (1kT)" as a future project with the "highest priority for the second half of the decade", subject to selection of a viable design. The other major recommendation for radio astronomy was the upgrade of the Australia Telescope Compact Array to mm wavelengths and participation in design studies for the 1kT. Interesting to note is that Australia did not join ESO as a full member despite negotiations that continued for quite some time but did enter into a partnership with ESO two decades later.

It did not take long for radio astronomy and the SKA to reach the highest levels in the Australian government. The trigger was a request from the OECD in 1996 for Australian government involvement in a newly created Mega-science Forum WG on Radio Astronomy proposed by Harvey Butcher via the Netherlands delegation. Martin Gallagher,[25] as Australian Science Attaché in Paris and delegate to the OECD Mega-science Forum, brought the WG to the attention of his government.

This led to CSIRO approval for site studies to commence (see Sect. 7.2.2), and for CSIRO to sign the MoA on SKA technology coordinated by Butcher in 1996 (see Sect. 3.2.2). An Australian technical workshop was held early in 1997 and research projects were identified in antenna design, radio frequency interference, signal processing, MMIC development, site investigation, and the science case. $2.4M capital investment was available for the MMIC work and Major National Research Facility (MNRF) funding of $200 k/year was obtained for strategic research. This grant was obtained jointly by the optical astronomy community for instrumental developments on large optical telescopes and the radio astronomy community for SKA related developments. In Australia the two groups adopted this joint strategy

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[24] *Australian Astronomy: Beyond 2000—Astronomy decadal plan, 1996-2005*, Hyland, H., et al., 1995, https://www.science.org.au/support/analysis/reports/ (accessed November 2022).

[25] Martin Gallagher went on to play a pivotal role in the SKA in the (Funding) Agencies for SKA Group (ASG) a decade later, as we describe in Chap. 4.

instead of being in competition in order to enhance their prospects of success against competition from other areas of science. This close cooperation did not last and returned to normal competition in future funding rounds. Also in December 1997, the 5th LTWG and 1kT (the Australian name for the SKA) technology meeting was held in Sydney (see Sect. 3.2.3).

Ekers was invited to address the Prime Minister's Science, Engineering and Innovation Council (PMSEIC) in December 1998 about radio astronomy and the Large Telescope project. He emphasised the historical development of a world-class radio astronomy infrastructure in Australia, its location in the southern hemisphere making it able to observe the Galactic Centre region for many hours a day, and good potential sites for the telescope. In his summary, the Prime Minister, John Howard, who had chaired the PMSEIC meeting, noted that "even the public seem to like astronomy".

The SKA's high political profile in Australia from the start was a major factor underpinning the concerted science, technology, and site efforts carried out in the country in subsequent decades. The project also enjoyed a high political profile in South Africa from the start of activities there in 2003, as we discuss later in this chapter.

A critical role in engaging the astronomical community in Australia was played by an advisory committee, the Australian SKA Committee (ASKAC) , established by Ekers and colleagues in 2000 under the auspices of the National Committee for Astronomy in the Academy. This functioned as the initial Australian interface to the international SKA organisation until the Australian SKA Consortium was formed in 2001.

In 2001, a mid-term review of the Decadal Plan[26] compiled by Brian Boyle (then at the Anglo-Australian Observatory) and Louise Webster (University of New South Wales, Australia) listed the SKA as equal top priority for major new international facilities with a 20% share for Australia in what was then estimated in the Decadal Plan to be a USD 500 million project. In the report, hosting the telescope was given more prominence than the science return, presumably to keep the Government interested and involved.

#### 3.2.6.4 Canada

In the early 1990s, Canadian national facilities for astronomy included the Dominion Radio Astrophysical Observatory at Penticton, British Columbia, and the James Clerk Maxwell Telescope in collaboration with the UK and The Netherlands. In addition, Canadian astronomers were major users of the NRAO 140-foot telescope and the Very Large Array in the US. It was difficult to get purely Canadian facilities

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[26] *Beyond 2000: The Way Ahead - A Mid-term Review of Australian Astronomy: Beyond 2000*, Boyle, B. J., Webster, L. et al., 2001, https://www.science.org.au/support/analysis/reports/ (accessed November 2022).

off the ground when far larger resources and facilities across the border in the US were available free of charge, which explained why Dewdney's Radio Schmidt concept (see Sect. 2.2.2.4), and a Canadian Long Baseline Array proposed by Ernie Seaquist (University of Toronto, Canada) were not successful. This was described by Russ Taylor (University of Calgary, Canada), later Executive Secretary of the International SKA Steering Committee, and SKA Project Scientist, as the US Catch-22: "If it's worth doing, why isn't the US doing it? If the US is doing it, why should we?"[27]

However, the URSI Large Telescope Working Group provided a new initiative for Canada to get behind, and Canadian astronomers, in particular Lloyd Higgs, Russ Taylor and Peter Dewdney, were involved in the LTWG from its inception in 1993. A year later in August 1994, an international meeting sponsored by the National Research Council and organised by the Radio Astronomy Committee of Canadian Astronomical Society led by Peter Dewdney and Russ Taylor (Committee Chair), was held in Penticton to explore radio astronomy science directions. A Very Large Radio Telescope and a Millimetre Array were identified as exciting directions to be working towards. This led, in early 1995, to a Planning Committee for a New National Radio Facility, chaired by Ernie Seaquist, to examine options for such a facility and make recommendations. Seaquist was a senior figure in Canadian astronomy from the University of Toronto, and later a member of the SKA Site Advisory Committee at the time of the site short-listing in 2006.

The NRC Planning Committee submitted a substantial report in December 1996 entitled "Canadian Radio Astronomy in the twenty-first Century—The Challenge" that recommended that the highest long-term priority for a "new radio astronomy facility" should be a partnership with other countries in the design, construction, and operation of the SKA. A specific recommendation was to develop a concept for a Very Large Radio Telescope first put forward by Tom Legg ((DRAO, Penticton) called the Large Adaptive Reflector (Legg, 1997). Canada's share should be $CA 50 million, starting in 2003.

This work was the opening that allowed Canada to sign the MoU to collaborate in a Technology Development Program for a Very Large Radio Telescope in August 1996 (see Sect. 3.2.2), and to obtain NRC funds for conceptual design studies of the LAR in December 1997. At the Sydney LTWG/1kT meeting that same month, Dewdney updated the participants on Canadian plans and on the LAR design work already in progress.[28]

The following year, in July 1998, Canada hosted the sixth LTWG meeting in Calgary, described earlier.

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[27] hba.skao.int/SKAHB-17, *Canada and the SKA Project, 1995-2012*, Presentation at the SKAHistory2019 Conference, Taylor, A. R., 2019.

[28] *Country Progress Report—Canada*, P. Dewdney, in Compilation of presentations at the December 1997 LTWG meeting in Sydney, (Ed. Brouw, W. N.), 1997, http://www.atnf.csiro.au/research/conferences/SKA1997/index.html

#### 3.2.6.5 USA

From the 1960s onwards, the US was a major player in radio astronomy, and with the advent of the VLA in 1980, it became *the* major player globally. The 1990s also saw completion of the construction of the Very-Long-Baseline Array, the start of construction of the Green Bank Telescope to replace the collapsed 300-foot Telescope, and the approval of the Millimetre Array (MMA), which later became a global project, ALMA, as the next large project in US astronomy (Vanden Bout, 2004). US radio astronomers and the National Radio Astronomy Observatory (NRAO) in particular had their hands full in the early 1990s.

Despite an October 1993 Note[29] on the value of exploring new technologies like fully sampled focal plane arrays for a large aperture radio telescope sent by Rick Fisher at NRAO to Robert Braun in February 1994, US participation in the LTWG was relatively low-key in the first 2 or 3 years. It was more a watching brief by LTWG member, Dick Thompson (NRAO) and others than active involvement. However, by the time of the Sydney LTWG/1kT meeting in 1997, other scientists at NRAO and US universities were contributing to discussions on the science case and telescope design constraints and specifications including a presentation by John Dreher (SETI Institute) on the cost advantage of an array comprising a large number of small diameter dishes—the LNSD concept[30] (see also Sect. 2.2.2.4). Jack Welch (University of California, Berkeley) gave a progress report from the USA.[31] By mid-1998, Dreher and colleagues had developed the basic design for the one-hectare array (1 hT) later called the Allen Telescope Array.

Ken Kellermann (NRAO) and Rick Fisher convened the first US SKA Meeting at the NRAO Green Bank Observatory, West Virginia, in October 1998 not long after the Calgary LTWG meeting. Over sixty people participated, ten of whom were international. However, there was growing grassroots discontent in the US university community with the increasing centralisation of radio astronomy in the NRAO that had caused, as collateral damage, the demise of a number of university radio observatories.[32] There was also the feeling that the universities were the places to be teaching the next generation of instrument builders and instrument users and they were not getting the support that they wanted. This resulted in a small meeting at University of California, Berkeley, shortly after the Green Bank meeting where it was decided to create an organisation, the US Square Kilometer Array Consortium,

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[29] hba.skao.int/SKAHB-18, Very Large Aperture Radio Telescope: Possible Fundamental Changes in Design, Fisher, J. R., 1993.

[30] *SETI Institute Report*, John Dreher, in Compilation of presentations at the December 1997 LTWG meeting in Sydney, (Ed. Brouw, W. N.), 1997, http://www.atnf.csiro.au/research/conferences/SKA1997/index.html

[31] *Country progress report—USA* in Compilation of presentations at the December 1997 LTWG meeting in Sydney, (Ed. Brouw, W. N.), 1997, http://www.atnf.csiro.au/research/conferences/SKA1997/index.html

[32] hba.skao.int/SKAHB-1, *SKA- Early US Science Interest*, Presentation at the SKAHistory2019 Conference, Tarter, J., 2019.

to coordinate US activity. Initially, the universities and the National Astronomy and Ionospheric Centre (NAIC) that operated the Arecibo Telescope were full members while NRAO was an at-large member. NRAO Director, Paul Vanden Bout, was concerned that National Science Foundation funds should not be used to pay for SKA Consortium subscription fees. However, it was soon realised that private funds from Associated Universities Incorporated (AUI), the legal entity operating NRAO, could be used instead, and NRAO became a full member. The Consortium was formally established in early 1999.

In the early years, interest in the Large Telescope concept in the US was driven primarily by the science and engineering challenges rather than by the international collaborative aspects, or impact on the domestic US economy, or any potential sociological or educational impacts that were later found to be important in obtaining funding in other countries. Some people saw the SKA in the US as a possibility for funding, either of their individual research activities, or institutional activities. As the project evolved, there was also an opportunity to exert leadership at all levels[33] as we describe later in this chapter.

#### 3.2.6.6 UK

Following Peter Wilkinson's seminal contribution to the creation of the SKA concept in 1990 described in Sect. 2.4.1.2, the UK's involvement in the SKA remained at a relatively low level for much of the next decade due to other higher priority projects in the two main centres of radio astronomy at Manchester University and Cambridge University. Wilkinson became a founder member of the LTWG and hosted the first meeting of the LTWG at Jodrell Bank in 1994 (see Sect. 3.2.1). Thereafter he attended most of its meetings and played an active role as UK representative, but no funding for SKA technical development was requested in the UK.

However, as global interest and involvement in the SKA continued to grow in 1998 and 1999, it became obvious that the UK could no longer afford to remain on the sidelines. Andrew Lyne, Director of the Jodrell Bank Observatory, signed the MoA on Collaboration on SKA Technical Development in 1998,[34] and Phil Diamond, newly appointed Director of the Multi-Element Radio-Linked INterferometer (MERLIN) at Jodrell Bank Observatory, attended the second meeting of the International SKA Steering Committee in August 1999 representing the UK.

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[33] hba.skao.int/SKAHB-19, *US Ideas, Motivations and Funding to Join the SKA Project*, Presentation at SKAHistory2019 Conference, Kellermann, K. I., 2019.

[34] hba.skao.int/SKAHB-20, *Memorandum of an Agreement to Cooperate in a Technology Study Program Leading to a Future Very Large Radio Telescope*, 1996, amended in 1998 (unsigned version).

#### 3.2.6.7 India

Govind Swarup kept Indian interest in the large radio telescope project visible by making presentations at LTWG and other meetings on scaled-up versions of the Giant Metre-wave Radio Telescope (GMRT) dishes as a design option. In reality, there were no additional resources available in India for any in-depth design work on the SKA while the GMRT was being brought into full operation.

## 3.3 Global “Grass-Roots” Collaboration, 1999–2005

The years 1999 to 2005 saw the SKA project enter a new phase, ushered in by the establishment of an International SKA Steering Committee in 1999 that aspired to coordinate the disparate national activities more actively than was possible under the 1996 MoU (see Sect. 3.2.2). The appointment of a full-time Director and Project Engineer followed, a comprehensive science case was published, and substantial funds for engineering development flowed both nationally and regionally in Europe. In 2005, the first contacts with the funding agencies, acting as a global group, took place, and the SKA started its transition to a recognised science mega-project operated by a legal entity and funded for detailed pre-construction design.

### *3.3.1 Governance*

#### 3.3.1.1 First Things First: A Steering Committee (1999) and a Director (2003)

With international science and technology meetings now a regular occurrence and centres of technology activity springing up around the world, it was time to take the next step in formalising the top-level governance of the SKA and lay the foundations for broadening the membership and scope of the 1996 Memorandum of Agreement on Cooperation outlined in Sect. 3.2.2.

Ekers and Butcher used the opportunity provided by the Dwingeloo conference on Perspectives on Radio Astronomy: Technologies for Large Antenna Arrays (see Sect. 3.2.6.1) in April 1999 to call a meeting of senior figures from many of the SKA countries (see Box 3.2) to discuss SKA strategic issues. This took place at ASTRON in Dwingeloo, chaired by Ekers. It is now recognised as the first meeting of the International SKA Steering Committee (ISSC) even though the ISSC was not formally established via Memorandum of Understanding until August 2000.

The rationale behind this initiative was clear: ‘It is in everyone’s interests to create and fund a Steering Committee. Since the SKA is a truly international project that does not have a single sponsoring agency, the only way to create such a committee is to "self-appoint" an ad hoc group consisting of active project scientists and engineers from each participating country.'[35]

### Box 3.2 Participants in the First SKA Steering Committee Meeting in April 1999

**Australia:** Wim Brouw and Ron Ekers (Australia Telescope National Facility)

**Canada:** Peter Dewdney (Herzberg Institute of Astronomy), Russ Taylor (U. Calgary)

**Europe:** Richard Schilizzi (Joint Institute for VLBI in Europe);

**Netherlands:** Harvey Butcher (Netherlands Foundation for Research in Astronomy)

**USA:** Bernie Burke (MIT), John Dreher (SETI Institute), Bill Erickson (U. Maryland), Ken Kellermann (NRAO), Jack Welch (U. Berkeley), Alan Whitney (Haystack Observatory)

The strategic issues on the agenda were obvious for a project of SKA's scope and ambition—international coordination, coordination of sub-projects and prototypes, technology selection process, number of telescopes, detailed specification process, science case, and marketing. These remained on the agenda, in various forms, for subsequent steering committee meetings over the following 12 years.

An important outcome of the 1999 meeting was the first step towards a Project Office. Russ Taylor one of the leaders of SKA involvement in Canada, was appointed International SKA Project Scientist with responsibilities to further develop the science case and expand the global science community involved in SKA. Initial tasks for the Steering Committee were to create a formal organisation based on a new Memorandum of Understanding (MoU) and establish a committee to monitor and evaluate technical progress on a continuous basis.

Like many steering committees before it, the SKA committee set out its vision for the project timescale, in suitably modest terminology if not ambition. Their 'tentative sequence of events' foresaw construction of the full SKA beginning around 2010.

It took over a year to align all the parties to the point that a formal Memorandum of Understanding for an International SKA Steering Committee (ISSC) could be signed. At least two international conferences were used as venues for informal discussions to resolve issues—the URSI General Assembly in Toronto in August 1999, and the International Society for Optics and Photonics (SPIE) meeting in Munich in March–April 2000[36] (Butcher, 2000). In Europe, it was felt that a prerequisite to any signature at global level was the formation of a regional

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[35] hba.skao.int/SKAHB-21, *Minutes of the 1st Meeting of the International SKA Steering Committee*, April 1999.

[36] At the SPIE Conference on Astronomical Telescopes and Instrumentation, 27 March–1 April 2000, a wide-ranging 3-day meeting on Radio Telescopes was organised by Harvey Butcher. Fifteen of the sixty-eight papers were directly related to SKA design activities.

consortium to coordinate and represent European interests in the same way as the national consortia in the USA and Australia did for their respective interests. By early 2000, this came to pass as part of a broadly-based European Commission Infrastructure Cooperation Network called RadioNet, coordinated by Schilizzi, which had been funded through the 5th Framework Program for Research and Technological Development (FP-5) to support cooperation in European radio astronomy.

The IAU General Assembly in Manchester in August 2000 provided a ready-made occasion to sign the ISSC MoU. It was there that Ron Ekers (Australian SKA Consortium), Don Morton (Herzberg Institute of Astrophysics, Canada), Guoxiang Ai (Beijing Astronomical Observatory, China), Rajaram Nityananda (National Centre for Radio Astronomy, India), Harvey Butcher (European SKA Consortium), and Jill Tarter (US SKA Consortium) formalised the collaboration.[37]

The MoU preamble (Box 3.3) reiterated many of the points made in the URSI 1993 Large Telescope Working Group remit and the 1996 MoA to Cooperate on Technology and set the framework for what proved to be a lasting collaboration.

**Box 3.3 Preamble to the MoU Establishing the ISSC in 2000**

The undersigned, representing their respective organisations, recognising:

their mutual interest to develop the Square Kilometre Array (SKA) radio telescope as a joint international endeavour, and
the need for a coordinating body to oversee and direct the development of a joint international Square Kilometre Array program, including a joint research and development program,

hereby agree to establish an International Square Kilometre Array Steering Committee to:

(i) promote the SKA as an international project,
(ii) to provide oversight and to act as a coordinating body to establish agreed goals and timelines for the project,
(iii) to develop a joint international technical and scientific proposal for the SKA, including an implementation and cost plan, and
(iv) to establish and oversee working groups as necessary.

Equal representation from Europe, the USA and “the Rest of the World” was a central tenet of the ISSC concept. This reflected the expected provision of funds for the design and construction of the SKA. Initial membership comprised six from the USA, six from Europe (Germany, Italy, The Netherlands (2), and UK (2)), and six from the Rest of the World (Australia (2), Canada (2), India, and China), and up to two at-large members (see Fig. 3.5).

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[37] hba.skao.int/SKAHB-22, Press Release concerning the Signing Ceremony establishing the International SKA Steering Committee (ISSC), 10 August 2000. See also hba.skao.int/SKASUP3-1 which is a short video of the signing ceremony.

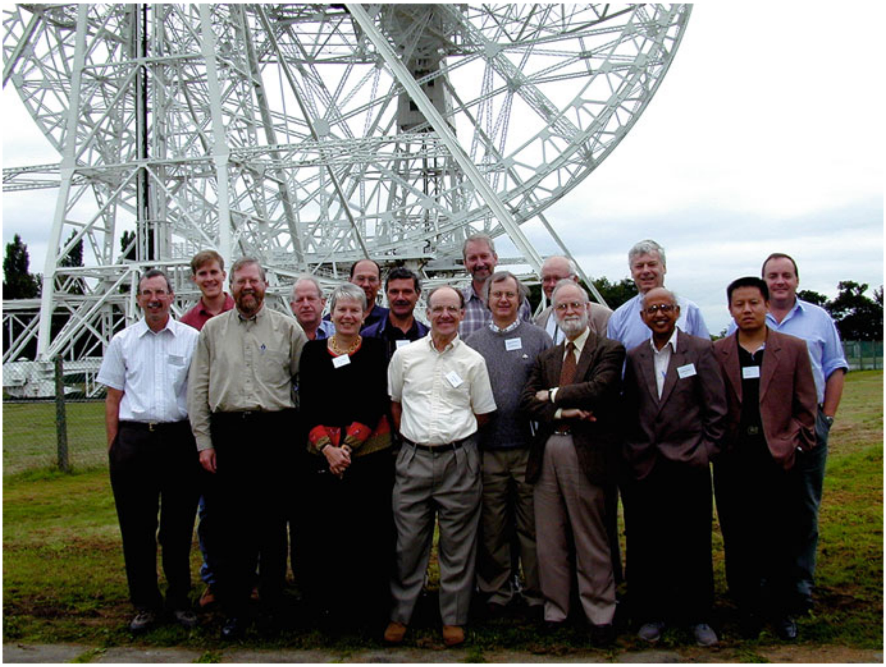

**Fig. 3.5** Initial ISSC members, 2000. Left to right: Bob Preston (USA), Douglas Bock (USA), Harvey Butcher (Netherlands), Wim Brouw (Australia), Jill Tarter (USA), Arnold van Ardenne (Netherlands), Franco Mantovani (Italy), Rick Fisher (USA), Russ Taylor (Canada), Peter Dewdney (Canada), Bernard Burke (USA, partially obscured), Ron Ekers (Australia, chair), Peter Wilkinson (UK), Govind Swarup (India), Bo Peng (China), Phil Diamond (UK). Not present for the photo: Dayton Jones (USA), Ken Kellermann (USA), Anton Zensus (Germany) and Richard Schilizzi (at-large member). (Credit: Ian Morison)

Management of the collaboration was further formalised at the Manchester meeting. An Executive Committee was appointed comprising the ISSC Chair—Ron Ekers, two Vice-Chairs—Jill Tarter and Harvey Butcher, and an Executive Secretary—Russ Taylor. A maximum contribution to the activities of the Secretariat was set at USD 2000 per member annually, a total of USD 32000.

**Box 3.4 Chairs of the International SKA Steering Committee (1999–2007) and the SKA Science and Engineering Committee (2008–2011)**

**ISSC**: Ron Ekers (1999–2002), Jill Tarter (2002–2004), Phil Diamond (2004–2006), Brian Boyle (2006–2007)

**SSEC:** Brian Boyle (2008), Ken Kellermann (2008–2010), Mike Garrett (2010–2011)

Vice-chairs followed Chairs at two-year intervals (see Box 3.4) apart from the July 2004 handover when Butcher indicated that he would prefer not to be elected as chair of the ISSC in view of the heavy LOFAR workload in the coming years. The difficulties surrounding the recent national decision to locate the LOFAR telescope in The Netherlands (see Sect. 3.2.6.1) may have influenced his decision to withdraw his name. The two-year term of office continued throughout the subsequent governance period from 2008 to 2011 following the replacement of the ISSC by the SKA Science and Engineering Committee (SSEC) as we describe in the next chapter.

It rapidly became clear to the ISSC that leadership of a complex global collaboration was a full-time task and in July 2001 members agreed to seek a full-time Director of International SKA Development as the next step in creating a central project office. Some 9 months later with funding in hand, the selection process was set in motion, resulting in the position being offered to Schilizzi based on his long experience in international collaboration in European VLBI. He took up the position in January 2003 on an annually renewable contract.

With the appointment of a full-time Director, Taylor decided to relinquish his part-time duties as ISSC Executive Secretary in August 2003. The duties of ISSC Secretary were taken up by Wim Brouw, one of the Australian ISSC representatives based at CSIRO, in August 2003, and then passed to the International SKA Project Office (ISPO, see next section) 3 years later, in 2006. Brouw remained an active member of the ISSC until the end of 2007. To accommodate the appointment of the Director, the maximum contribution to the activities of the SKA project was raised to USD 10,000 per member annually in 2004.

Observers at ISSC meetings were encouraged as part of the drive to expand the collaboration. In this respect, the July 2001 meeting was noteworthy for the first appearance of a representative from the fledgling radio astronomy community in South Africa. This was Justin Jonas, a pulsar astronomer based at Rhodes University in Grahamstown. He reported that SKA had ranked second to the Virtual Observatory in a list of possible future astronomy initiatives in the country. He hoped that South Africa could contribute to the technical development of the SKA and noted that South Africa had the potential to be a good site for the SKA, or SKA elements. Both of these aspirations were fulfilled in the decade to follow.

The growing presence of South Africa particularly from 2004 onwards as one of the candidate sites for the SKA, led to a decision to draw up a new Memorandum of Agreement to allow the ISSC to expand to 21 members with South Africa joining Australia, Canada, India and China in the Rest of the World group, and the number in each of the European and US groups increasing by one to maintain parity. This came into force on 1 January 2005. A representative from France, Wim van Driel, joined the European group. Amongst the other provisions the MoA recognised the ISPO and raised the ceiling for the annual contributions to the ISPO from USD 10000 to €40,000 per ISSC membership.

Representatives from Japan were regular observers from 2002 to 2006. In 2005, there was hope that Japan would join the SKA following support expressed at the

**Fig. 3.6** “Good luck for the Project”. The Daruma doll (credit: Jill Tarter)

annual symposium on Radio Astronomy. The question was not if, but how and when, Japan would join the SKA. In a memorable exchange,[38] Ekers urged Makoto Inoue (Nobeyama Observatory, Japan) to take action, pointing out that the lessons from ALMA should have taught Japan that the earlier you get into a project the better. In Ekers’ view, Japan was late to join the US and ESO as the third party in the International ALMA collaboration, but they were not treated as an equal partner. To initiate closer cooperation between Japan and the SKA, the ISSC asked Schilizzi to set up discussions on the incorporation of Japanese members into the ISPO Working Groups and Task Forces as one of the best ways forward for Japan to become a full member of the ISSC. However, these endeavours were not successful due to higher priorities for Japanese astronomy elsewhere. At the time of writing, 15 years later, Japan is still an Observer at SKAO Council meetings.

As an example of the cultural interchange that marked the SKA project, Hisashi Hirabayashi from the Japanese Institute of Space and Aeronautical Science, ISAS, presented the then ISSC Chair, Jill Tarter, with a Daruma doll in 2002 as a symbol of perseverance and good luck for the project. This entered SKA folklore and was passed on to the incoming ISSC Chair from the outgoing Chair. Figure 3.6 shows the doll with one eye coloured in, the other eye to be coloured in at the moment of achieving a long-held goal. The record does not show what goal was identified to be fulfilled, but presumably something along the lines of successful operation of the SKA. The record also does not show what happened to the doll post-2007.

Observers from Russia also attended on an occasional basis.

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[38] hba.skao.int/SKAHB-23, *Minutes of the 14th ISSC meeting, 2005.*

#### 3.3.1.2 Beyond the Steering Committee: Project Management Structure

At the August 2000 Manchester ISSC meeting, three advisory committees were created to report to the ISSC—an Engineering Working Group (EWG) to be chaired by Rick Fisher from NRAO, a Science Working Group (SWG) to be chaired by Russ Taylor, and a Site Selection and Evaluation Committee (SESC) to be chaired by Bruce Thomas from CSIRO. Rick Fisher declined to accept the EWG Chair position and was replaced by Peter Hall from CSIRO. The EWG was renamed the International Engineering Management Team (IEMT) in 2002 but returned to being called the EWG after the establishment of the International SKA Project Office in 2004. Russ Taylor served as SWG chair for 2 years and was followed by Chris Carilli from NRAO (2002–2004), Steve Rawlings from Oxford University (2004–2006), and Bryan Gaensler from University of Sydney (2006–2008). Joe Lazio from the NASA Jet Propulsion Laboratory was appointed SKA Project Scientist and SWG Chair from 2008 to 2011. The SWG was renamed the International Science Advisory Committee (ISAC) in 2002 but, like the IEMT, returned to being called the SWG in 2004.

The IEMT was charged with auditing SKA technical activities around the world, identifying and proposing possible collaborations, and identifying technical or system engineering needs in the international SKA effort (as discussed in Sect. 6.2.1). The ISAC's task was to establish the primary science goals, unique to the SKA, the shared science goals complementary with other next generation instruments, and the secondary science goals (see Sect. 5.9.2). The primary tasks of the SESC were to set out the site selection principles for ISSC approval and map out the site selection process (see Chap. 7).

#### 3.3.1.3 International SKA Project Office (2003)

Establishment of a formal project office, the International SKA Project Office, ISPO, followed the appointment of the Director, in August 2003. This was located at the Dwingeloo Observatory in the Netherlands, home of ASTRON and the Joint Institute for VLBI in Europe, both former institutes for Schilizzi. Despite the ISSC intention that the Director should not be located at their home institute in order to avoid perceptions of local bias, Schilizzi remained at the Dwingeloo Observatory on the grounds that the contract was for 1 year at a time which did not provide sufficient job security for a major change in circumstances. This remained the case until the selection of the University of Manchester as the host for the SKA project office in 2008 (see Sect. 9.2).

The appointment of a Director and the establishment of the ISPO led to a revised management structure in 2004 that reconvened the ISAC, IEMT and SESC as Working Groups reporting to the Director (Science WG, Engineering WG, Site Evaluation WG), as mentioned above. This reflected the fact that project-related work at the international level was becoming increasingly important, in addition to the very valuable internal advisory roles provided by these groups. Later WGs on Outreach, Simulations, and Operations were formed that reported to the Director. In the course of time, some WGs created sub-committees or task forces on specific subjects such as the EWG Industrial Liaison Task Force (see Chap. 10). Also, in the course of time, the ISSC established international advisory committees for Engineering (IEAC, see Sect. 6.2.2.3) and Site Selection (ISSAC, see Sect. 7.3.4) to provide advice directly to the ISSC.

In 2004, Peter Hall was appointed International Project Engineer within the ISPO, an obvious choice in view of his achievements in previous years as Chair of the IEMT and EWG. His tasks for the initial 2 years were non-trivial and included developing a design requirements document based on the science requirements and coordinating studies of common elements of SKA design. This was to culminate in guidelines for proposals for the final design concept. Overseeing the site characterisation activities of RFI testing and definition of the engineering infrastructure, also fell within his remit. Hall was on secondment from CSIRO but remained based in Australia.

As Hall remarked in a retrospective talk at an SKA meeting in 2008, the ISPO in 2004 consisted of “two men and a pot-plant” supported by a substantial global WG structure! ISPO numbers grew modestly to four by 2007, but then expanded in subsequent years with SKA Preparatory Phase funding (PrepSKA, see Sect. 4.4) to over 15 staff in 2011.

### 3.3.2 The Coordinating Role of ISSC and ISPO, 1999–2005

At the Manchester meeting in August 2000, the first international project plan in outline form saw the light of day. An ISSC working group chaired by Bob Preston from the Jet Propulsion Laboratory, one of the most active members of the Committee, set out an initial management structure for the SKA. The plan also included a more detailed timeline for the project, still with 2010 as the goal for start of construction. However, in August 2003, the Director presented the first detailed project plan[39] in which construction would start in 2012 leading to full operation in 2019. As the years passed and project realities became apparent, these dates slipped as we discuss in Sect. 4.6.1.

In addition to the planning and strategy discussions, much of the ISSC activity in this six-year period revolved around the site selection process, overseeing the development of the science case and technical developments, and ensuring the ISPO had sufficient funding to carry out its work. In 2005 preparations for the first interactions with national funding agencies, acting as a global group, took place.

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[39] hba.skao.int/SKAHB-24, *SKA Management Plan*, Discussion Paper for 10th ISSC Meeting, Schilizzi, R. T., 2003.

Dealing with the aftermath of that meeting changed the course of the project as we describe in Sect. 3.4.

The ISPO acted as the operational arm of the ISSC, with the Director expected to help shape policy, and propose initiatives and courses of action. It is fair to say that the main accomplishments of the ISSC and the ISPO in this period were to create a strong sense of common purpose in the SKA project, and to prepare the way for substantially increased funding represented by the European-led SKA Design Studies (SKADS) and PrepSKA, and the US Technical Development Program (TDP).

### 3.3.3 National and Regional Governance Structures, Long Range Plans, and Funding, 1999–2005

Underpinning the international coordination activities described in the previous section, national efforts in the "pioneer" SKA institutes/countries (see Sect. 3.2.6) continued and from 2000 onwards additional institutes or groups in other countries organised themselves and began to contribute to the overall project. This section sketches these national and regional in the case of Europe, developments up the start of the "Transition Era" in 2006. The cumulative total of funding for SKA-specific work approved by the end of 2005 amounted to over €70 million of which over half was to be contributed by the European-led SKADS program.[40]

The US SKA community led the way on national governance structures by being the first to establish an SKA Consortium following the April 1999 meeting in Dwingeloo that established the international steering committee. By the time the MoU to formally establish the ISSC in August 2000 was signed, similar national consortia had been formed in Australia and Canada, and, regionally, in Europe.

The SKA appeared in long-range plans in The Netherlands (1993), and Australia (1996), and, in 2000, in Canada, the UK and the US. By 2005, the same was true for the European Strategy Forum for Research Infrastructures (ESFRI), as we discuss in Sect. 4.3.2.2.1.

Funding for SKA technical research was already in place in The Netherlands, Australia, Canada and China from the mid-1990s, and from the early 2000s in the US. But it was in Europe that the first large tranche of funding for SKA Design Studies (SKADS) was granted, in 2005, by the European Commission as part of the 6th Framework Program for Research and Technological Development (FP-6). "Matching" national funds for SKADS were also made available. FP-6 was the overall framework for the EU's activities in the field of science, research and innovation in the 2002–2006 period. Its principal objective was to contribute to the creation of a genuine European Research Area (ERA) by fostering more integration and coordination in Europe's previously fragmented research sector.

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[40] hba.skao.int/SKAHB-25, *SKA Resources*, Supporting Paper for the 13th ISSC Meeting, Schilizzi, R. T., 2005.

The technical design work carried out under the grants mentioned is described briefly in Chap. 6. Chapter 10 summarises industry engagement strategies and activities in the various countries. The individual national and regional stories from 2006 to 2012 continue in Sect. 4.3.2.

#### 3.3.3.1 Australia

***Governance*** Australia formed an SKA Consortium Committee in 2001. Chief amongst its Terms of Reference were to: (i) provide a single, coherent interface between Australia and the international SKA project, (ii) report to, and consult with, the Australian astronomical community regarding all aspects of the SKA project, (iii) promote the SKA to Government and Industry, and (iv) coordinate R&D within Australia. The members of the Committee came from the national research organisations (CSIRO and the Anglo-Australian Observatory), universities (Sydney, Melbourne, Australian National University and Swinburne University of Technology), industry, and the federal government's Department of Science and Technology.

The approach to membership taken was different to that of the US SKA Consortium a year earlier (see Sect. 3.3.3.8). In Australia, all potential stakeholders from science to industry and government were active members of the Consortium from the start to ensure coordination and collaboration was built in, and potential funding avenues explored. In the USA, the consortium membership involved astronomers and engineers only, reflecting the greater separation of the science community and government agencies in the early stages of a large project.

***Funding*** An additional 3 years of funding of $A1.5M in 2000 from CSIRO followed on from the original 1997 allocation and was used for "strategic development of the SKA" including engineering prototypes, exploration of possible sites if the SKA were located in Australia, and a number of postdoctoral and postgraduate positions for SKA research. It was recognised that innovative new antenna designs would be needed to make the full SKA feasible technically and financially, and CSIRO embarked on a "smart antenna" project which incorporated digital beamforming and radio frequency interference rejection into the design. At this time, attention turned to the use of Luneberg Lenses as the SKA antenna element to allow multiple concurrent observations in different directions on the sky (see hba.skao.int/SKASUP6-30). The government of the state of Western Australia was especially enthusiastic in its support of site-related activities.

A significant milestone was the formal signing of a five-year Major National Research Facility (MNRF) agreement on SKA research in 2001 between the Australian Government, CSIRO, the University of Sydney, Swinburne University of Technology, and several other collaborators. This provided $A20M funding to support work on antenna elements including focal plane arrays, SKA simulations, RFI testing of the sites near Murchison in Western Australia, the SKA Molonglo Prototype (SKAMP, University of Sydney) project, and configurations for the Australian SKA site bid.

MNRF-funded research on the use of Luneberg lenses for the SKA elements was discontinued in 2004 due to a number of substantial technical problems that were identified. The direction changed to developing focal plane array technology for parabolic reflectors to enable wide field-of-view SKA observations, and an extended New Technology Demonstrator (xNTD) project involving 20 dishes was created, supported by an additional $A 15 million from CSIRO and the Australian Government.

In 2004, the West Australian State Government allocated $AU 4 million in further support for Australian efforts on an SKA potentially located in a remote area of that State. This was to fund infrastructure such as fibre optic cabling, buildings, power supplies and local road upgrades for radio astronomy projects at Mileura, including the New Technology Demonstrator.

***SKA Site*** In September 2004 the Australian SKA Consortium Committee (ASKACC) was invited by the International SKA Steering Committee to submit a proposal for a site for SKA (see Chap. 7). Conditions in the Request For Proposals required ASKACC to select a single Australian candidate site from the three proposed in the Initial Australian Site Analysis Document. The West Australian site was selected.

Following a recommendation, in June 2004, from the Australian Prime Minister's Science, Engineering and Innovation Council Working Group on Astronomy, a Federal Government Forum on establishing an Australian radio-quiet zone was held in the Australian Parliament House in August 2004. This led eventually to the creation of a radio quiet zone following the selection of Australia on the short list in 2006 (see Sect. 7.4).

#### 3.3.3.2 Canada

***Governance*** The Canadian SKA Consortium (CSKAC) was established under the auspices of the National Research Council, the Association of Canadian Universities for Research in Astronomy and Canadian Astronomical Society (CASCA). Members of the Consortium were drawn from the Herzberg Institute of Astrophysics, and a number of universities (Queen's, British Columbia, McGill, York and Calgary). In addition, three representatives came from industrial partners. Russ Taylor was appointed Chair of the CSKAC.

***Long Range Plan*** The Canadian Long-Range Plan (LRP) for Astronomy for 2000–2010 recommended participation in ALMA construction as first priority, and participation in the design phase of the SKA as second priority. The Long-Range Panel strongly recommended the Canadian Large Adaptive Reflector (LAR) concept (see hba.skao.int/SKASUP6-28) be carried forward into prototypes for further detailed studies. It also recommended Canada start positioning itself for entry into the construction of the SKA.

A mid-term review of the Long-Range Plan in 2005 strongly re-affirmed its original recommendation that Canada position itself to play a leadership role in the international SKA initiative, and that a Phase B study of the LAR be supported to ensure its successful and timely completion for the selection of the SKA design by the international SKA consortium.

***Funding*** The LRP recommended $CA 28 million funding[41] in 2000 for SKA development ($CA 20 million for the NRC for LAR design and prototyping and $8 million for the universities). As proposed, the development of innovative solutions for the LAR (aerostat, reflector, and phased array feed) took central place throughout this period until the technology down-select in January 2006 described in Sect. 6.2.1. It failed to reach the short-list due to an ISSC decision to pursue small diameter dish arrays rather than large diameter elements. Post-2006, about $CA 20 million was made available to support SKA-related technology developments including new technology antennas (see Sect. 6.4) throughout the period to 2012.

#### 3.3.3.3 China

***Funding and Governance*** Section 3.2.6.2 outlined the multiple large diameter spherical dish concept for SKA to be located in the karst region of Guizhou Province, and FAST as a pilot project. In 1999, FAST was designated a key project in the Chinese Academy of Sciences and received support from the Ministry of Science and Technology of China and funding of the equivalent of $US 1 million. The Guizhou provincial government also supported the SKA and FAST plans in part as a means of developing their radio communications industry.

The national funding allowed the creation of the Large Radio Telescope/FAST Laboratory in the newly established National Astronomical Observatories in China, with Rendong Nan as the Laboratory Director and Bo Peng as Deputy Director (see Fig. 3.7). The FAST Laboratory began R&D collaborations with about 20 domestic partners including Xidian University, Tsinghua University, Tongji University, as well as institutes of Remote Sensing Application, Radio Measurement, Systems Science, and Mechanics, and the Nanjing Astronomical Instruments Research Centre.

The initial goal was to design and build scaled models for the surface element of the main reflector and the feed support system. In early 2005, the construction of a 30 m diameter demonstrator called MyFAST began at Miyun Observatory near Beijing.

***SKA Siting*** The main activities underpinning China’s bid for the SKA site during this period were choosing a site for FAST in the area chosen for the SKA as a whole (see Fig. 7.1), measuring the levels of Radio Frequency Interference, and preparing

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[41] hba.skao.int/SKAHB-17, *Canada and the SKA Project, 1995–2012,* Presentation at SKAHistory2019 Conference, Taylor, A. R., 2019.

**Fig. 3.7** Rendong Nan (right) and Bo Peng (left), the prime movers for the FAST project in China, at the ceremony celebrating the start of construction of FAST in December 2007 (Credit: National Astronomical Observatory of China)

the submission to the SKA site competition at the end of 2005 (see Chap. 7). The Guizhou regional Bureau of Radio Management agreed to work and collaborate on designating a Radio Quiet Zone as soon as the final site for the FAST was chosen and the FAST project approved as a National Mega-science Project of China.

As we will see unfold in Chap. 7, the site short-listing process in 2006 decided in favour of Australia and South Africa. However, the national momentum behind the FAST project carried it on to funding approval by the Chinese National Development and Reform Committee in 2007. This was the culmination of a "Long March" of 13 years of research and development by Nan, Peng and their partners in about

**Fig. 3.8** The 500 m diameter FAST dish in Guizhou Province in China. It is an active-surface spherical dish with collecting area of 196,000 $m^2$ located in a karst depression, and operates at frequencies from 70 MHz to 3 GHz (with plans to upgrade to 8 GHz in the future) (Credit: National Astronomical Observatory of China)

20 domestic institutes including the Remote Sensing Institutes of the Chinese Academy of Sciences, Xidian University, and Tsinghua University.[42]

FAST was officially inaugurated as a major radio astronomy facility on the world scene in September 2016 (Fig. 3.8), having cost the equivalent of about €200 million (Renminbi 1.19 billion). The original cost estimate at start of construction in 2007 was about €100 million.[43]

The National Astronomical Observatory of China and associated academic institutions and industry continued their involvement in the SKA, in parallel with the construction of FAST. China is a member of the Inter-Governmental Organisation, the SKA Observatory (see Sect. 4.7) and, at the time of writing, a major participant in construction of the first phase of the SKA.

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[42] hba.skao.int/SKAHB-16, *SKA Forerunner - FAST,* Presentation at SKA History2019 Conference, Peng, B., 2019.

[43] B. Peng, priv. comm. to R. T. Schilizzi, 29 March 2022.

**Fig. 3.9** The central part of the Low Frequency Array (LOFAR) in the Netherlands (Credit: ASTRON)

### 3.3.3.4 Europe

#### 3.3.3.4.1 Netherlands

The Netherlands continued to lead the way in SKA in Europe throughout the 1999–2005 period, both at national and European levels. Design work on aperture array systems continued (see Sect. 6.5) with the One-Square-Metre Array (OSMA), the Thousand Element Array (THEA), and the Electronic Multi-Beam Radio Astronomy ConcEpt (EMBRACE) as part of the SKA Design Studies program (SKADS), as did design work and planning for funding and siting LOFAR (see Fig. 3.9). The European initiatives—the European SKA Consortium and the proposal for European Commission funding for SKADS are discussed below.

#### 3.3.3.4.2 UK

In late 1999, the Particle Physics and Astronomy Research Council established a ‘Visions Panel’ to set out the long term (10–15 years) science goals for UK astrophysics. SKA was included, in the same category as the ESO Extremely Large Telescope project in the European Southern Observatory, a competition we will revisit in Sect. 4.3.2.2.2.

At the institute level, a small ‘SKA Focus Group’ was established at Jodrell Bank Observatory (JBO) in 2000, chaired by Alan Pedlar, to oversee JBO involvement with the SKA. Transmission of broad-band signals from antennas to correlator using optical fibres formed the main technical research initiative. This technology could also be applied to the local interferometer, MERLIN, and was an early example of "dual-use" funding proposals to national funding agencies. The SKA pre-cursors became the prime examples of technology development for dual use.

The UK took centre stage in August 2000 in hosting the ISSC meeting in Manchester at which the MoA was signed (see Sect. 3.3.1.1). An engineering workshop, "Technical Pathways to the SKA", was held in conjunction with the ISSC meeting.

#### 3.3.3.4.3 Europe-Wide

***Governance*** As noted above, the impetus for grouping the European SKA efforts under one umbrella came when funding for a European Infrastructure Cooperation Network (ICN) for Radio Astronomy was made available in 2000 as part of the European Commission Fifth Framework Program. As one of the RadioNet activities, €100,000 was allocated over 4 years to help establish European collaborations and coordinate activities for the SKA project in Europe including workshops and strategy meetings. The European SKA Consortium (ESKAC) was duly formed in March 2000 and included representatives from institutes in Germany, France, Italy, Poland, Spain, Sweden, the Netherlands and the UK. Harvey Butcher from ASTRON in the Netherlands and Phil Diamond from Jodrell Bank Observatory were appointed chair and vice-chair. This was not a new concept for Europe, the European VLBI Network had laid the groundwork for continent-wide collaboration 20 years earlier (see Sect. 2.3).

ESKAC's mission was fourfold: (i) foster European and global technical and scientific activities related to the SKA, (ii) encourage, support, and stimulate individual national, joint international and European funding applications for scientific and technical development and operation of the SKA, (iii) foster coordinated European technical and scientific input to the SKA project, and (iv) serve as a conduit for exchange of scientific and technical information between its members, their communities, and the SKA organisation. It proved an effective voice for European views on SKA issues in the ISSC and SSEC until its dissolution when the SKA Organisation was established at the end of 2011.

A new ESKAC Memorandum of Understanding was agreed in 2005. On ISSC membership, four members were to come from The Netherlands, UK, France, and Italy as the largest SKADS contributors and selected by the national SKA consortia; two ISSC members were to be selected automatically "by position" (the coordinators of RadioNet and SKADS); and one other member was to be selected *ad personam* by the ESKAC Board following a standard nomination and voting procedure.

***Funding*** In RadioNet spin-off funding from the EC in 2001, €1.5 million was allocated to the Faraday focal plane array project in which ASTRON led a group comprising Jodrell Bank Observatory (JBO) in the UK, the Institute of Radio Astronomy (IRA) in Bologna, Italy and the Torun Centre for Astrophysics

(TCfR), Poland. In later EC Framework Programs, RadioNet continued to provide support for SKA-related technical development under Joint Research Activities.

In 2003, work on preparing for SKADS began in Europe, centred on aperture arrays. One of the main goals was to establish the economic viability of “aperture plane” array technology for radio astronomy by constructing one or more demonstrators with a total area up to 1000 $m^2$. The second main goal was ambitious: to develop a costed design for the entire SKA based on one or more collector concepts involving phased arrays.

Arnold van Ardenne from ASTRON and Peter Wilkinson from Jodrell Bank Observatory spearheaded efforts to generate an ultimately successful proposal for SKADS to the European Commission for €10.4 million. This was funded in 2004 and completed in 2009. Matching funding from the national sources contributed another ~€28 million. At its peak, 30 organisations (national institutes, universities and industry) drawn from EC member states and non-EC countries (Australia, South Africa, Canada and Russia) contributed to SKADS (see Sect. 6.5.5.2 and Fig. 6.29). It was unusual that the EC’s financial contribution was only a little over a quarter of the project total of ~€38M which led to a range of new administrative problems to be overcome by the Commission and the national funding agencies.

Another ambitious goal was to act as the key cohering organisation for the international scientific and technology R&D effort for the 4 years of the SKADS project. This led to some creative tension between the SKADS Board and ESKAC, and with the global project office in both its ISPO and SPDO guises.

### 3.3.3.5 India

Throughout the 1999–2005 period as the Giant Metre-wave Radio Telescope (GMRT) was under construction, Govind Swarup and colleagues continued to adapt the low-cost GMRT dish design for smaller and larger diameter antennas than the original 45 m, also with the goal of operating at higher frequencies than the 1.4 GHz limit of GMRT. The new concept was called a pre-loaded parabolic dish (PPD, see Sect. 6.4.4.3). This continued until the antenna technology down select at the end of 2005 when it became clear that the astronomical community was pushing for a higher frequency limit for SKA operation (8 GHz) than the PPD dish could provide.

In the meantime, the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research (NCRA) in Pune began to prepare for the SKA and other radio astronomy projects in other areas than antenna design. A workshop organised by NCRA and the Radio Research Institute in Bangalore (RRI) in 2004 highlighted the opportunities for the burgeoning Indian software industry and hardware R&D companies in radio astronomy technologies required for GMRT upgrades and developments in SKA and LOFAR.

To carry this further, the Square Kilometer Array Consortium of India (SKACI) was formed in 2005, with the NCRA and the RRI as initial members. J.N. Chengalur

(NCRA), K.S. Dwarakanath (RRI), A. Pramesh Rao (NCRA), and N. Udaya Shankar (RRI) represented those institutes.

#### 3.3.3.6 New Zealand

SKA developments around the world, and especially in Australia, became a catalyst for New Zealand to start developing radio astronomy in order to join Australia in their bid for the SKA site. Its location 2000 km east of what they called New Zealand's "West Island" would provide even higher angular resolution observations than requested in the call for SKA site proposals. In September 2004 the Centre for Radiophysics and Space Research (CRSR) was founded in Auckland University of Technology (AUT) with Sergei Gulyaev as Director. The initial goals were to establish a Very Long Baseline Interferometry capability with Australia and to search for suitable SKA remote sites in NZ. In 2005, it formally joined the SKA global community and played a role throughout the Transition and much of the Pre-Construction Eras.

#### 3.3.3.7 South Africa

How South Africa came to be involved in the SKA project is a fascinating story in itself, one that is intertwined with a new approach to Research & Development at governmental level in the post-Apartheid era from 1994 onwards[44,45] (Adam, 2002).

Roger Jardine and Rob Adam, respectively Director-General and Deputy-Director-General of the Department of Science and Technology (DST) in the South African government, and Khotso Mokhele, President of the National Research Foundation (NRF) had spent several years in the 1990s leading the preparation of a White Paper[46] setting out the new strategy and priorities for R&D in the country following the end of Apartheid. Astronomy was one of nine priorities chosen. The Southern African Large Telescope[47] (SALT) , an international optical telescope, was the first project supported by the government in 1998. Following the ground-breaking ceremony for SALT in 2000, Mokhele convened a National Astronomy and Space Science Workshop to map out future possible projects. Patricia Whitelock (Deputy Director, South African Astronomical Observatory) and George Nicolson (Director, Hartebeesthoek Radio Observatory, and the prime mover of radio

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[44] hba.skao.int/SKAHB-27, *South Africa's Motivation for joining the SKA*, R. Adam, Presentation at SKAHistory2019 Conference, 2019.

[45] G. Nicolson, email to R. Schilizzi, 29 September 2022.

[46] hba.skao.int/SKAHB-28, *White Paper on Science & Technology - Preparing for the 21st Century*, Government of South Africa, Department of Arts, Culture, Science and Technology, September 1996.

[47] Southern African Large Telescope (SALT) https://www.salt.ac.za/

astronomy in South Africa) suggested including the SKA in the workshop since it was already enjoying considerable support in the radio astronomy community around the world. Justin Jonas (Rhodes University) presented the case at the workshop and the SKA duly emerged as one of the two top priorities. This led to the invitation, mentioned earlier, from Ron Ekers (then ISSC Chair) to Justin Jonas to participate as an observer in the ISSC meeting in Berkeley, California in July 2001.

Following the ISSC invitation in late-2001 to a number of countries to submit Letters of Interest in hosting the SKA (see Sect. 7.3.1), Mokhele, Jonas and Nicolson requested funds from the Department of Science and Technology in mid-2002 for 7 million Rand (€1 million) over 2 years for the preparation of a hosting proposal and employment of several staff to carry out Radio Frequency Interference (RFI) and other studies, and for RFI equipment for field measurements.

The first direct contact of the South African government with the SKA project came in September 2002 when Ekers, as chair of the ISSC and the IAU WG on Future Large-Scale Facilities (see Sect. 3.2.5.1) was invited by Whitelock in her capacity as President of the South African Institute of Physics, in consultation with Nicolson, to give a talk about radio astronomy and the SKA at a meeting of the Institute of Physics in Potchefstroom. This led to a meeting in Pretoria a week later in which Ekers, together with Nicolson and Jonas, enthused Adam, DST Director-General, about the SKA and made the case that South Africa and other countries in Africa should "throw their caps in the ring" for the SKA site.

This proposal was taken up by the DST in November 2002 and, as Adam describes,[48] the case was made outside science. The appeal was the prospect of a world-class scientific and engineering project on the African continent, the big data challenge, and the potential to use the SKA project to attract and retain young people in science and technology in Africa. "Having a project located in your country creates a centre of science and engineering, which stimulates technology in local industry and science and technology in universities." This wider case allowed two other major government ministries in addition to Science and Technology to get involved in SKA planning, Foreign Affairs via the African development angle (see Fig. 3.10), and Trade and Industry via industrial standards and leading-edge technology competitiveness. Provincial and local government also became involved because of regional development.

With this increasing involvement in SKA, it was clear that a project manager would be required and Bernie Fanaroff[49] was engaged to fill that position. A South African SKA Steering Committee was formed in January 2003, chaired by Adam, with

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[48] hba.skao.int/SKAHB-27, South Africa's Motivation for joining the SKA, R. Adam, Presentation at the SKAHistory2019 Conference, 2019.

[49] Bernie Fanaroff was an internationally known radio astronomer who had served as Director-General in the Mandela Presidency reporting to the Minister without Portfolio responsible for the Government's Reconstruction and Development Program.

**Fig. 3.10** Group photograph of delegates at the Africa regional SKA workshop held in Pretoria in October 2004. Delegates came from South Africa, Namibia, Botswana, Mozambique, Mauritius, Madagascar, Kenya, Ghana and Zambia (credit: SKA South Africa)

Mokhele, Fanaroff, Jonas and Nicolson as the initial members (see Fig. 3.11). Later, other members were added to the Steering Committee from the DST and the NRF.

Once the candidate site in the Karoo desert had been chosen, a plan for radio astronomy was developed focusing on a series of ever larger radio telescopes on the site—KAT-7[50], MeerKAT, and then Big KAT. Significant funding (Rand 30 million, about €3.3 million) was made available from the central government in 2004,[51] more than expected by Fanaroff and his team, for engineering design, site bid development and human capital development. The perception that South Africa was punching above its weight, and other countries were involved in the competition for site selection, had piqued the competitive instinct in government. In addition, the SKA project was popular, particularly in the Mbeki presidency (see Box 3.5), because it was seen as an “amazing footprint of modernity” in the African continent, and the iconic high-tech project in South Africa post-apartheid.[52] Section 4.3.3.2 carries on this story in the following period of development for the SKA and charts the outlines of the funding process leading to MeerKAT.

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[50] KAT stands for Karoo Array Telescope.

[51] hba.skao.int/SKAHB-29, News from the South African SKA Steering Committee, Supporting paper for the 12th ISSC meeting, July 2004.

[52] hba.skao.int/SKAHB-27, South Africa’s Motivation for joining the SKA, R. Adam, Presentation at SKAHistory2019 Conference, 2019.

**Fig. 3.11** The five South African "musketeers". Left to right: Bernie Fanaroff, Rob Adam, Khotso Mokhele, George Nicolson, and Justin Jonas. Photo taken at the Conference on SKA History held at SKAO Headquarters at Jodrell Bank, UK in April 2019. (Credit Rob Adam)

### Box 3.5 Quote from the Executive Summary of the 2005 SKA Site Bid by Southern Africa Countries (See hba.skao.int/SKAHB-441 *South African Bid to Host the Square Kilometre Array*, 2005)

President Thabo Mbeki, in his address at the opening of the 10 m Southern African Large Telescope (SALT) on 10 November 2005, said that the Government is "determined to provide everything necessary to create the optimal environmental and other conditions to support and facilitate the research efforts of the world's astronomers, including the most up-to-date information and communications technological infrastructure" in order to make Southern Africa a hub for astronomy in the Southern Hemisphere.

On the last day of 2005, the site bid was delivered to the SKA Director and, eight months later, the southern Africa site was one of the two on the short-list (see Sect. 7.4), a considerable achievement in 5 years from a standing start.

#### 3.3.3.8 USA

**Governance** As noted in Sect. 3.2.6.5, the US radio community was the first to form an SKA Consortium (USSKAC), in March 1999. It was formed for the purpose of coordinating an SKA development program in the United States, with a primary focus on a “Large-N” SKA design consisting of a large number (of order hundreds to one thousand) “stations” each consisting of some number of antenna elements. Initial members were the California Institute of Technology, including the Jet Propulsion Laboratory; Cornell University, including National Astronomy and Ionosphere Centre; Georgia Institute of Technology; Harvard-Smithsonian Centre for Astrophysics; Massachusetts Institute of Technology, including Haystack Observatory; Ohio State University; the SETI Institute; the University of California Berkeley; and the University of Minnesota. For the reasons noted in Sect. 3.2.6.5, the National Radio Astronomy Observatory was initially represented by at-large members for the Consortium’s first two meetings in 1999, but became a formal member thereafter.

**Funding** Also in early 1999, preparations were in full swing for the US Academy of Sciences 2000 Decadal Review of Astronomy and Astrophysics (ASTRO2000). This provided a good opportunity to obtain funding to support the design and prototyping of the Large N-small D concept (LNSD, many relatively small dishes) for the SKA that had been under consideration for a number of years by the University of California at Berkeley and the SETI Institute as the one-hectare telescope (1 hT, later the Allen Telescope Array ATA). Additional technical components under consideration for funding were: (i) large-N configuration studies at MIT Haystack Observatory to explore the advantages of such configurations for image quality; (ii) RFI suppression techniques, full-sampling array feed design and implementation, and simulations of the sub-mJy sky at NRAO; and (iii) an array for space navigation at JPL for the Deep Space Network.

Copies of the OECD radio astronomy working group report and annexes were sent directly to the Academy of Sciences by Harvey Butcher as coordinator of the activities undertaken under the 1996 MoA to ‘Cooperate in a Technology Study Program Leading to a Future Very Large Radio Telescope’ (see Sect. 3.2.2). Presentations on SKA to the Radio-Millimetre-Sub-millimetre (RMS) Panel advising the 2000 US Decadal Survey Committee were made in February 1999 by Russ Taylor as SKA Project Scientist and Ron Ekers as Chair of the International SKA Steering Committee[53,54] emphasising the global nature of the project. These efforts were successful, and the Decadal Review process recommended $22 million for SKA technical development for the SKA in the coming decade (McKee & Taylor,

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[53] hba.skao.int/SKAHB-30, *Report to H. Butcher on the meeting of the Radio-Millimeter-Sub-millimeter (RMS) Panel*, February 1999, in Washington DC, USA, Taylor, A. R., 1999.

[54] hba.skao.int/SKAHB-17, *Canada and the SKA Project, 1995–2012,* Presentation at SKAHistory2019 Conference, Taylor, A.R., 2019.

2001).[55] However, a subsequent multi-institute proposal to the National Science Foundation Advanced Technology Initiative (ATI) program in 2001 led by Jim Cordes at Cornell University for a three-year SKA Technical Development Program (TDP) generated only $2.5 million and a promise that further funding may be available later in the decade.

The funding supported ongoing efforts by the SETI Institute and UC Berkeley to build the Allen Telescope Array, development work in the US on LOFAR by the Naval Research Laboratory and MIT/Haystack Observatory, implementation of NRAO's EVLA, and work at JPL on large-array designs for the next generation Deep Space Network. The only direct funding for new SKA design work came from a separate ATI grant to Sandy Weinreb at JPL and Per-Simon Kildahl at Chalmers University of Technology in Sweden for wide-band single pixel feed development for radio astronomy (see Sect. 6.6.1.1).

By the time the main ATI grant was due to end in 2005, the NSF Astronomy Division had decided to undertake a "senior review" of all the facilities and operations supported by that division which meant a final decision on funding of the TDP was delayed pending the outcome of the senior review. This delay lasted until 2007. In view of the later departure of the US from the global SKA project in 2011, one can only speculate whether an NSF grant of the recommended $22 million early in the decade before Europe obtained its SKA funding might have changed the course of the SKA, resulting in a US-led project.

**Siting** USSKAC organised a US Site and Hosting Committee in 2002 to prepare an 'Initial Site Analysis Document' for the ISSC, based on a Strawman Design Whitepaper[56] authored by Ken Kellermann and colleagues. The US Consortium proposed to host the SKA in the South-West of the US where the NRAO's VLA is located with SKA antenna locations spread across the US and parts of northern Mexico. But in the end, there was insufficient support in the US Consortium for submitting a full proposal for siting the SKA in the US (see Sect. 7.3.5). The primary reasons[57] were reluctance among the university community for NRAO to take charge of US involvement in SKA matched by reluctance from the NRAO Director

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[55] Recommendation on *Square Kilometer Array Technology Development* in the ASTRO2000 report, McKee, C. J, and Taylor, J., "The SKA is an international ground-based centimeter-wave radio telescope array with $10^6$ square meters of collecting area that will enable study of the first structures and the first luminous objects to form during the dawn of the modern universe, and will provide unprecedented images of protostellar disks and the neutral jets launched by young stars. SKA's sensitivity will be a factor of 100 greater than that of existing centimeter-wave facilities. The increase in sensitivity has great discovery potential, and SKA will revolutionize the study of objects and phenomena that are currently undetectable at centimeter wavelengths. The U.S. SKA development program will, in collaboration with the international radio astronomy community, aggressively pursue technology and technique development in this decade that will enable the construction of the SKA in the following decade."

[56] The Strawman Design centred on the Large Number of Small Diameter (LNSD) dishes concept (see hba.skao.int/SKASUP6-9).

[57] K. I. Kellermann, email to R. T. Schilizzi, 6 April 2022, R. Schilizzi personal archive.

to get involved in SKA in a major way while ALMA was still demanding substantial resources. In addition, the person designated by the Consortium to coordinate the site bid, Neb Duric from the University of New Mexico, left radio astronomy for another research field.

## 3.4 The End of Grass-Roots Governance: Funding Agencies Begin to Take a Global Role in the SKA: June 2005 to February 2006

By early 2005, the international governance and management structure of the SKA project was well established, and national SKA governance structures had also evolved to be able to manage the increasingly large grants being received. What was not in place was any well-defined route towards the multi-national funding required for SKA construction, then estimated as 1 billion Euros (Schilizzi, 2004).

Although it might seem that contact on funding between the ISSC and the group of funding agencies/government departments already supporting national SKA activities, or intending to do so, would have been a good idea as early as possible, the ISSC meeting minutes show that the topic caused lively debate for a number of years in the early 2000s.

"Politics" was never very far from anyone's mind in discussions on the big questions confronting the project as a whole—site selection, technology selection, governance, and funding. There was, however, a feeling among a number of ISSC members that the selection of site and technology was best left to the experts and run by the ISSC, and that approaching the agencies with these questions already solved would be evidence of project maturity and its readiness for serious funding on an international scale.

An ISSC meeting in early 2003 discussed the relative timing of the site and technology decisions and approaches to Funding Agencies.[58] Debate focused on two approaches without coming to a formal conclusion: (i) decide on site, technology and governance simultaneously in order that trade-offs could be made that allowed the various partners to remain engaged in the project; or (ii) first make the site decision in order to reduce the level of politics and focus on the best site for the science.

A year later in further debate on this issue,[59] ISSC member, Brian Boyle (CSIRO, Australia), and some others supported the first approach and argued that staying objective and quantitative for as long as possible on the site selection and having an independent grading process, was essential to obtain broad support. In that same discussion, Harvey Butcher pointed out that the LOFAR site selection had shown that it was most likely that a small number of sites will be almost equal in satisfying

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[58] hba.skao.int/SKAHB-31, *Minutes of the 9th ISSC Meeting*, January 2003.

[59] hba.skao.int/SKAHB-437, *Minutes of the 11th ISSC Meeting*, January 2004.

the selection criteria and that political factors will ultimately play a role. Stefan Michalowski, Executive Secretary of the OECD Global Science Forum, commented along similar lines to Schilizzi in 2004[60] that:

> Site decisions are the most contentious in international projects and unless one site is clearly better than all others, the site decision must be made by the politicians.

Michalowski felt that, in general, financial inducements are hard to separate from "best science" considerations.

### 3.4.1 The Heathrow Meeting in June 2005

Until 2005, contacts with Funding Agencies on funding SKA activities had been at individual national level, apart from the approach to the European Commission by Arnold van Ardenne, Peter Wilkinson and colleagues in the European SKA Consortium that led to the SKADS project (see Sects. 3.3.3.4 and 6.5). The contacts with the OECD Global Science Forum, described in Sect. 3.2.5.2, did not involve funding but did have both international and national impact.

This changed in early 2005 during an ISSC discussion on a collective approach to the funding agencies.[61] There remained a vocal minority in the ISSC, primarily among the US delegation, that was in favour of delaying the first contact as long as possible since that would signal that scientists were losing control of the project. Others (Butcher, Boyle, Schilizzi) voiced the need to move to a site selection procedure and a governance structure that was firmly in place in 2010 with enough detail to satisfy the governments, and so maximise the chances of major funding for the full SKA. To avoid the pitfalls that were seen as having occurred in other large international projects, the ISSC felt a strong need to 'guide' the process.

**Box 3.6 Countries and Observers Represented at the Heathrow Meeting of Funding Agencies on SKA in June 2005**

Australia (Martin Gallagher), Canada (Greg Fahlman), France (Anne-Marie Lagrange, Laurent Vigroux), Germany (Thomas Berghoefer), Italy (Paolo Vettolani), Japan (Shoken Miyama), Netherlands (Annejet Meijler, Ronald Stark), South Africa (Rob Adam), Spain (Carlos Alejaldre), UK (co-chair, Richard Wade), USA (co-chair, Wayne van Citters). Observer: ESO (Catherine Cesarsky).

Also present were two representatives from the large optical telescope community: Gerry Gilmore (UK) and Doug Simons (USA).

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[60] hba.skao.int/SKAHB-32, Stefan Michalowski, 6 October 2004, conversation with R. Schilizzi, Schilizzi Notebook 4.

[61] hba.skao.int/SKAHB-33, Minutes of the 13th ISSC Meeting, March 2005.

**Fig. 3.12** The co-chairs of the June 2005 Heathrow meeting of Funding Agencies on large optical telescopes and the SKA. Left: Richard Wade, Program Director and Deputy Chief Executive at the UK Particle Physics and Astronomy Research Council (Credit: Richard Wade), *Right:* Wayne van Citters, Director of the Division of Astronomical Sciences at the US National Science Foundation. (Credit: Wayne van Citters)

ISSC member, Peter Wilkinson, proposed that the ISSC make contact with Richard Wade, the Director of the Astronomy Program at PPARC, UK (Fig. 3.12 left), on how best to raise the profile of the SKA with Funding Agencies around the world in order to engage them in discussions and decisions on global governance and funding for the SKA. This was done. Wade was open to the idea since it transpired that several funding agencies and government departments (see Box 3.6) had already agreed to meet in June 2005 at Heathrow airport to discuss their views on proposed extremely large (optical) telescope (ELT) projects around the world. This was an outcome of several OECD Global Science Forum discussions on global collaboration on big science projects. Wade and his counterpart in the US National Science Foundation, Wayne van Citters (Fig. 3.12 right), were co-chairing the meeting and were charged with establishing the agenda. It was an excellent opportunity to include an initial discussion on the SKA.

This was a turning point for the SKA and marked the start of the transition from a grass-roots project to one in which the partnership with the Funding Agencies grew slowly as confidence was built on both sides to the point when, 6 years later, the project became a legal entity with funding agencies and government departments formally involved in the project. Funding Agency involvement was a key requisite for 2007 European Commission funding for the SKA Preparatory Phase (PrepSKA), and this led to growing co-ownership of the project.

The ISSC submitted two position papers to the “Heathrow Group” outlining the project science, technology choices (including seven antenna concepts), governance, site selection plans, and overall project plan, and inviting agency comments on a number of governance and funding issues. Curiously, no ISSC members were invited to attend the meeting while two ELT proponents, Gerry Gilmore and Doug Simons, remained in the meeting room following the morning’s discussion of large optical telescopes.

As far as ISSC members "guiding the process", only Harvey Butcher is known to have briefed the Netherlands delegates ahead of time. He wrote a well-argued four-page note that included a set of potential positions to take concerning the main factors requiring further study before proceeding to decision-making on SKA construction. These were cost, site selection and operations and the global nature of the project, in particular, governance, procurement, and industrial participation. He suggested that The Netherlands, in view of its prominence on the global SKA stage, should propose that a funding agency working group be formed to address the issues and that a second meeting of the agencies on SKA should be hosted in The Netherlands to discuss WG outcomes.

Following the Heathrow meeting, which was not minuted, no formal statement was issued by the Funding Agencies/governments. Subsequent discussions by ISSC Executive Committee members with Wade, who chaired the SKA discussion, and several other delegates provided a summary of positions taken and conclusions reached (see Box 3.7). The SKA science case was seen to be strong, but the technological readiness was low as evidenced by the variety of antenna concepts under consideration. This cast the proposed timescales into doubt. The Extremely Large [optical] Telescopes were in a better state of technological readiness and had higher priority with the agencies. A suggestion was made by one of the ELT proponents at the meeting that ESO adopt the SKA as a project. This was not taken up at the time but re-emerged in early 2006 (see Sect. 3.4.2) and again in 2008–2009 (see Sect. 4.4.3.2).

**Box 3.7 Heathrow Meeting, June 2005: Agency Comments and Reflections on the SKA Position Paper**

*Australia*—There is commitment and momentum for SKA in Australia, but it wasn't clear how to maintain the momentum.

*Canada*—Extremely Large Telescope (ELT, optical) was higher priority; SKA misses a connection to government. No funding until ALMA and ELT are settled. The ISSC and ISPO are ahead of the project as a whole. The number of technical demonstrators should be reduced.

*France*—First priority was ELT. Second SKA. No new money available.

*Germany*—Small community, Max-Planck-Institute for Radio astronomy is the only major centre.

*Italy*—For the next 3 years, the Sardinia Radio Telescope and VLBI are the priorities.

*Japan*—ELT has a much higher priority.

*Netherlands*—fully involved in the European SKA Design Study (SKADS), no new money available.

*South Africa*—the SKA appeared to be a proliferation of bottom-up projects rather than a coherent whole, and it was unclear what the Agencies were being asked to fund. The timescales were unrealistic.

(continued)

**Box 3.7** (continued)

*UK*—ELT first priority, SKA to follow as soon as possible thereafter.

*USA*—SKA not ready to be proposed. It would be 3–4 years before the NSF could think of providing support for SKA technical development in the US as part of the next decadal survey review.

It was also clear that the global nature of the SKA had both a positive and negative impact. Positive because global collaboration was in favour at government levels at the time as a means of funding large science projects. Negative, because within the USA there was no prospect of serious funding for the SKA until at least 2010 when the next decadal survey took place, although the NSF recognised the strength of the science case and wished US scientists to remain involved in the planning.[62]

A key statement in the ISSC paper was the plan for the final decision on site selection to be taken in 2006.[63] One almost parenthetical remark by Wade to ISSC Chair, Phil Diamond, on this point had far-reaching consequences—SKA site selection in September 2006 (by the ISSC) was premature. The Funding Agencies must be involved (as forecast by Stefan Michalowski a year earlier[64]) and the current 'state of readiness' of the project was not sufficient to enable the agencies to come to a decision on that time scale.

The final comment from the Funding Agencies was that 'The agencies do not want to take "ownership" of the SKA yet because the project is not sufficiently mature.' In their view, the ISSC had raised too many issues in their paper, which were too detailed and too early in the project development. However, they did accept the invitation from the Netherlands delegation to meet again in The Hague in February 2006 to review SKA progress.

This sparked a vigorous debate in the ISSC.[65] Butcher felt that the "comments about project immaturity reflected the inadequacy of the governments/agencies in their ideas of organising the SKA process. As long as there was no vehicle to run the global effort, notions of 'immaturity' in design will prevail as an easy way out of making a commitment." Ekers noted that the competition between the two US ELT proposals was seen as healthy, as was the competition with the ESO ELT. The global consensus on the SKA presented by the ISSC did not fit current models. Also clear was that the ELT was perceived to be ahead of SKA, partly because ALMA was seen

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[62] hba.skao.int/SKAHB-34, *Briefing Note to the ISSC following the 10 June 2005 Meeting of Funding Agencies at Heathrow Airport*, ISSC Executive Committee, Supporting Paper for the ISSC Teleconference, June 2005.

[63] hba.skao.int/SKAHB-35, *Position paper on the SKA,* ISSC, submitted to the Funding Agencies May 2005, Supporting Paper for the ISSC Teleconference, June 2005.

[64] hba.skao.int/SKAHB-32, Stefan Michalowski, 6 October 2004, conversation with R. Schilizzi, Schilizzi Notebook 4.

[65] hba.skao.int/SKAHB-36, *Minutes of the ISSC Teleconference*, June 2005.

as a major radio astronomy facility, and hence the next project should be in the optical/infrared domain. Several ISSC members including Jill Tarter, Butcher and Bob Preston were in favour of leaving the site selection process unchanged, despite the Funding Agencies' comment, since the competing sites were expecting a final decision in 2006. ISSC members from countries in the competition were divided in their views—Australia (Boyle) supported a ranking of suitable sites at this stage; China (Bo Peng) supported a ranking of all proposed sites while South Africa (Jonas) favoured a final selection proceeding from the original site selection process that was nearing completion.

However, the majority opinion in the ISSC was that "the genie was out of the bottle" as far as the Funding Agencies were concerned, and their advice should now be followed (see Box 3.8). The ISSC determined to reverse the "not sufficiently mature" perception of the project and took two far-reaching decisions: (1) it appointed a "Tiger Team" chaired by the Director to create a Reference Design for the SKA by the end of the year building on the work done by the Engineering Management Team and its successor, the ISPO Engineering WG (see Sect. 6.2.1). A Reference Design would allow a far better definition of the SKA's cost and scientific capability, without precluding other technologies eventually replacing some or all parts of any reference design adopted; and (2) It agreed that the outcome of the site selection process should change from a "final decision" on the location of the SKA to a decision on the ranking of the four sites based on scientific, technical and infrastructure cost grounds. This was to form the basis of a recommendation on acceptable sites the ISSC would submit to the governments and funding agencies involved in the SKA in September 2006.[66]

### Box 3.8 Working with Funding Agencies

There was a cultural difference between Europe and the US in terms of how closely to work with funding agencies. In Europe, getting the funding agencies to co-own the project was felt to be a prerequisite to eventually obtaining funds, and success was measured by the level to which an agency person was prepared to argue for your project behind closed doors. For many of the younger agency and government staff, the SKA was a potential career-making project if their role in shepherding the project through the many ups and downs was successful. Similar close relationships with the US National Science Foundation staff members were not standard for international projects.

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[66] hba.skao.int/SKAHB-37, *Issues concerning the Request for Proposals for siting the SKA*, ISSC, August 2005, Supporting Paper for the 14th ISSC meeting held in November 2005.

In a follow-up briefing session with Wade, Diamond and Schilizzi discussed the ISSC decisions on site ranking and a Reference Design, as well as the need for a new project plan taking these decisions into account.[67] Wade agreed that the "Heathrow Group (HG)" was the appropriate body to receive the ISSC recommendation on site shortlist, and to make proposals to higher government authorities on participants in the Roundtable Discussion that would lead to the final site decision. The HG had all the appropriate links to governments, and there was no other obvious recipient for the ISSC recommendation. In addition, despite there being no record that the HG discussed a phased construction schedule for the SKA at Heathrow, Wade noted that there was considerable support within the HG for the concept since that would allow a start on SKA construction while construction of the ELT, which had a considerably higher priority, was in full swing.

The ISSC decisions and briefing sessions notwithstanding, the ISSC Executive Committee (XC) remained cautious about the interactions with funding agencies, in particular the suitability of the Heathrow Group (HG) to receive the ISSC scientific site ranking for further decisions. Some members pointed out that the HG was, at that moment, not a formal group, it had no responsibility, it did not minute its meetings, it had no leader, and had not actually asked for a ranking of sites. This was something the ISSC had decided after the Heathrow meeting would be the outcome of the ISSC selection process rather than outright selection of one site. It would be premature for the ISSC to relinquish control of the selection process to an informal entity after all the work done on the site selection by ISPO and the site proposers. The XC agreed that it was essential to continue engaging the governments/funding agencies in SKA decisions, but the project should wait until a clearer picture existed as to which formal entity the ISSC should submit its site ranking.

In at least one agency delegation, there was also a question on the Funding Agency side about leadership of this global collaboration. Reflecting on the Heathrow meeting in a conversation with Schilizzi,[68] the Australian delegate, Martin Gallagher, noted that the SKA was clearly on a slower path than the ELTs, and a different process would need to be in place for the SKA if it was to be funded concurrently with the ELTs. He supported building the SKA in phases as proposed in the ISSC submission and noted the need for a large Member State to act as "project champion" to lead such a process. With the US unable to play a major role for several years due to the looming Decadal Survey, Europe and the UK in particular, was the obvious choice. This would signal serious international commitment. But in Gallagher's opinion, the European actors at the meeting had not come across as well-prepared for this.

This began to change once the ISSC decisions on the Reference Design and site ranking were made known to Wade in July 2005. This led to serious preparation for

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[67] hba.skao.int/SKAHB-38, *Summary of the main points of 12 July 2005 discussion with Richard Wade*, Schilizzi, R. T., 15 July 2005.

[68] hba.skao.int/SKAHB-39, Martin Gallagher, comments on SKA project, R. Schilizzi Notebook 5, 12 July 2005.

the next meeting in The Hague on both sides and together, with the UK and The Netherlands as meeting host, in the leading role for the agencies. A sense of working together began to emerge. By the time of the Hague meeting in February 2006, it was possible for the ISSC to look back on 2005 as a year of major steps forward in the project:

> 2005 was a seminal year for the Square Kilometre Array (SKA): the SKA science case and a comprehensive description of SKA engineering studies were published; the site selection process moved forwards with four proposals [from Argentina-Brazil, Australia, China and Southern Africa] being received at the end of the year and comparative site characterisation being completed; investment of ~€80M was committed to SKA R&D and pathfinder projects around the world; the funding agencies of interested governments met to discuss the project for the first time at Heathrow in June 2005. In addition, the International SKA Steering Committee (ISSC) and the International SKA Project Office (ISPO) and its working groups have produced a detailed project plan and have defined an SKA reference design.[69]

### 3.4.2 ESO as a Possible Host for European SKA Activities?

Another thread in the governance story began to emerge in Europe in late 2005. For several of the European funding agency representatives at the Heathrow meeting, it seemed sensible to bring European participation in SKA under the umbrella of the largest astronomy organisation in the world, the European Southern Observatory (ESO) . ESO was a Treaty Organisation founded in 1962 with a European-wide membership, and a well-established, long-term funding channel from participating governments. The thinking went that it would be far simpler for European funding agencies if SKA were to be a new department of ESO and so take advantage of an existing organisation rather than set up a new entity.

To this end, Tim De Zeeuw, chair of the Scientific Strategy Working Group of ESO Council invited Phil Diamond (ISSC Chair), Anton Zensus (ESKAC Chair) and Schilizzi (SKA Director) to a meeting at ESO in January 2006 shortly before The Hague Funding Agencies meeting in order to explore possible roles for ESO within the SKA project. Following an earlier consultation with RadioNet Board and European SKA Consortium members to agree the approach, Diamond presented three options for SKA in Europe: (i) set up a separate legal entity to manage the European SKA project on behalf of radio astronomy; (ii) ESO Council becomes the inter-governmental umbrella for SKA within Europe enabling SKA to access ESO services; and (iii) ESO takes on the SKA and it becomes an integral part of the ESO program. If within ESO, a requirement from the radio astronomy community was that funding lines for the SKA and ESO's own ELT project were independent.[70]

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[69] hba.skao.int/SKAHB-40, *An Inter-Agency Group for the SKA (A Discussion Document)*, ISSC, v2.7, 17 January 2006.

[70] hba.skao.int/SKAHB-41, *Ways forward for the SKA in Europe*, Presentation to ESO Scientific Strategy Working Group, Diamond, P. J., 24 January 2006.

Without such a safeguard there was concern that the SKA would be "parked" behind the ELT in terms of priority.

A clear preference emerged in the ESO Working Group for option (iii) but with the ESO Council controlling the budget for all projects including the SKA, rather than there being separate earmarked funds for SKA. There was little enthusiasm for the "bolt-on" option of a separate radio astronomy division, as there would be little return to ESO. There was an equal lack of enthusiasm among the radio astronomy participants for the SKA to be integrated into ESO with no independent control of its budget, which was the preferred choice of the Working Group.[71]

A month after the Hague meeting in a discussion with Diamond, two funding agency representatives, Colin Vincent (PPARC, UK) and Ronald Stark (NWO, Netherlands) voiced some scepticism about integration of the SKA project into ESO, partly since some restructuring of ESO was expected following the completion of Catherine Cesarsky's term as Director-General in 2007. And there this issue was left until 2009 when Tim de Zeeuw had become ESO Director-General; we take up this story again in Sect. 4.4.3.2.

### 3.4.3 The Hague Meeting in February 2006: "Blood on the Floor"

Again, the ISSC provided position papers on the SKA as input to the meeting—the "Discussion Document" on the formation of an Inter-Agency Group[72] (the source of the quote at the end of Sect. 3.4.1), and a revised Project Plan[73] taking into account the changed approaches to site selection and technology development resulting from the Heathrow meeting discussed briefly in Sect. 3.4.1 and more extensively in Sects. 7.3.7 and 6.2.1 respectively.

The Discussion Document noted:

> As the SKA gathers momentum and astronomers and funding agencies look towards proposals for construction funding at the end of the decade it is necessary to start addressing the issues that will lead towards an appropriate and sustainable international status for the project in its next phase.
>
> The view of the ISSC is that this is best achieved by the formation of an inclusive inter-agency group that will work with the ISSC in developing the SKA. Such a group could be analogous to the FALC: Funding Agencies for the Linear Collider.

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[71] hba.skao.int/SKAHB-39, Schilizzi, R. T., SKA Notebook 5, 24 January 2006.

[72] hba.skao.int/SKAHB-40, *An Inter-Agency Group for the SKA (A Discussion Document)*, ISSC, v2.7, 17 January 2006.

[73] hba.skao.int/SKAHB-42, *International SKA Project: Project Plan*, ISSC, January 2006

> The membership of the proposed group, possibly called the FASKA [Funding Agencies for SKA], should be defined by the Funding Agencies meeting in The Hague in February 2006.

Compared to an earlier draft of the Discussion Document,[74] the last sentence was a substantial change. This followed a robust Special Teleconference of the ISSC on 16 January 2006[75] and a subsequent telling email discussion among a number of leading members of the ISSC. The earlier draft, with minor clarifications indicated by square brackets, read:

> One crucial activity to be undertaken by the [inter-agency group] in 2006 would be the writing of a Memorandum of Understanding for the establishment of an SKA Board, possibly in 2007. While the broad membership of [the group] would be appropriate for drafting the MoU, only those agencies actively contributing to the project would sign the MoU and contributions would be recorded in an annex to the MoU.

The earlier formulation brought a simmering issue in the ISSC to the fore during the ISSC teleconference: how to account for the different tempos and levels of funding for SKA development in different parts of the world in any new governance structure, and in particular in leadership of the project in that new structure. Related to this was how realistic were the project schedule and construction costs set out in the project plan.

Diamond, ISSC Chair, addressed this issue directly in an email to the ISSC,[76] again with minor additions in square brackets for clarity:

> …there is a significant fraction of the global community and the ISSC [Europe, Australia and South Africa] that has money now, has prospects of significant funding in the near term, and is generating the political will within its governments to push the SKA forward. Then there is a second group, within which the USA is dominant, that has unfortunately little prospect of significant funding [before the US Decadal Review had run its course], and little prospect of generating the necessary political will to get involved with other governments and make the decisions that need to happen.

Diamond felt that the first group could not be slowed down or their funding would dry up and the SKA would 'wither and die'. A means had to be found to ensure the second group stayed involved, provided appropriate input, and participated in making decisions in a way acceptable to the governments financially supporting the first group.

Jim Cordes[77] (Cornell University) expressed a widely held view among US ISSC members that:

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[74] hba.skao.int/SKAHB-43, *An Inter-Agency Group for the SKA (A Discussion Document)*, ISSC, v2.5, 15 January 2006.

[75] hba.skao.int/SKAHB-44, Minutes of the Special Teleconference Meeting of the ISSC, 16 January 2006.

[76] hba.skao.int/SKAHB-45, Emails on the future governance of the SKA, 19–21 January 2006, Diamond, P. J., Terzian, Y., Cordes, J., Dewdney, P. E. D.

[77] hba.skao.int/SKAHB-45, Emails on the future governance of the SKA, 19–21 January 2006, Diamond, P. J., Terzian, Y., Cordes, J., Dewdney, P. E. D.

> ...funding for the SKA could not be considered in a vacuum that ignores how current resources are spent on cm/m wavelength astronomy. Since radio astronomy has been especially good at encouraging global sharing of facilities, the decision-making processes for the SKA should be based on a systems view that takes account of how resources for cm/m facilities are best allocated over the next decades. These decisions are major ones and should be made with full participation of all the stakeholders'. He held that any analysis of current funding would show the US as a major contributor to radio astronomy with a major stake in what happens in the SKA for its own sake as well as for continued funding for US facilities, even if it was not contributing significant amounts of direct funding to SKA at any given time.

In the context of the Project Plan, he also contended that the project plan total cost estimate (€1 billion) and 2014 start of construction reflected an ideal situation, its presentation to Funding Agencies now was "presumptuous". Until this point, the ISSC, with little demur from its members, had always approved project plans including start of construction early in the 2010s decade.

However, Cordes was a pragmatist at heart, and had already conceded during the ISSC teleconference a few days earlier that the SKA Board, if established, would be the embodiment of the Golden Rule: "Whoever has the gold, rules".[78]

To the Europeans this change of heart on the part of the US ISSC members appeared driven by the latter's understandable desire to continue as a major force in the project and be represented on any future SKA Board. Again, to the Europeans, this meant that the US, to maintain its position, would need to delay the global project timescale to match that of decisions on US funding, something that would put the whole project in danger.

Dewdney, one of the ISSC members for Canada at that time, pointed out[79] that there was nothing preventing an official plan that acknowledged that the SKA would be built in stages, the first of which to be funded initially in Europe and subsequent stages funded in the US and elsewhere. All current and future participating countries would have input at all stages. The important point was getting such a plan adopted by the funding agencies, and an SKA Board with US representation could be set up to reflect that plan.

This point won the day and led to the more inclusive formulation on Board membership in the final version of the ISSC discussion document on the formation of an Inter-Agency Group.

This was the first occasion when a crack in project solidarity became apparent. Although the crack closed up after the Hague meeting following the agencies' decision to take a cautious approach to involvement in the SKA and form a Working Group rather than a formal SKA Board (see below), the fault-line remained, as we discuss in Sect. 4.5.3 regarding the US withdrawal from the project at the end of 2011 following the 2010 US Decadal Review. With hindsight, the project schedules created by the ISSC and the Project Office were optimistic and an earlier realisation

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[78] hba.skao.int/SKAHB-39, Schilizzi, R. T., SKA Notebook 5, 16 January 2006.

[79] hba.skao.int/SKAHB-45, Emails on the future governance of the SKA, 19–21 January 2006, Diamond, P. J., Terzian, Y., Cordes, J., Dewdney, P. E. D.

of that might have led to a more explicit phased approach for the SKA acceptable in the near-term, as well as in the white paper submitted to the Decadal Review in 2009. This may have led to a different outcome from the 2010 Decadal Survey.

Invitations to the Hague meeting went to the countries of the parties subscribed to the ISSC Memorandum of Agreement and to Argentina, Brazil, the European Commission, Japan, the OECD and New Zealand.[80] In the event, only the Chinese and OECD Global Science Forum representatives could not attend, the former due to the Chinese New Year celebrations, and the latter due to a schedule clash.

At the meeting in a spectacular location on the top floor of the Dutch Ministry of Education, Culture and Science, delegates heard presentations by the ISSC on science (Boyle), the project (Schilizzi), and organisational aspects (Diamond) , and then went into closed session. Two main conclusions resulted from the Agency enclave:

*Site selection*: a shortlist of acceptable sites was required with no prioritisation, rather than a ranked list of the four sites. No suitable site was to be excluded at this stage. The Funding Agencies clearly envisaged a political-level negotiation at the end with the "acceptable" sites to see which site came up with the best offer in terms of host country premium. As Richard Wade put it, they wanted to see *'blood on the floor'*!

*SKA Board:* in recognition that the project had made substantial progress since the Heathrow meeting, the agencies decided to form a working group, the Funding Agencies for SKA (FASKA), comprising representatives from all countries with an interest in the SKA independent of any commitments of funding. It would meet twice a year to discuss the SKA project with the ISSC and in closed session. A sub-set of the plenary group of agencies, the Funding Agencies Working Group (FAWG)—UK (chair), USA, Netherlands, Australia, South Africa, Canada and the European Commission—was formed to prepare discussion issues for the full working group. These included the site selection process beyond short-listing, future governance, and constraints on the timeline including phasing issues with regard to other large astronomy projects and how they might be addressed. The acronym, FASKA, did not survive its first use, and was replaced by SKA Funding Agencies Group or plenary group of Funding Agencies until the PrepSKA period when the Group took on formal roles in the project development and changed its name again (see Sect. 4.4.2).

***Concluding Remarks*** There is no doubt the Funding Agency comments at the Heathrow and Hague meetings had a profound effect on the SKA project. The

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[80] Attendees at the Hague meeting were: Marcelo Arnal (Argentina), Graham Cooke (Australia), Greg Fahlmann (Canada), Anne-Marie Lagrange (France), Praveer Asthana (india), Paulo Vettolani (Italy), Makoto Inoue (Japan), Jan van der Donk, Annejet Meiler, Ronald Stark (The Netherlands), Rob Adam, Bernie Fanaroff (South Africa), Rafael Bachiller (Spain), Finn Karlssen (Sweden), Richard Wade, Colin Vincent (UK), Wayne van Citters (USA), Robert Jan Smits, Elena Righi-Steele (European Commission), Peter Quinn (ESO), Phil Diamond, Brian Boyle, Yervant Terzian, Richard Schilizzi (SKA Project).

Reference Design was formulated in December 2005 some years earlier than had been the ISSC's intention; the final site selection in 2006 became a site short-listing; the potential for the SKA to be built in scientifically useful stages—phased implementation—was adopted as a fundamental part of the Project Plan (see next chapter); and, as a consequence of the site short-listing, major SKA precursor telescopes were designed and built in Australia and South Africa, the two short-listed candidate sites, as fall-back outcomes were the site decision to go against them.

The Hague meeting marks the point when the SKA project began its transition from a global grass-roots collaboration to a global project with a new legal entity at its heart and funded to take on the Pre-Construction Phase. In the next chapter, we trace how this transition was accomplished in project governance and funding. Other chapters describe the transition from a set of independent national and regional, in the case of Europe, engineering efforts into a coherent global SKA design process (Chap. 6), the maturing of the site selection process following the Funding Agency intervention at the Heathrow meeting in 2005 (Chaps. 7 and 8), and the formulation of a focused policy on industry engagement (Chap. 10).

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# Chapter 4
# Transition to a Science Mega-Project, 2006–2012

## 4.1 Introduction

The Hague meeting of funding agencies involved in the SKA in February 2006 (see preceding Chapter) signalled the start of the transition of the SKA from an astronomer-led semi-formal collaboration on a global scale to a fully-fledged inter-governmental organisation in 2021 capable of designing and constructing the world's largest radio telescope. A journey of 15 years.

Following the Hague meeting, the SKA landscape was becoming clearer but the path to a working telescope was less so. The magnitude of the task was described at the time by the SKA Director as follows[1]:

> The Square Kilometre Array is a complex global project with many interacting players and parameters. The players involved are the global astronomical community, the International SKA Steering Committee, the design concept teams, the International SKA Project Office Working Groups and Task Forces, the independent Advisory Committees, Governments and Funding Agencies, and Industry. The parameters include the science drivers, engineering solutions versus practicality, cost, site constraints, available human resources, national and regional scientific interests, national and regional technical interests and prowess, positioning with respect to other major scientific infrastructures, diverse uncoordinated national and regional funding channels, and diverse national policies on involvement of industry in the development and procurement of major scientific infrastructure.

This chapter describes a time of great change in the project, a time when the governance was transformed from a Steering Committee to a new astronomy organisation and major decisions on the course of the project were made. Creating a new organisation to lead and manage the development and construction of a global

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[1] hba.skao.int/SKAHB-46. *Options for the Square Kilometre Array 2005-2010*, R. T. Schilizzi, supporting paper for the 15th ISSC meeting, February 2006.

R. T. Schilizzi et al., *The Square Kilometre Array*, Historical & Cultural Astronomy,
https://doi.org/10.1007/978-3-031-51374-9_4

astronomy mega-project had never been done before[2] and all parties involved, the astronomical community and the funding agencies, were working in uncharted territory.

The driving force for this change, globally, was the European Commission-funded Preparatory Study for SKA (PrepSKA) which began to be discussed in 2005 and was funded in 2008. It had as its top-level deliverable a "signature-ready" agreement for construction of the SKA. National SKA funds supported most of the human resources involved in PrepSKA and other SKA-related activities. It became the collaboration vehicle that dominated the global SKA landscape from 2008 to 2011.

To set the scene for PrepSKA, it is necessary to sketch the changing relationship between the project and funding agencies in the 2006–2007 period as well as the national and regional activities (such as the European SKA Design Studies, SKADS) and roadmaps for large astronomy projects in place or under development at that time. With this background, we enter the PrepSKA period. To deliver a "signature-ready" agreement for construction of the SKA, the SKA parties—the astronomy community represented by the International SKA Steering Committee (ISSC) and the funding agencies represented on the Funding Agencies Plenary Group—had to enhance their own governance roles in the project as well as the management structures to handle properly the tasks in PrepSKA. We describe that evolution in governance for the ISSC and Funding Agencies Group from the situation in 2006 to the creation of the Founding Board in March 2011, and finally to the establishment of the first legal entity (a UK Company Limited by Guarantee) for SKA in December 2011. Subsequently, the parallel path to an Implementation Plan and Agreement for the Pre-Construction Phase is described, and three important project-wide issues that arose on the way are analysed. The chapter concludes with a brief look at the governance and management structures implemented for the new legal entity for the Pre-Construction Phase.

To help the reader navigate through the many overlapping threads of activity, discussion and decision in this chapter, Fig. 4.1: provides a graphical view of the timeline for the different governance entities and activities in the 2006–2012 period. The accompanying Table 4.1: Major milestones, events and decisions in the 2006–2012 period provides a chronological overview of the major milestones, events and decisions in the same period.

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[2] The Atacama Large Millimeter-submillimeter Array (ALMA) is a partnership among existing organisations in Europe, North America and East Asia in cooperation with the Republic of Chile (see Wikipedia) and is not in itself a legal entity.

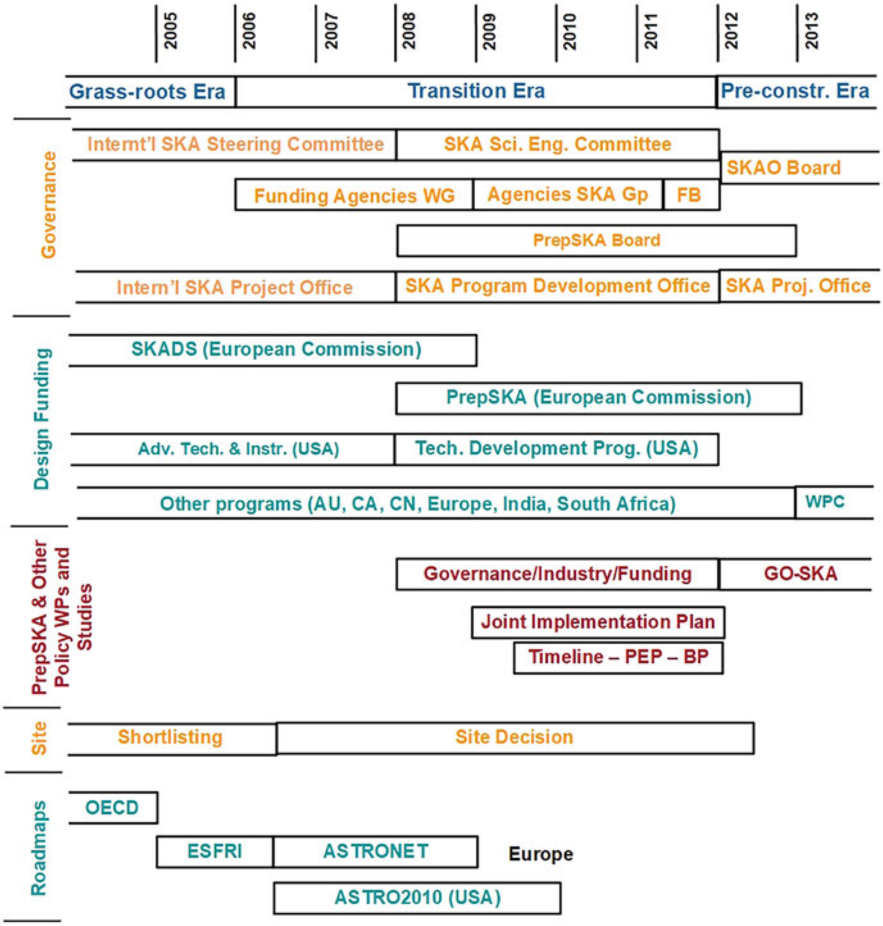

**Fig. 4.1** A timeline showing when the different SKA governance entities were in operation and when the major activities took place. Acronyms: FB—Founding Board; SKADS—SKA Design Studies (see Sect. 3.3.3.4.3); PrepSKA—Preparatory Phase for the SKA; AU—Australia; CA—Canada; CN—China; IN—India; RSA—Republic of South Africa; WPC—Work Package Consortia; GO-SKA—Governance Options for the SKA; PEP—Project Execution Plan; BP—Business Plan; OECD—Organisation for Economic Cooperation and Development; ESFRI—European Strategy Forum for Research Infrastructures. Note that the terms “Pre-construction Phase” and “Pre-construction Era” are used interchangably in this chapter

**Table 4.1** Major milestones, events and decisions in the 2006–2012 period

| | |
|---|---|
| 2006 | Decision on a short-list of two possible locations for the SKA telescope: Australia and Southern Africa (led by South Africa);<br>South Africa and Australia start major SKA Pathfinder projects;<br>SKA included on the European Strategy Forum for Research Infrastructures (ESFRI) list |
| 2007 | Manchester chosen as location of SKA Program Development Office (SPDO) for the period 2006–2011 |
| 2008 | European Commission—Framework program 7 preparatory phase for SKA (PrepSKA) begins;<br>SKA given equal-top priority for future large ground-based astronomy facilities in the European ASTRONET survey roadmap |
| 2010 | Further technology down-select to a "baseline design" for SKA phase 1[a] and an "Advanced Instrumentation Program";<br>SKA not included for construction funding in the 2010–2020 decade in the US Decadal Survey of Astronomy and Astrophysics (ASTRO2010). |
| 2011 | Manchester chosen as location of SKA Organisation Headquarters in the pre-construction phase;<br>Legal entity for SKA organisation established in the UK;<br>Pre-construction phase begins |
| 2012 | Decision to locate the SKA telescope in both Africa and Australia |

[a] To remind the reader, SKA Phase 1 was defined as 10% of the collecting area of the full SKA, called SKA Phase 2 or SKA2. A 3rd phase SKA3 was also envisaged to enable observations at frequencies from 10 to >25 GHz

## 4.2 The Project-Funding Agency Relationship Develops, 2006–2007

There was little disagreement in the International SKA Steering Committee (ISSC) with the outcomes from the February 2006. Hague meeting described in Sect. 3.4.3. It was hard to argue that the funding agencies should not have a role in setting out the process for site selection—short-list followed by decision—since they would be paying for the consequences. And the very existence of the Plenary Funding Agencies Group was a victory for the ISSC, if not the complete victory envisaged with an SKA Board governed by an MoU among the agencies. The US remained involved, also a victory. Informal comments to ISSC Chair, Phil Diamond (Jodrell Bank Observatory, UK), by two participants in the closed agency session in the Hague revealed that informal statements of the relative priority of the Extremely Large (optical) Telescopes (ELTs) and SKA in various countries had changed substantially since the Heathrow meeting in mid-2005 (see Sect. 3.4.1), with SKA moving in the positive direction. The SKA was now on the map!

A discussion about possible organisational structures for the SKA on the longer term arose in the ISSC centred on two distinct alternatives for a legal entity—the 'corporate model' in the US, and the 'foundation model' in Europe.[3] However, there

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[3] hba.skao.int/SKAHB-47. Minutes of the 15th meeting of the ISSC, March 2006. The corporate model envisaged a not-for-profit company, and the foundation model envisaged a national scientific

was no obvious way to reconcile the two, especially with the distributed 'rest of the world' involved as well. This led Brian Boyle (CSIRO, Australia) to point out that the SKA was proud of being born global and that an international treaty should be the end goal, although this would not be straightforward.[4] Prescient words that took 15 years to come to fruition.

Several ISSC members suggested that the scientists should stay ahead of the Funding Agencies Working Group (FAWG) and guide their governance ideas to make sure the perceived shortcomings[5] that arose in setting up some other large international projects were not repeated. The ISSC should push the process, rather than be pulled along. To this end, a paper "Considerations on policy issues for the SKA"[6] was approved by the ISSC with the intention to set the direction of funding agency-ISSC discussions for a considerable time (see Box 4.1). In particular, it contended that once the site and cost-sharing decisions had been made, governance of the project during final design and construction, and possibly operations, should be consolidated in one body responsible for the project as a whole, e.g. an SKA Council. This would have executive authority under appropriate oversight. Members would be policy makers and astronomers appointed by the governments, and it would operate its own technical and scientific organisation or contract the technical and scientific organisation to a management organisation.

Among other issues raised in the policy paper was the desirability of an "open skies" access policy (see Box 4.1). This was a pre-emptive "shot across the bows" of the funding agencies who were expected to favour SKA access based on contribution levels to telescope construction, as was the case for optical facilities in general. At its first meeting a month after the Hague meeting, the FAWG agreed to use the "Considerations" document to guide Funding Agency thinking.[7] On the other hand, it took 18 months before the funding agencies reacted to the open skies issue, in the negative. While the open skies policy continued to be advocated by the scientific community throughout the Transition Era,[8] it was not adopted by the funding agencies and that has remained the case to the present day.

Clearly, there was no shortage of confidence on the part of ISSC members that they knew how to govern the project. However, at the end of 2006 the funding

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foundation similar to ASTRON and the Joint Institute for Very-long-baseline interferometry in Europe (JIVE) from 1993 to 2015. The latter is now a European Research Infrastructure Consortium, JIV-ERIC.

[4] hba.skao.int/SKAHB-47. Minutes of the 15th meeting of the ISSC, March 2006.

[5] hba.skao.int/SKAHB-48. *SKA Governance: Some Considerations and Examples*, presentation by Ethan Schreier at the 15th meeting of the ISSC, March 2006.

[6] hba.skao.int/SKAHB-49. *Considerations on policy issues for the SKA*, ISPO, February 2006, Supporting paper for the 15th ISSC meeting.

[7] hba.skao.int/SKAHB-50. Notes relating to a meeting on 6 March 2006 among Colin Vincent (FAWG Chair, Science and Technology Facilities Council, STFC), Ronald Stark (Netherlands Organisation for Scientific Research, NWO) and Philip Diamond (ISSC Chair).

[8] For example, Ekers presentation to SSEC /ASG meeting Rome, March 2011. See hba.skao.int/SKAHB-106. Minutes of the 6th meeting of the SSEC, March–April 2011.

agencies fired their own shot across the bows of the ISSC, warning that many obstacles remained in the way of funding approval for the SKA.

### Box 4.1 Considerations on Policy Issues for the SKA, Post-Hague Meeting, February 2006, a Summary

[Reference: hba.skao.int/SKAHB-49 *Considerations on policy issues for the SKA*, February 2006, Supporting paper for the 15th ISSC meeting].

*Governance*

The global SKA project expects to develop in several well-defined phases, requiring an evolving governance structure to succeed the MoA in place until the end of 2006.

In the 2007–2009 period, decisions on the site, cost-sharing, and governance are expected to be taken by an inter-governmental entity. The governance of the project is likely to be shared between the ISSC, responsible for the scientific and technical progress of the project, and the intergovernmental body.

A process leading to agreement on which governments are to be involved in the [site] decision process needs development by the FAWG.

The major concern is the role in the decision process of the USA in the likely absence of any formal commitment to the project before 2012.

Following the site and cost-sharing decisions, governance of the project during final design and construction, and possibly operations, should be consolidated in one body responsible for the project as a whole, e.g. an SKA Council. This would have executive authority under appropriate oversight. Members are policy makers and astronomers appointed by the governments and it operates its own technical and scientific organisation, or contracts the technical and scientific organisation to a management organisation.

*Timeline for site decision and start of Phase 1 construction*

Funding opportunities exist in Europe and Australia. If it transpires that other interested parties are unable to contribute to the Phase 1 construction funding in the 2007–2009 timeframe, we may assume Europe will take the lead in funding construction of Phase 1, supported by at least Australia. In that case, the time scales for final design and start of Phase 1 construction appear to be reasonably well-matched to the funding opportunities.

*Negotiation phase leading to site selection*

The decision on the SKA site will not be taken in isolation; it will be part of inter-governmental discussions on cost-sharing for the design and construction phase of the telescope, its governance structure, and the procurement rules to be adopted.

The financial consequences of selecting one of the scientifically acceptable sites over another will be an integral part of the decision process.

(continued)

**Box 4.1** (continued)

*Open Skies policy*

Radio astronomy has a tradition of a completely open competition for observing time to ensure that the best science is carried out on the facilities, and that different facilities constructed and operated by different entities can be shared by a larger scientific community.

Following a meeting of the FAWG in December, again at Heathrow, Richard Wade briefed Brian Boyle, Ken Kellermann (NRAO, USA) and Wim Brouw (CSIRO, Australia) - ISSC Chair, vice-Chair and Secretary respectively - and Richard Schilizzi (SKA Director) by telephone conference[9,10] on the results of discussions on the SKA. On the positive side, the science case for the SKA was making an impact and there was appreciation for the momentum and enthusiasm building up in the candidate host countries. This was tempered by Wade's description of the project as racing towards a "brick wall" as far as funding on the timescales foreseen by the project was concerned. It would be best to focus on the stepwise Phase 1-Phase 2 approach to get a broader community involved and hold off on major decisions until the project was ready globally. According to Wade, this looked like being 2020 from the financial point of view, a decade later than being planned (ambitiously) by the ISSC and International SKA Project Office (ISPO). However, less than a year after the Heathrow meeting, the brick wall began to crumble in Europe following the positive outcomes for the SKA from the ESFRI and ASTRONET road-mapping exercises described in Sect. 4.3.2.2. The ASTRONET road-map defined a trajectory for co-funding the European ELT (E-ELT) and a phased roll-out of the SKA.

ISSC and ISPO confidence that they had all the necessary management expertise continued to be put to the test when the "Transition Era" of governance got into full swing from 2008 to 2011 and the funding agencies assumed an increasingly dominant role, as we will see later in this chapter.

### 4.2.1 Governance Concepts for SKA, 2006–2007: International SKA Forum

It took until the end of 2007 to come up with proposed governance arrangements for the next stage of SKA development. Additional factors came into play in the interim that steered the project in specific directions. Chief among these were new initiatives

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[9] hba.skao.int/SKAHB-51. Notes written during the briefing by Richard Wade on the FAWG meeting at Heathrow, Schilizzi Notebook #7, 12 December 2006.

[10] hba.skao.int/SKAHB-52, Report on the briefing by Richard Wade on the FAWG meeting at Heathrow by Ken Kellermann to the US National Radio Astronomy Observatory SKA Working Group, December 2006.

to stimulate European scientific collaboration in the European Research Area in the European Commission's 7th Framework Program (FP7). This led to funding for the SKA Preparatory Phase project (PrepSKA), as well as new road-mapping exercises carried out under the auspices of the European Council by the newly established European Strategy Forum for Research Infrastructures (ESFRI) and, for astronomy and astrophysics as a discipline, by ASTRONET, a consortium of European funding agencies and research organisations. We will deal with each of these factors in turn after a short discussion of the interim governance arrangements for the project and funding agencies.

The short-term remit of the Funding Agencies Working Group (FAWG) defined at its meeting in August 2006 in Prague[11] was: (i) to develop an understanding of the time imperative and schedule for SKA construction and understand the constraints on phasing of participation and commitment; (ii) to define the boundary conditions for governance; and (iii) to define the site selection process, post-bid qualification stage. The Secretariat of the FAWG comprised Richard Wade as Chair of the Plenary Group of Funding Agencies interested in the SKA, Colin Vincent as FAWG Chair, and Michelle Cooper as Secretary, all from STFC in the UK.

The FAWG also agreed in principle in Prague to form an International SKA Forum to facilitate engagement between scientists and representatives from departments and funding agencies. The first Forum meeting took place a year later in Manchester and continued annually until the final meeting in Banff, Canada, in 2011. The original Forum concept foresaw it being part of the governance structure to actively provide momentum and focus for project development in addition to information exchange. However, after the first Forum meeting in 2007, the FAWG dispensed with the umbrella function for the Forum, and the format thereafter focussed on information exchange, project promotion and public outreach, with the FAWG and its successors, the Informal Funding Agencies Group (IFAG, 2007–2008) and the Agencies SKA Group (ASG, 2009–2011) continuing to function as the top-level governance body on the Agency side. Later Forum meetings also included representatives from potential industry partners.

To provide time to establish the Forum and develop a new governance structure for the design phase of the SKA, the FAWG recommended continuing the 2004 ISSC MoA for an additional year to the end of 2007.[12] This was consistent with the FAWG's view that there was no prospect of the final site selection occurring in 2008, a long-held ISSC goal. 2009 or 2010 was regarded as a more sensible timescale (see Sect. 8.3.1).

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[11] hba.skao.int/SKAHB-53. Minutes of the Funding Agencies WG meeting, August 2006

[12] hba.skao.int/SKAHB-54. Minutes of the 16th meeting of the ISSC, P. Diamond report on the FAWG meeting in Prague, August 2006.

## 4.3 Large-Science-Project Roadmaps and SKA

This section sketches the larger context within which the SKA was attempting to manoeuver on its way to recognition as a large science project.

### *4.3.1 Setting the Scene: The OECD Global Science Forum Workshops 2003–2004*

In September 2001, the OECD Global Science Forum (GSF, see Sect. 3.2.5.2) convened the first in a series of discipline-focused workshops, in Copenhagen, to review scientific priorities and challenges in condensed matter research, and match these requirements to future large facilities such as neutron and photon sources. This was followed up a year later by a similar workshop in high-energy physics. This prompted the German delegation to the OECD in late 2002 to propose a workshop to study future large-scale international programmes and projects in astronomy and astrophysics with a view to establishing an OECD-wide consultation to assist national administrations in their strategic planning. The lack of any process to coordinate planning on priorities and cost sharing between countries was a key issue, as was the need for a mechanism to compare the processes in different countries and adopt best practices.

Two astronomy workshops were held, in Munich in December 2003 and Washington in April 2004, chaired by Ian Corbett from the European Southern Observatory (and later a member of the SKA Site Advisory Committee in 2011–2012, see Sect. 8.3.6). Ron Ekers was a member of the Workshop Steering Committee. Specific outcomes expected at the outset were a roadmap of potential large facilities and projects for the next 10–15 years, and an enumeration and analysis of issues relevant for long-term priority setting by government officials and scientific organisations interested in international coordination and cooperation. The roadmap did not materialise, but the analysis did.

In a comment on defining a long-term strategic view, the OECD report[13] (OECD Global Science Forum, July 2004) noted that "The selection and phasing of big future projects increases in difficulty as costs go up and timescales stretch out.… The workshops considered whether, in an era… where most large projects intersect with the plans of many countries, it would be valuable to develop a consensus global long-term vision of major long-term projects. A mechanism for achieving such a consensus vision has yet to be achieved. However, international collaboration has continued to take place on a case-by-case basis.".

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[13] hba.skao.int/SKAHB-126. Final report on the OECD Global Science Forum Workshops on Future Large-Scale Projects and Programmes in Astronomy and Astrophysics, December 2003 and April 2004.

Behind the scenes, the Workshop Steering Committee explored the possibilities for an international body—the "mechanism for achieving a consensus vision"—to facilitate the global coordination of plans for large projects in astronomy. This was unsuccessful for a number of reasons. The leading Space Agencies did not attend the Workshops despite invitations to do so, while the US funding agencies argued that their decadal survey process was far more effective, and that the USA had little to gain from any proposed global coordination activities. The International Astronomical Union (IAU) was asked to act as "facilitator" but Ekers, as IAU President at the time, was unable to garner the required support from the Executive Committee with some members seeing this as inappropriate level of involvement in national activities.

In parallel with these workshops, the GSF convened related workshops on Best Practices in International Scientific Coordination in Tokyo in February 2003 and on Management Practices for Establishing Large International Scientific Research Projects at Fermilab near Chicago in October 2004. Science talks incorporating the SKA were given by Brian Boyle, Reinhard Genzel (Max Planck Institute for Extraterrestrial Physics, Germany) and Jill Tarter (SETI Institute) at the astronomy workshops and SKA-specific talks at the other two workshops by Schilizzi.

There is no question that this investment of effort raised the profile of the SKA as an exciting new large international project in the minds of other physicists and astronomers as well as governments, for example in Australia (see Sect. 3.2.6.3). The investment of effort eased SKA's entry into more detailed consideration in Europe by ESFRI in 2005, the European Commission (PrepSKA, 2007) and ASTRONET (2005–2008) as described in the next section.

## 4.3.2 *National and Regional Roadmaps*

In 2005–2006, several of the countries involved in the SKA had national roadmaps or long-term plans in place for astronomy, including Australia, South Africa, Canada, and the USA. Europe was in the process of developing such a plan. The first three countries' plans were mentioned in Sect. 3.3.3. Here, the US and European plans, and SKA's place in them, are outlined in more detail as these were expected to provide at least two-thirds of the SKA construction funds. Table 4.2 lists the projects mentioned in the roadmaps. Achieving high priority recognition in both roadmaps was a pre-requisite for the funding, and the survival, of the SKA as a project in its then current form.

### 4.3.2.1 US Decadal Survey 2000, National Science Foundation Senior Review 2006

The 2000 Decadal Survey set the scene for astronomy developments in the USA, both ground- and space-based throughout the 2000–2010 decade (McKee & Taylor,

**Table 4.2** Large ground- and space- based astronomy projects in the US and European roadmaps in the 2005–2007 timeframe

| Ground-based | Roadmap | Space-based | Roadmap |
|---|---|---|---|
| GSMT | ASTRO 2000 | LISA | ESA Horizon 2000 Plus |
| EVLA | ASTRO 2000 | Next Generation Space Telescope | ASTRO 2000 (USA)<br>ESA Horizon 2000 Plus |
| LSST | ASTRO2000 | GAIA | ESA Horizon 2000 Plus |
| E-ELT | ASTRONET | Herschel | ESA Horizon 2000 Plus |
| SKA | ASTRONET | Integral | ESA Horizon 2000 Plus |
| | | Infra-red Space Observatory | ASTRO 2000 (USA)<br>ESA Horizon 2000 Plus |
| | | XMM-Newton | ESA Horizon 2000 Plus |
| | | Athena | ESA Cosmic Visions |
| | | Euclid | ESA Cosmic Visions |

2001). The National Science Foundation (NSF) funded ground-based instruments as did the Department of Energy, while NASA funded space astronomy missions. As mentioned in Sect. 3.3.3.8, the 2000 Survey Committee recommended USD 22 million for SKA technical developments, of which USD 14.5 million eventually materialised in two NSF grants. SKA technical development was fifth priority among 12 moderate scale initiatives.[14] Chief among the major initiatives were the Next Generation Space Telescope (NGST, later renamed the James Webb Space Telescope), the Giant Segmented Mirror Telescope (GSMT), the Expanded Very Large Array (EVLA) and the Large Synoptic Survey Telescope (LSST). The NRAO MM Array which later became a US-Europe-Japan collaboration, Atacama Large Millimetre-submillimetre Array (ALMA)[15] had already been approved in the previous decadal survey, and was under construction, as was the Spitzer Space Infra-Red Telescope Facility (launched in 2003), and Stratospheric Observatory for Infrared Astronomy (SOFIA, operational in 2007).

International collaboration was seen as advantageous as it provided opportunities for U.S. astronomers to participate in major international projects for a fraction of the total cost. Examples from previous decades were the European Solar and Heliospheric Observatory (SOHO), XMM-Newton, Planck Surveyor, and FIRST missions. The Survey Committee expected international collaboration to play a crucial role in several of their recommended initiatives, including the Next Generation Space Telescope, the Expanded Very Large Array, and the Square Kilometre Array technology development.

In 2005 the NSF established a Senior Review Committee, chaired by Roger Blandford (Stanford University), to examine its portfolio of astronomical facilities

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[14] See hba.skao.int/SKASUP4-1, US Decadal Survey 2000 Prioritized Initiatives.

[15] The proposed cost of the MM Array was USD 135 million (Astronomy and Astrophysics in the New Millenium, 2001, The National Academies Press, ISBN 978-0-309-07312-7) or about one tenth of the final cost of ALMA.

and other activities with the goal of redistributing roughly 15% of annual spending to find operating funds for the planned new instruments included in Table 4.2. In the light of a flat budget outcome for the rest of the decade this meant not operating some existing facilities.

The Senior Review's recommendations in 2006 concerning the SKA were two-fold[16]: (i) "US participation in the international Square Kilometre Array program, including precursor facilities, should remain community-driven until the US is in a position to commit to a major partnership in the project". (ii) The strategic challenge for large facility design and construction was how to accommodate a number of potential projects to follow completion of the construction of the Advanced Technology Solar Telescope in 2014. "There is a strong scientific case for proceeding with the GSMT, the LSST and the SKA projects as soon as feasible thereafter. A realistic implementation plan for these projects involves other agencies and independent and international partners. Some choices need to be made soon; others can await the conclusions of the next decadal survey."

The first recommendation led directly to the release of an additional USD 12M in 2007 for SKA in what became the Technology Development Program (TDP, see Sect. 6.4.7.2). As far as the second recommendation is concerned, SKA was among those that awaited the conclusions of the 2010 Decadal Survey, preparations for which were already being made in 2006. These we describe in more detail later in the chapter.

#### 4.3.2.2 Europe

In 2006, no equivalent roadmap to the US Decadal Survey existed in Europe for ground- and space-based astronomy taken together. A separate roadmap existed for space science but not for ground-based astronomy. The European Space Agency (ESA) had initiated a long-term planning process in 1983 with the Horizon 2000 program that was extended in Horizon 2000 Plus. XMM-Newton (X-ray), Herschel (Infra-red) and Gaia (astrometry) emerged as the ESA-led "cornerstone" missions from those exercises. The Cosmic Vision program followed in 2004 and comprised a variety of astronomy missions to 2035 including Euclid (cosmology), Athena (X-Ray) and LISA (gravitational waves). Each of these programs was the result of a bottom-up process that began with a consultation of the broad scientific community.

For ground-based astronomy, four groupings had a stake in steering its future direction, the astronomers, the European Commission, the national funding agencies, and the European Southern Observatory.[17] New in the mix, mid-2000s, were

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[16] *From the ground up: balancing the NSF astronomy program*, Report from the NSF Division of Astronomical Sciences Senior Review Committee, October 2006, https://www.nsf.gov/publications, accessed November 2022.

[17] hba.skao.int/SKAHB-55. *Astronomical politics in Europe*, Peter Wilkinson, SKA Newsletter, Vol. 8, July 2005.

the European Commission and the national funding agencies. The European Commission was in the process of developing a European Research Area (ERA) and, for prioritising big science projects, was advised by the European Strategy Forum for Research Infrastructures (ESFRI), a committee formed of senior scientists representing the views of the member states. National funding agencies began to act collectively for the first time in ASTRONET, an ERA network initially funded by the European Commission, with the aim of developing a roadmap similar to the US Decadal Survey. The ESFRI roadmap was a top-down process set up by the national governments to look at requirements and timescales for infrastructures across science as a whole. ASTRONET was a bottom-up process to look at astronomy alone and driven by the funding agencies.

#### 4.3.2.2.1 European Strategy Forum for Research Infrastructures (ESFRI)

The ESFRI mission statement[18] is "to support a coherent and strategy-led approach to policy making on research infrastructures in Europe, and to facilitate multilateral initiatives leading to the better use and development of research infrastructures, at EU and international level."

Delegates to ESFRI are "nominated by the Research Ministers of the Member and Associate Countries, and include a representative of the Commission, working together to develop a joint vision and a common strategy. This strategy aims at overcoming the limits due to fragmentation of individual policies and provides Europe with the most up-to-date Research Infrastructures, responding to the rapidly evolving Science frontiers, advancing also the knowledge-based technologies and their extended use."[19]

ESFRI was formed in 2002 by the European Council of heads of state or government of the EU's member states and published its first roadmap for pan-European research infrastructures in 2006. Updates followed in 2008, 2010, 2016 and 2021.

The SKA was proposed for ESFRI consideration as a European research infrastructure in 2005 by the Netherlands delegate in a strategic move instigated by Harvey Butcher from ASTRON in The Netherlands and Peter Wilkinson from Jodrell Bank Observatory in the UK. Both were European members of the International SKA Steering Committee. It was included in the first roadmap in 2006 (see Box 4.2), and in 2016 was designated one of 37 Landmark Projects. ESFRI Landmark Research Infrastructures were those that had been implemented, or had started implementation, under the ESFRI Roadmap and were already major elements in the European Research Area. Each project on the ESFRI Roadmap has been subject to regular review in order to stay on the roadmap.

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[18] ESFRI, https://www.esfri.eu, accessed November 2022.

[19] ESFRI, https://www.esfri.eu, accessed November 2022.

**Box 4.2 SKA in the ESFRI 2006 Roadmap**

The entry in the ESFRI Roadmap read as follows:

> In radio astronomy the next generation telescope should be the Square Kilometre Array (SKA). The SKA will have a collecting area of 1 million square metres distributed over a distance of at least 3000 km. This area, necessary to collect the faint signals from the early universe, will result in a 100 times higher sensitivity compared to existing facilities. The radically new concept of an "electronic" telescope will allow very fast surveys. Thus it will be possible to tackle many important problems, e.g. tests of the theory of relativity or the formation and evolution of galaxies. The site for SKA will be outside Europe. [Reference: https://www.esfri.eu]

As we will discuss shortly, ESFRI recognition was a pre-requisite for inclusion in a "directed call" for proposals for Preparatory Studies by the European Commission.

#### 4.3.2.2.2 ASTRONET

ASTRONET first started in 2005 as a consortium of European funding agencies and research organisations. The principal aim was to encourage a common science vision for all of European astronomy, and its key goals were to deliver a comprehensive strategic plan and an infrastructure roadmap.[20] The strategic plan should cover "the ambitions of all of astronomy, ground and space, including links with neighbouring fields, to establish the most effective approach towards answering the highest priority scientific questions".

ASTRONET followed a two-step process: (i) establish an integrated science vision with strong community involvement to identify key astronomical questions to be answered in the next 20 years; and (ii) construct a roadmap which defines the required infrastructures and technological developments, leading to an implementation plan.

The key astronomical questions were: (i) What is the origin and evolution of stars and planets?; (ii) How do galaxies form and evolve?; (iii) Do we understand the extremes of the universe?; (iv) How do we (and the Solar System) fit in? A Science Vision Working Group and four supporting panels examined each of the key questions (one panel per question), and established the approach, experiment or new facility, needed to make progress. This work led to specific scientific recommendations that were incorporated in a draft version of the Science Vision, made available to the entire astronomical community in late 2006. The draft was discussed in-depth during a symposium in Poitiers, France, in January 2007. The final Science

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[20] *A science vision for European astronomy* (Eds. Tim de Zeeuw and Frank Molster), 2007, ISBN 978-3-923524-62-, published by ASTRONET, https://www.ASTRONET-eu.org/, accessed November 2022.

Vision report concluded SKA would make major contributions to the first three of the key questions.[21]

This was a significant step forward in wider community recognition.

Creating the ASTRONET Roadmap was the second step in the process. A similar review structure was put in place as for the Science Vision exercise, this time with a Coordinating Working Group and five thematic panels. Phil Diamond (UK) and Thijs van der Hulst (NL), as senior European radio astronomers, were members of the coordinating Working Group. The relevant panel for the SKA and the optical E-ELT covered ultraviolet, optical, infrared and radio/mm astronomy. The work of various panels was informed by the ASTRONET Science Vision and the responses from the 100 plus projects in contention to a Coordinating WG questionnaire, as well as five long-range plans developed by ESA and ESO, the Astro-particle ERA-NET, and the EC-funded infrastructure coordination networks, RadioNet (radio astronomy) and OPTICON (optical astronomy). The initial draft of the roadmap was released for community consultation at the Infrastructure Roadmap Symposium in Liverpool, UK in June 2008, and finalised a few months later.[22]

For the SKA, the crucial recommendation was "The E-ELT (Extremely Large Telescope) and the SKA, are the two flagships for European ground-based astronomy in the future. Both of them are therefore included in the European Roadmap at the highest priority level."

Based on the project plans provided by both projects in the questionnaire responses, the Roadmap Working Group judged it possible to establish a phasing plan with significant spending on the E-ELT through ESO starting in 2010 and SKA Phase 1 funding ramping up from 2012. At the end of the E-ELT construction peak in 2016, SKA Phase 2 construction would begin. This phased approach would maintain the necessary momentum and expertise to achieve successful European participation and leadership for both projects. The ability to build a radio interferometer like the SKA in stages allowed what appeared to be an elegant solution for the competition for European funds between the two "flagship" projects. However, the phased funding approach for E-ELT and SKA was only feasible if significant additional funds become available soon after 2010 in order for the E-ELT construction to proceed in a timely manner, and even more so when the construction phases of these two big projects overlapped.

This equal top priority ranking with E-ELT in the European Roadmap, and a plausible phased approach for both projects allowing them to be done at the same time financially, was a decisive moment for SKA's progress in Europe and globally. It showed that there was wide community support for the SKA, and, together with PrepSKA funding, allowed most of the funding agencies in the FAWG to move off

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[21] *A science vision for European astronomy* (Eds. Tim de Zeeuw and Frank Molster), 2007, ISBN 978-3-923524-62-, published by ASTRONET, https://www.ASTRONET-eu.org/, accessed November 2022.

[22] *The ASTRONET Infrastructure Roadmap: a Strategic Plan for European Astronomy*, (Editors: Michael F. Bode, Maria J. Cruz & Frank J. Molster), (2008), ISBN: 978-3-923524-63-1, published by ASTRONET. https://www.ASTRONET-eu.org/, accessed November 2022.

the fence and begin to take an active role in the SKA as we describe later in this chapter.

#### 4.3.2.3 The Large Astronomy Project Landscape in 2006 in the USA and Europe

Table 4.2 lists the large astronomy projects mentioned in the preceding sections on the US and European space and ground-based astronomy roadmaps.

#### 4.3.2.4 Other Roadmaps

A second Decadal Survey in Australia in 2005, "New Horizons: A Decadal Plan for Australian Astronomy 2006–2015", was carried out by a sub-committee of the Australian Academy of Science's National Committee for Astronomy chaired by Brian Boyle. The Survey report reaffirmed SKA's pre-eminent place in the roadmap as the "highest priority new program for Australian radio astronomy" and equal top priority for the SKA and the ELT in the international category. This led to AUD 101M (about €60M) being allocated for the development of the Australian SKA Pathfinder (ASKAP) in two stages in 2006 and 2007, as we discuss briefly in Sect. 4.3.3.1.

Likewise, in Canada, a mid-term review of their Long-Range Plan (see Sect. 3.3.3.2) in 2005 confirmed SKA's place behind ALMA and the Thirty Metre Telescope project in the priority list. In 2008, Russ Taylor and his university colleagues obtained a $CA eight million grant from the Canada Foundation for Innovation for SKA and ALMA development, and in 2009 Taylor was awarded at $CA 1.5 NSERC Strategic Research Opportunity (SRO) Grant from the Natural Sciences and Engineering Research Council of Canada and an $CA 2.5M CANARIE Network Enabled Platform (NEP) grant from Canada's national research and education network, CANARIE.

In China, provisional approval for the construction of FAST—the Five-hundred metre Aperture Spherical Telescope (see Sects. 3.2.6.2, 3.3.3.3 and 7.3.5.4)—was forthcoming from the Central Government in 2007; the estimated costs were the equivalent of €70M.

No explicit roadmap was made in South Africa at this time, but the funding scenario was to provide top-down money to create an astronomy hub in the country. This eventually led to the equivalent of about €150–160 million being spent on the 7-element Karoo Array Telescope (KAT-7) and MeerKAT, the 64-element South African SKA Precursor array (see Sect. 4.3.3.2).

### *4.3.3 SKA Pathfinders and Precursors*

In 2006, SKA Pathfinders had already made their way onto national roadmaps (LOFAR in the Netherlands, and MeerKAT in South Africa) or were funded to do so (ASKAP in Australia). Originally, these three instruments were designated Pathfinders, but after a surge of interest in 2008 in the designation from many existing telescopes, the small number located on the two candidate SKA sites were called Precursors to distinguish them from the others. This applied to MeerKAT and the Hydrogen Epoch of Reionisation Array (HERA) in South Africa, and ASKAP and the Murchison Wide-field Array (MWA) in Australia. Supplementary material SKASUP4-2[23] provides a compilation of the designated SKA Pathfinders. Both ASKAP and MeerKAT were much larger than needed for demonstration of potential SKA designs and became state-of-the-art scientific instruments that also demonstrated national prowess in support of their bids to host the SKA.

#### 4.3.3.1 Australian SKA Pathfinder (ASKAP) and the Murchison Widefield Array (MWA)

Following the Australian Decadal Survey of Astronomy 2006–2015, the Australian Government's National Collaborative Research Infrastructure Strategy (NCRIS) for Radio and Optical Astronomy[24] provided AUD 19 million funding for the extended New Technology Demonstrator (xNTD) in September 2006. The opportunity for NCRIS funding was made known to the Commonwealth Scientific and Industrial Research Organisation (CSIRO) by the Australian Government Chief Scientist at the time, Jim Peacock and a funding proposal was submitted to the government. The proposal tapped into the reservoir of goodwill towards the SKA project already existing in the Government following Ekers' presentation to the Prime Minister's Science, Engineering and Innovation Council (PMSEIC) a few years earlier (see Sect. 3.2.6.3). An additional AUD 30 million came from the CSIRO.

The xNTD was envisaged as an array of 30 dishes equipped with phased array feeds (see Sect. 6.4.7.1.2) and was to be part of the Mileura International Radio Array (MIRA) together with the Low Frequency Demonstrator. There had been pressure from the astronomy community to build an astronomically useful facility not just a demonstrator. The goals were to deliver a major upgrade to Australian radio astronomy capability with a telescope on the proposed SKA site while maximising Australia's prospects for playing a leading role in the technology development for the SKA as well as being selected as the site for this facility. There was also an expectation that eventual investment in the full SKA would mitigate the risks inherent in developing the new phased array feed technology.

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[23] hba.skao.int/SKASUP4-2, SKA Pathfinder*s*.

[24] hba.skao.int/SKAHB-56. *NCRIS Investment Plan for Radio and Optical astronomy*, 2006.

**Fig. 4.2** Some of the dishes in the 36-antenna Australian SKA Pathfinder (ASKAP) telescope on Wajarri Yamaji Country. Credit: CSIRO/Red Empire Media

The NCRIS funding was then expanded by a direct allocation of another $52M by the Department of Energy, Science and Technology (DEST) in May 2007, xNTD was renamed ASKAP (see Fig. 4.2) to make the alignment with SKA in Australia clear, and the number of antennas in the array increased to 36. This funding was directly driven by the international SKA partnership case. The Low Frequency Demonstrator also changed name to the Murchison Wide-field Array (MWA, see Fig. 4.3).[25]

Phased array feeds were an obvious future technology direction for survey science with ASKAP, but they had yet to be demonstrated in an operational interferometer. There was a split in the community on whether it should be a modest ten antenna demonstration which was the preference of the engineers, or large enough to have science impact. The decision for a relatively large, 30-element array was driven by the funding available in DEST rather than by any specific science case.[26] Later, as the site competition became more intense, continued

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[25] The path to the MWA was different and only loosely linked to SKA opportunities at that time. It was a complex collaboration at the start among Australian and US universities that eventually evolved to Curtin University in Perth taking on responsibility for MWA's operation and further development. It influenced the engineering development and calibration procedures for SKA-Low.

[26] In retrospect it was too big a jump in capability, and the pressure to get a large new facility operational on a very tight time scale to satisfy national funding requirements caused some research development steps to be skipped. Ultimately this resulted in ASKAP and its phased array feeds not

**Fig. 4.3** Some of the 256 “tiles” of the Murchison Widefield Array (MWA) on Wajarri Yamaji Country (Credit: MWA/Dragonfly Media)

funding for ASKAP was seen, internally in government circles, as providing a fall-back major facility if the site outcome did not go Australia’s way.

With the national importance attached to ASKAP in the context of the site decision as well as the amount of money committed, the project was, not surprisingly, accorded priority over the centralised SKA effort in terms of engineering resource allocation and any schedule clashes with SKA.[27]

#### 4.3.3.2 South African SKA Precursor (MeerKAT)[28]

Following the decision to bid to host the SKA in Southern Africa in late-2002 and the choice of a candidate location in the Karoo desert for the core site, a plan for radio astronomy was developed to raise the profile of South Africa focusing on a series of ever larger radio telescopes on the site (see Sect. 3.3.3.7). A conventional approach to funding the early demonstrator telescopes was taken in 2003 with a proposal by Justin Jonas for a Research Technology Collaboration Centre (RTCC) at Hartebeesthoek Radio Astronomy Observatory (HartRAO) to coordinate efforts between SKA South Africa, academia and industry. An initial budget of 30 million Rand (€3.3 million) was planned, to be sourced from an innovation fund operated by

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meeting its system temperature specifications and not being selected as the preferred SKA-mid frequency option. There was also competition for engineering staff resources with other major ongoing developments to the existing facilities in Australia.

[27] This applied to the MeerKAT project in South Africa as well. One example of the schedule clash is given in Sect. 8.4.2 in relation to the sensitive Radio Frequency Interference (RFI) measurement campaign at the central telescope core sites in both countries. Due to delays in the design and testing of the RFI equipment, the measurement campaign schedule overlapped with Precursor construction activities in both countries, and the length of the RFI campaign was substantially curtailed.

[28] Much of the material in this section was provided by George Nicolson in emails to Schilizzi on 28 September and 21 December 2022.

**Fig. 4.4** Some of the dishes in the 64-element South African MeerKAT array (Credit: South African Radio Astronomy Observatory)

the Department of Trade and Industry (DTI) and the National Research Foundation (NRC). However, once a decision was taken to build a demonstrator, additional funds were needed and other sources, such as the National Lottery, were approached for a further 30 million Rand.

Ideas for demonstrators began with a science-capable version of the EMBRACE aperture array (see Sect. 6.5.5.2.2) under development by the European SKA Consortium[29] to be located at HRAO. This quickly changed in early-2004 into a 25-element array of 12 m diameter low-cost mesh reflectors in the Karoo desert, and then into a 20-element array of 15 m diameter solid surface reflectors capable of high-quality imaging. The latter concept was pursued via a prototype of the 15 m antenna called the eXperimental Design Model (XDM) and a seven-element array, the Karoo Array Telescope (KAT-7) now with 12 m diameter dishes, built as a testbed to develop the technology for the planned larger array called MeerKAT. By the time the demonstrator had evolved via the XDM single dish into KAT-7 in 2006, funding estimates had grown to 90 million Rand (€10 million), most of which was from unconventional sources within the government. This was facilitated by personal contacts between senior Department of Science and Technology (DST) individuals—Rob Adam (Director-General) and Adi Paterson and Bernie Fanaroff (SKA Project Manager)—with the Finance Ministry officials rather than any traditional proposal-review-funding process.

The progression to the 64 element MeerKAT was driven by increased availability of funding, rather than by a well thought out plan. The eventual total cost of MeerKAT (Fig. 4.4) was about 2 billion Rand (about €150 million) of which 1.1

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[29] *Wide Field Astronomy & Technology for the Square Kilometre Array,* 2011, Proceedings of Science, https://pos.sissa.it/132. See also Sect. 3.3.3.4.3.

billion Rand went into telescope design and construction and 0.9 billion Rand into the telescope infrastructure.

XDM and KAT-7 provided local instruments to support the growing radio astronomy community in South Africa until MeerKAT came into operation in 2017 (see Fig. 4.4). It also became a high-profile stimulus for science and technology education and training in the wider African context via a Bursary Program. The construction and successful operation of KAT-7 demonstrated that the Karoo area was a viable potential site for the SKA in the same way as ASKAP did for the Murchison area for Australia. KAT-7 was a sufficiently large interferometer to show South Africa had the required expertise and innovation to contribute to the SKA design and to support the construction of the SKA if it was to be built in southern Africa. This success relieved the internal pressure on MeerKAT to deliver results on the timescale foreseen for the SKA site decision. However, as with ASKAP, MeerKAT was a sufficiently large project that its national deadlines took priority over commitments to the international SKA project. Also, as with ASKAP, MeerKAT was to provide a fall-back major facility if the site outcome did not go South Africa's way.

As noted earlier, the ASKAP development was constrained by early decisions that were taken before the design was completed. In South Africa it was possible to take a different approach that allowed the design to follow an evolutionary path for MeerKAT, making technology improvements at each stage and taking advantage of new developments in antenna design, receivers, signal processing and correlator. As noted by Nicolson, this flexibility was necessary because the design teams were constantly learning along the way and technology was advancing.

## 4.4 PrepSKA: The Driver for Global Collaboration, 2007–2012

At the August 2006 Funding Agency meeting in Prague, FAWG members plus SKA representatives, Diamond and Schilizzi, heard the first details of plans for a European Commission Seventh Framework Program (FP7)-funded program of Preparatory Phase Studies of infrastructures on the ESFRI Roadmap, from the Commission delegate, Elena Righi-Steele. Inclusion on the ESFRI short-list was to be the selection criterion for inclusion in a directed Call for Proposals for Preparatory Phase Studies. SKA was already in the process of being evaluated for inclusion on the ESFRI Roadmap following the initiative by the Netherlands Government instigated by Harvey Butcher and Peter Wilkinson earlier in 2006 (see Sect. 4.3.2.2.1) and was thought to have good prospects. A Preparatory Study was seen by the agencies as a likely trigger for significant national support in the future since the program was open to participation by non-European agencies and institutes on a self-funding basis. Righi-Steele noted that an FP7 bid for a preparatory study would not require, or imply, full commitment to the SKA.

From the European Commission point of view, it had a long track record in supporting European collaboration in radio astronomy, particularly Very Long Baseline Interferometry (see Sect. 2.3) starting in 1989 and had funded (€10.3M) a major SKA design study on Aperture Arrays, SKADS, in the previous Framework Program 6 (FP6) (see Sect. 3.3.3.4.3). Including SKA in the new FP7 Program was an obvious continuation of previous policy, and one with strong prospects of success.

Formal recognition by ESFRI was duly forthcoming in October 2006, paving the way for the ISSC, led by Diamond, to prepare a proposal, PrepSKA, for submission to the European Commission early in 2007. The final deliverable of each Preparatory Study, PrepSKA included, was to be a "signature-ready" Agreement to fund construction. On the way to that Agreement, it was expected that studies of detailed design, governance, project management, financial engineering, and industry engagement would take place. Most importantly, it was a requirement that interested agencies and governments were responsible for the "policy work-packages"—governance, funding, and industry engagement. Supplementary material SKASUP4-3[30] lists the organisations participating in the PrepSKA proposal and SKASUP4-4[31] describes the work-packages in more detail.

PrepSKA was approved in October 2007[32] for a start in April 2008, and completion in 2011. It provided the focus for Steering Committee/Project Office activities on the SKA design, site characterisation, telescope operations and management, as well as Agency activities on resourcing, governance and legal frameworks, site selection, and procurement.

The specific questions to be answered during PrepSKA were: What is the design for the SKA, and where will it be located? What is the legal framework and governance structure under which SKA will operate? What is the most cost-effective mechanism for the procurement of the components of the SKA, and how will it be funded?

Note that the PrepSKA goals did not include the continued development of the original science case outlined in Chap. 5. This had already taken place under Large Telescope WG and ISSC leadership (see Chap. 3) and would continue to develop as dictated by new results in the field and engineering design requirements without additional funding.

European Commission (EC) funding amounted to €5.5 million. Nominal direct matching national funds for the design and site characterisation amounted to about €15 million. Additional matching funds for the Funding Agency activities on resourcing, governance and legal frameworks, site selection, and procurement had already been committed by the Agencies. Several other national and regional SKA-related projects with design funds already committed were included in the

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[30] hba.skao.int/SKASUP4-3, Participating Organisations in PrepSKA.

[31] hba.skao.int/SKASUP4-4, PrepSKA Work Packages.

[32] hba.skao.int/SKAHB-57. *A Preparatory Phase Proposal for the Square Kilometre Array*, P. Diamond et al., May 2007.

**Table 4.3** Contributors to PrepSKA activities included in the PrepSKA proposal but without direct PrepSKA funding

| Country/ region | Program name | Post-2006 design funds committed (M€) |
|---|---|---|
| Europe | FP6 design study: SKADS | 29 |
| Netherlands | LOFAR | 15 |
| Netherlands | APERTIF | 5 |
| Australia | MIRA (later ASKAP) | 15 |
| South Africa | MeerKAT | 22 |
| USA | EVLA; Technical Development Program | 12 |
| Canada | SKA design; EVLA correlator | 7 |
| Total | | 107 M€ |

PrepSKA proposal, without EC funding, as contributors to the Preparatory Phase activities (see Table 4.3). Many were designated subsequently as SKA Pathfinders or Precursors.

The original plan was to integrate the R&D work from around the globe in order to develop a fully costed design and deployment plan for the SKA and investigate the options for the policy-related questions with active collaboration between funding agencies and scientists. The Implementation plan would form the basis of funding proposals to governments to start the construction of the SKA. This aim was scaled back during the course of PrepSKA as it became apparent that 3 or 4 years was insufficient to progress the engineering design to the point where it was construction-ready, and the “signature-ready Agreement” for start of construction became a Joint Implementation Agreement for the SKA Pre-Construction Phase starting in 2012. This step-change in ambition impacted PrepSKA and the direction of the work-packages.[33]

The key new elements in the FP7 EC Preparatory Phase funding mechanism compared to the FP6 funding mechanisms that underpinned the SKA Design Study (SKADS) were the initial link to ESFRI-recognised large infrastructures and the requirement of the EC “Strategy on emerging large research infrastructures” that the governance, funding model and industry engagement Work Packages, collectively the “policy WPs”, must be led by (European) funding agencies. In SKA’s case, this investment of time and resources by the Agencies brought co-ownership of the SKA project with it, to the benefit of the project.

In the remainder of this section, we review the PrepSKA Work Package aims briefly, and discuss the changing roles and responsibilities of the partners and the governance structures put in place to support the PrepSKA and associated national activities. Also discussed are the practical outcomes of the governance and funding model work packages. Other chapters discuss the PrepSKA outcomes for

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[33] hba.skao.int/SKAHB-61. *PrepSKA WP6 Final report*, 4 Nov 2014.

engineering design (Chap. 6), site characterisation (Chap. 8), industry engagement and procurement (Chap. 10), and the wider impact of the SKA (Chap. 11).

### *4.4.1 PrepSKA Work-Packages*

The main PrepSKA activities were grouped into two technical and three policy work-packages, with additional work-packages for overall management of the program (WP1) and the final deliverable, the Implementation Plan (WP7).[34]

The two technical work-packages were led by the SKA Program Development Office (SPDO), the successor to the ISPO (see Sect. 4.4.2.1). WP2 on SKA Design initially focused on producing a costed, top-level design for the SKA and a detailed system design for SKA Phase 1. As time progressed this was scaled back to focus on the pre-construction phase as we discuss in Sect. 4.6. A detailed analysis of the telescope design work and its management can be found in Chap. 6. Work-package 3 on Site Characterisation, on the other hand, concentrated on additional studies of the short-listed SKA sites in Southern Africa and Australia. Section 8.4 describes the results of this work and its impact on the site decision.

The policy work-packages, WP4-6, were led by the funding agencies in the Netherlands, Italy and the UK respectively, and involved developing options for viable models of governance and the legal framework for the SKA (WP4); developing options for the approach to procurement and the involvement of industry (WP5); and investigating potential financial models required to ensure the construction, operation and, ultimately, the decommissioning of the SKA (WP6). Sections 4.4.3.1 and 4.4.3.3 discuss the outcomes of Work-Packages 4 and 6, and Chap. 10 discusses the efforts to satisfy the goals of Work-Package 5.

In WP7 the activities, reports and outputs of the various working groups were to be integrated to form the SKA Implementation Plan[35] including the costed system design for the telescope[36] and a study of the Economic and Social Benefits of the SKA.[37] The Implementation Plan is discussed later in this chapter in Sect. 4.6 where the Business Plan and Project Execution Plan that underpinned the incorporation of the SKA Organisation at the end of 2011 are discussed. Together with the legal documentation (see Sect. 4.7) and a detailed Work Breakdown Structure for the pre-construction phase produced in 2012 by the Project Office, these documents formed the complete and costed strategy required for the revised main PrepSKA deliverable.

Establishing a framework for coordination of the telescope design effort took considerably longer than anticipated. The proposal and its evaluation took the best

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[34] See hba.skao.int/SKASUP4-4, PrepSKA Workpackages.

[35] hba.skao.int/SKAHB-58. *PrepSKA deliverable report 7.3*, May 2014.

[36] hba.skao.int/SKAHB-59. *PrepSKA deliverable report 7.1*, P. E. Dewdney et al., May 2014.

[37] hba.skao.int/SKAHB-60. *PrepSKA deliverable report 7.2*, S. T. Garrington, May 2014

part of a year, followed by staff recruitment over the next 2 years. Somewhat unexpectedly for a community that had a track-record of collaboration, learning how to work together on a global scale within a formal system engineering structure rather than a free exchange of ideas was not straightforward. The national, and regional in Europe's case, SKA R&D programs had substantial funding (see Table 4.3) and high visibility locally with attendant responsibilities for delivering results on time for the funders. The result was that it took time for the international responsibilities to take centre stage. PrepSKA was under-resourced nationally and, consequently, squeezed for time for much of its life.

As already noted, PrepSKA was funded initially as a 3-year program. However, the engineering design was a four-year program, so there was pressure to move things along sometimes faster than was possible in such a distributed design effort. In the event, the engineering design passed the Conceptual Design Review stage by early 2011 (see Sect. 6.2.2.9), and that proved sufficient for the funding agencies and governments to agree to establish the SKA Project as a legal entity at the end of 2011 as we discuss later in this chapter. The additional year of design effort was funded as a no-cost extension to the PrepSKA contract with the European Commission.

### 4.4.2 Governance Structures to Support the PrepSKA Tasks

Figures 3.1 and 4.1 sketched the main elements of central SKA governance throughout the Transition Era. A tri-partite structure emerged to run the project: (1) the International SKA Steering Committee (ISSC) was replaced by the SKA Science and Engineering Committee (SSEC) in 2008, (2) the Working Group (FAWG) was replaced by the Informal Funding Agencies Group (IFAG) in late 2007. The IFAG was replaced by the Agencies SKA Group (ASG) in January 2009 which, in turn, was replaced by the SKA Organisation Founding Board (FB) in March 2011, and (3) the *PrepSKA Board*. Supplementary material SKASUP4-5[38] provides lists of the members who served on the various committees over the period we cover in this book. At the same time as the SSEC was being established, a parallel evolution of the central project office from the International SKA Project Office (ISPO) to SKA Program Development Office (SPDO) was taking place.

As will become clear, the role of the ISSC and its successor, the SSEC, changed in the course of the Transition Era from one of being in control of almost all aspects of the SKA project in 2006 to one in which, from 2008, responsibility was shared with the funding agencies and the PrepSKA Board. Together with the SPDO, the SSEC was responsible for the central project deliverables of a convincing, well-supported science case and a feasible engineering design, while lead responsibility for the post-PrepSKA governance and funding, procurement policy and the site

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[38] hba.skao.int/SKASUP4-5. *Members of the ISSC, SSEC, Funding Agency groups, Founding Board and PrepSKA Board.*

selection process passed gradually to the funding agencies, as we describe in Sect. 4.4.3.1, and in Chap. 8.

The SSEC and SPDO partnered the ASG in its work on governance, procurement and site selection. The SKA Director and subsets of SSEC members were active members of the ASG Working Groups and Tiger Teams (special purpose, short term WGs created to resolve specific issues), and the SSEC as a whole spent considerable time in their own meetings debating issues that arose from those efforts as well as in joint meetings of the SSEC and ASG from 2009 onwards. The communication, comment, and diplomatic criticism at these joint meetings created a surprisingly strong spirit of collaboration and joint ownership of the project.

The transitions to the new governance structures as well as their roles and responsibilities are now described.

#### 4.4.2.1 SKA Science and Engineering Committee (SSEC) and SKA Program Development Office (SPDO)

***SSEC*** As the details of the PrepSKA program became clearer, the ISSC began to work towards a new International Collaboration Agreement (ICA) for the radio astronomy partners in early 2007 to be ready for the PrepSKA era. It was already clear that the FAWG would continue as the agency equivalent of the successor to the ISSC, and the International SKA Forum would function as the meeting place for the two parties to discuss all aspects of the SKA project across the globe. But there would be an additional element of governance, the PrepSKA Board, with responsibility for the specific PrepSKA Program, and membership drawn from the participating institutes and agencies. The complications of this tri-partite governance were not lost on anyone involved, but in the absence of explicit funding agency endorsement of the SKA at that time, there was no obvious alternative.

The ISSC recognised that the initial SKA MoAs had been successful in establishing the current ISSC/ISPO structure which had delivered a comprehensive science case, reference design concept and site shortlist. But the project had matured to a stage where decisions went beyond those of a purely scientific and technical nature to include the increased investment in SKA-related precursors and pathfinders, further site characterisation and other preparatory work including governance, legal and procurement issues. We return to the tensions caused by the investment in pathfinders and precursors later in the chapter. In addition, there was the new dynamic caused by the interactions with funding agencies and the advice received from them. Taken together, it was clear that the central project office would need to expand, and such expansion would require more funding, particularly for a Central Design Integration Team (CDIT).

The ISSC Executive Committee's initial concept for the International Collaboration Agreement foresaw the ISSC evolving to a structure called the SKA Steering Committee (SSC). This would be governed by an MoA endorsed by the plenary group of the funding agencies and signed by the SKA Consortia in Australia, Canada, China, Europe, India, South Africa and USA, and operate for the period

1 January 2008–31 December 2011. There would be 11 members, three each from Europe and the USA, and one each from Australia, Canada, China, India and South Africa. One of its primary responsibilities would be to provide funds for the SKA Program Development Office (see below).

The SKA Steering Committee idea did not survive the scrutiny of the full ISSC or FAWG entirely intact. The concept of a Steering Committee did not fit the new multi-levelled governance situation so a new name was required, the SKA Science and Engineering Committee (SSEC). The reduction in numbers did not sit well with current ISSC members either. Mike Garrett noted that the number of SSEC members from Europe must reflect the institutes involved since it looked probable that Europe would provide the first large tranche of money. So the total remained at 21 with equal representation from Europe, USA and the Rest of the World countries[39,40] (Fig. 4.5), and even increased in 2010 to 24 as the number of countries in the Rest of the World Group increased by one (Korea, via the Korea Astronomy and Space Science Institute). The ICA was signed in October 2007[41] (see Box 4.3).

### Box 4.3 Signatories to the 2007 International Collaboration Agreement for the SKA Program

The European SKA Consortium
The US SKA Consortium
The Rest-of-the-World Group:
The Australian SKA Coordination Committee, Australia
The Canadian SKA Consortium, Canada
The National Research Foundation, South Africa
The National Astronomical Observatories of the Chinese Academy of Sciences, China
The National Centre for Radio Astrophysics, TIFR, India

As with the ISSC, an SSEC Executive Committee (XC) was established, eventually comprising the SSEC Chair, vice-Chair, past-Chair, Secretary, and the Director, as well as representatives from Australia and South Africa. The XC met once per month, mostly by teleconference.

The principal roles of the SSEC set out in the 2007 International Collaboration Agreement were to provide scientific and technical guidance for the SKA Program while acting as the primary forum for interactions and decisions on scientific and technical matters for the SKA among the institutes. In addition, the SSEC would represent the SKA to the regional and national funding agencies.

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[39] hba.skao.int/SKAHB-63. Minutes of the 17th meeting of the ISSC, March 2007.

[40] hba.skao.int/SKAHB-64. Minutes of the 18th meeting of the ISSC, October 2007.

[41] hba.skao.int/SKAHB-65. International Collaboration Agreement for the SKA (Square Kilometre Array) Program, 2007.

**Fig. 4.5** Delegates to the second meeting of the SKA Science and Engineering Committee (SSEC) in February 2009, held at Jodrell Bank Observatory, UK. Left to right: front row—Steve Rawlings (Europe), Thijs van der Hulst (Europe), Peter Dewdney (SPDO), Ken Kellermann (SSEC Chair, USA), Richard Schilizzi (SPDO), Sean Dougherty (Canada), Yervan Terzian (USA), Luigina Feretti (Europe). Second row—Bo Peng (China), Dayton Jones (USA), Bob Preston (USA), Colin Greenwood (SSEC Secretary, SPDO), Ethan Schreier (USA, Invited), Trish Henning (USA), Michael Garrett (SSEC vice-chair, Europe), Joe Lazio (SPDO), Roy Booth (South Africa), Ron Ekers (Australia, Invited), Geoff Bower (USA). Back row—Yashwant Gupta (India), Hiroyuki Nakanishi (Japan, Observer), Yuri Kovalev (Russia, Observer), Bong Won Sohn (South Korea, Observer), Jim Cordes (USA), Russ Taylor (Canada), Sergei Gulyaev (New Zealand, Observer), David DeBoer (Australia), Peter Quinn (Australia), Justin Jonas (South Africa), Arnold van Ardenne (Europe). Participants not present in the photo: Domingos Barbosa (Europe), Huib Jan van Langevelde (Europe). (Credit: Anthony Holloway, University of Manchester)

Representation of SSEC views to the funding agencies became a much more active interaction as the PrepSKA goals became more focussed, and it became an SSEC and SPDO responsibility to help set the parameters of the policy work-packages with the Agencies SKA Group (ASG), as well as work together with the ASG to achieve the goals.

The SSEC also was responsible for the formal oversight of the SPDO and its activities and outcomes as well as ensuring its continued funding in the same way as the ISSC had been responsible for the International SKA Project Office (ISPO) in the past.

As it had done for the ISSC, the International Engineering Advisory Committee (see Sect. 6.2.2.3) continued to provide a much-valued sounding board for the SSEC on engineering matters.

***SPDO and Its Funding*** The PrepSKA proposal foreshadowed a major role for the central project office (still called the ISPO when the proposal was submitted) in leading WP2 on design and WP3 on site characterisation. To do this as well as carry out its broader mandate from ISPO days (see Sect. 3.3.2)—coordinate the institutions involved in SKA development to achieve a structured and efficient global effort and progress from technology development and system design towards construction of the SKA—the SSEC recognised that additional funds were required to staff the office appropriately. For that, a formal Memorandum of Agreement[42] (see Box 4.4), a new organisational structure, and a new name, the SKA Program Development Office (SPDO), were required.

### Box 4.4 Signatories to the 2007 Memorandum of Agreement to Establish the SKA Program Development Office (SPDO)

Cornell University, USA
Joint Institute for VLBI in Europe, The Netherlands
University of Calgary, Canada
Commonwealth Scientific and Industrial Research Organisation, Australia
National Research Foundation, Republic of South Africa

These were all legal entities representing the interests of SKA in their respective countries or regions with the agreement of their national and regional SKA consortia. They had the responsibility of providing the agreed share of the Common Fund for SPDO operations. They also provided the necessary institutional backing for the SSEC in the future negotiations with the potential host institution for the SPDO (see Chap. 9). This formal approach harked back to that adopted by Harvey Butcher for the first MoA to Cooperate on Technology Development for a Very Large Radio Telescope, signed in 1996 (see Sect. 3.2.2).

The MoA was signed in October 2007 at the same time as the ICA establishing the SSEC and provided for a 'Common Fund' for the SPDO salaries and administration costs based on contributions from nominated lead institutions within each consortium. The MoA would take effect at the start of 2008. The Common Fund

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[42] hba.skao.int/SKAHB-66. Memorandum of Agreement to establish the Square Kilometre Array Program Development Office, 2007.

**Fig. 4.6** SPDO staff in 2011. Standing—left to right: Georgina Harris, Rob Millenaar, Lisa Bell, Wallace Turner, Billy Adams, Duncan Hall, Tim Stevenson, Neil Roddis, Phil Crosby, Kobus Cloete, Andre Gunst, Roshene McCool, Colin Greenwood. Seated—left to right: Minh Huynh, Joseph Lazio, Richard Schilizzi, Peter Dewdney, Greta Collins. Not present: Johanna Bowler. (Credit: Anthony Holloway, University of Manchester)

amounted to about €600 thousand per year, which together with some of the PrepSKA funding allocated for WP2 and WP3, allowed for a peak of 18 SPDO staff (Fig. 4.6) to be employed. At the time of signing of the SPDO MoA, the staff complement in the ISPO was four—the Director—Richard Schilizzi; the Project Engineer—Peter Hall; the Executive Officer—Colin Greenwood; and Office Manager—Lisa Bell. Greenwood also took on the task as ISSC Secretary in 2007, then SSEC Secretary in 2008, and Company Secretary following the establishment of the SKA legal entity in late 2011. Peter Dewdney succeeded Peter Hall as Project Engineer at the transition from ISPO to SPDO in 2008. Schilizzi continued as SPDO Director untl the end of 2011.

With PrepSKA and matching national funding imminent, and a new governance structure and substantial expansion in staff at the central office (SPDO) on the way, the ISSC also decided in 2007 to carry out a competitive selection of a longer-term host for SKA Headquarters (see Chap. 9). The decision to select the University of Manchester as host led to the need for a separate MoU[43] defining the roles and responsibilities of the University and the SSEC, one of which was that SPDO staff would be employees of the University.

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[43] hba.skao.int/SKAHB-67. Memorandum of Understanding between The University of Manchester and the International SKA Steering Committee on hosting the International SKA Project Office, 2007.

The central element of the SP'O organisation was to be a Central Design Integration Team (CDIT) to coordinate the tasks in PrepSKA WP2 on SKA design and integrate the domain knowledge generated by national and regional teams into a costed SKA design (see Fig. 6.2). The Project Engineer would lead the overall SKA design effort and PrepSKA WP2 in particular. Domain Specialists in the various sub-domains—receptors, correlator, synchronisation and data transport, and software—were to provide global leadership in those areas during the SKA system design and associated prototyping and integration activities.

Recognising that good communication between the SPDO-CDIT and regional teams was crucial, national and regional liaison engineers were designated with responsibility for strategic and operational links to the ISPO-CDIT, particularly to the domain specialists and system engineer. They were also to manage prototyping contracts between the SPDO and collaborating groups and ensure that SPDO priorities were reflected in their engineering programs.

In fact, this approach did not prove as successful as hoped. Good communication in the "spoke and wheel" model of the CDIT was not easy to establish with this relatively hands-off approach, and the model of interaction quickly changed to one based on system engineering (see Sect. 6.2.2.2), with a System Engineer, Kobus Cloete, being appointed in 2009. The domain specialists were also appointed in 2008 and 2009. The system engineering approach at global level also took some time to establish due to the lack of experience in this approach in most radio astronomy centres and the resource disparity between the central office and the national and regional programs. Resourcing issues for PrepSKA WP2 continued throughout most of the life of PrepSKA (see Sect. 4.5.2).

The other key PrepSKA activity for the SPDO was the coordination of WP3 on Site Characterisation carried out by the Site Characterisation Working Group (previously the ISPO Site Evaluation WG) under the leadership of the SPDO Site Engineer, Rob Millenaar.

The SPDO also continued with the Working Groups formed during the ISPO era (see Sect. 3.3.1.3). The Engineering WG took on a new role. Led by Dewdney, its task evolved to one of coordinating activities in PrepSKA WP2 with membership comprising the SPDO engineers and the PrepSKA WP2 national and regional liaison engineers. The Science Working Group led by SKA Project Scientist, Joe Lazio, continued to develop the scientific goals of the project, including science simulations, both for SKA Phase 1 and the full SKA with the goal of generating requirements on the telescope design. The Simulations WG, led by Leonid Gurvits, continued to work on simulations of optimum array configurations for the SKA. Coordination of the industry engagement strategy re-emerged as a significant project theme when Phil Crosby joined the SPDO on secondment in 2009. The Operations WG, chaired by Ken Kellermann, continued to develop thinking on telescope operations strategies and their impact on telescope design (see Sect. 6.2.2.13). The Outreach Committee chaired by Ian Morison and later Jo Bowler continued to build up a considerable body of material (website, brochures, fact sheets, animations, newsletters etc) to stimulate outreach to the academic community and general public, as well as to industry and governments in the participating countries. Figure 4.7

Fig. 4.7 A compilation of some of the fact sheets produced by the Outreach Committee and their national counterparts

shows a compilation of some of the diverse fact sheets produced by the Outreach Committee and national counterparts.

#### 4.4.2.2 Funding Agencies: From Working Group to SKA Organisation Founding Board

The funding agencies followed the SSEC-SPDO example a year later in 2009. With the advent of PrepSKA funding in April 2008, the Funding Agencies Working Group (FAWG) transitioned from a group offering informal advice to the SKA Steering Committee to an active participant in the realisation of the project as co-signatories (via STFC) on the PrepSKA contract with the European Commission. As noted in Sect. 4.4.1, they began work on several policy issues as well as the site selection process that continued throughout the Transition Era until the establishment of the SKA Organisation as a legal entity at the end of 2011. One of the other primary roles for the Agencies was to monitor progress in SKA telescope design in the international project and balance that against their own national efforts and funding opportunities. The project schedule and timeline became a focus of attention as did the Implementation Plan and Business Plan that would function as a "negotiating brief" for individual governments.

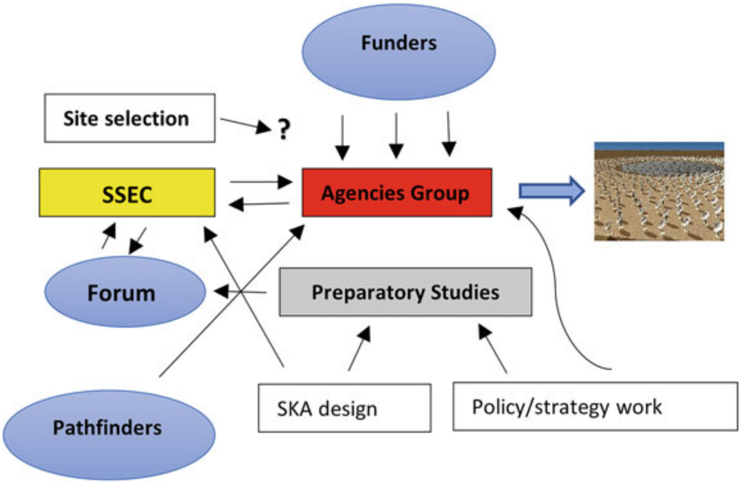

**Fig. 4.8** The SKA players and complex interactions involved, as seen in mid-2008 at the start of PrepSKA (credit: John Womersley, UK Science and Technology Facilities Council)

Related issues such as competition for resources both externally with other projects and internally between the international SKA project and the Precursor and Pathfinder projects were also on the table.

The Agencies' own governance as an informal group also came under internal scrutiny and evolved several times as the project matured, and with those changes came a deeper relationship with the SSEC. As the new relationship was being defined in late 2007, it was agreed that the Agencies would advise the SSEC but not take any decisions formally itself, while the SSEC would take decisions on project and internal governance matters "with the concurrence of the funding agencies".[44] This illustrates the creative language found to describe the power balance.

The advent of PrepSKA in April 2008 had introduced another layer of governance to the project, the PrepSKA Board, mandated by the contract with the European Commission. Membership of this board was drawn primarily from the FAWG and SSEC, so there was considerable overlap in subject matter during separate meetings of the three governing bodies. The PrepSKA Board reported to the Commission, but that was relatively "light touch" involving annual reports on progress and a mid-term review. Having three, independent, but overlapping elements of SKA governance (see Fig. 4.1) kept the Director busy.

The increasing complexity of SKA governance, and the multiple tasks ahead of the project as a whole were captured in a presentation on the SKA decision process by John Womersley in August 2008 at the SKA Forum meeting in Perth, Australia (see Fig. 4.8). Womersley, then Director of Programmes at the UK Science and

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[44] hba.skao.int/SKAHB-64. Minutes of the 18th meeting of the ISSC, October 2007.

**Fig. 4.9** John Womersley (STFC, UK), Chair of the Agencies SKA Group, addressing the SKA Forum in Assen, The Netherlands in June 2010 (Credit: Hans Hordijk Fotografie, The Netherlands)

Technology Facilities Council was speaking in his capacity as Chair of the Funding Agencies Working Group (see Fig. 4.9).

#### 4.4.2.3 Agencies SKA Group (ASG), 2009–2011

This increasing complexity of governance, as well as the increasing recognition of the SKA by the community as shown in the ASTRONET roadmap and the increasing Funding Agency ownership of the project via the PrepSKA Work Packages, led Womersley to propose that the function and format of the Group should evolve to a more formal operation in which it could receive outputs from the SKA Program and act on them. On the apparent complexity, he concluded that was not necessarily a problem provided a balance between the scientist-driven aspects of the program and strong agency engagement was found. However, important for the funding agencies at this stage was to avoid any suggestion that their involvement in the SKA program was in any way a formal endorsement of the project. This was a dance that went on for quite some time.

Following preparatory work by the South African and Australian delegations in 2007 and 2008 respectively and by a working group led by Simon Berry (STFC,

**Fig. 4.10** Members of the Agencies SKA Group (ASG) and some of the other participants at the International SKA Forum meeting in June 2010 in Assen, The Netherlands. (See hba.skao.int/SKASUP4-5 for the ASG membership.) *Left to right. Front row*: David Luchetti (Australian Government), Michelle Cooper (STFC, UK), John Womersley (STFC, UK), Patricia Vogel (NWO, Netherlands), Tshepo Seekoe (South Africa). *Second row*: Michael Garrett (ASTRON, Netherlands), Sherrie-Lee Samuel (STFC, UK), Patricia Kelly (Australian Government), Giampaolo Vettolani (INAF, Italy), Miriam Roelofs (NWO, Netherlands), Maaike Damen (NWO, Netherlands), *Third row*: Elena Righi-Steele (European Commission), Kirsten Verkaik (NWO, Netherlands), Jan van der Donk (Dutch Government). *Fourth row*: Corrado Perna (INAF, Italy), Jim Ulvestad (NRAO. USA). *Fifth row*: Bernie Fanaroff (South Africa), Simon Berry (STFC, UK), Richard Schilizzi (SPDO), Colin Greenwood (SPDO), Ken Kellermann (NRAO, USA), Rowena Sirey (ESO), Vern Pankonin (NSF, USA). *Sixth row*: Franz-Josef Zickgraf (German Government), Markus Schleier (German Government). *Back row*: Rob Adam (Nuclear Energy Corporation of South Africa), David DeBoer (CSIRO Australia), Brian Boyle (Australian Government), Greg Fahlman (NRC, Canada). (Credit: Hans Hordijk Fotographie, The Netherlands)

UK), the funding agencies agreed in February 2009[45,46,47] to establish the Agencies SKA Group (ASG, Fig. 4.10) with the aim of delivering a non-binding Joint Agreement on the Implementation of the SKA by the conclusion of PrepSKA in 2011–2012. The Joint Agreement would include details on the site, funding,

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[45] hba.skao.int/SKAHB-68. Minutes of the Closed Session of the Agencies SKA Group meeting, February 2009.

[46] hba.skao.int/SKAHB-69. Minutes of the Open Session of the Agencies SKA Group meeting, February 2009.

[47] hba.skao.int/SKAHB-70. Notes by the SKA Program Development Office on the Open Session of the meeting of the Agencies SKA Group, February 2009.

governance, and procurement in order to present a complete proposal for submission to governments. Work towards a Joint Implementation Plan would take place via four work-streams: Joint Implementation Agreement, Post-Preparatory Phase funding and governance, site selection process, and schedule and timeline.

John Womersley expanded on the ASG aims a few months later,[48] as well as on the relationship with the SSEC. The ASG had "three primary aims: (i) Deliver a non-binding Joint Agreement on the Implementation of the SKA, with emphasis on Phase 1 and 2, to coincide with the conclusion of PrepSKA in 2011/12; (ii) Achieve sufficient consensus and provide decisions and recommendations on key policy areas of the SKA Project, where appropriate. Where not possible, recommend an appropriate framework for such decisions; and (iii) Prepare the groundwork for the subsequent establishment of a formally constituted SKA Steering Group at an appropriate time.'

On the relationship with the SSEC, Womersley had this to say: "(i) Consult and interact with the SSEC on cost, scientific and technical matters, and the PrepSKA project on policy and site issues, on an ongoing basis, in both cases receiving and providing advice as required to advance the overall SKA programme aims and enable decisions to be taken; and (ii) act as a destination for the outputs of the PrepSKA project."

As mode of operation, the ASG agreed it would make recommendations to Ministers rather than make decisions, as such, while ASG discussions on the issues should lead to sufficient consensus to allow the SKA program to move forward on a case-by-case basis without necessarily having all countries involved. The term "sufficient consensus", proposed by Bernie Fanaroff,[49] was sufficiently vague that all delegations to the ASG could live with the formulation.

The final stage in governance evolution in the 2006–2011 period was the formation of the SKA Founding Board in April 2011 to supersede the ASG and prepare the way for the establishment of the SKA Organisation (SKAO) as a legal entity.

#### 4.4.2.3.1 SKA Founding Board, 2011

One of the main PrepSKA tasks for the funding agencies was to come up with a proposal for the long-term governance and legal framework for the SKA in its construction and operational phases (Work Package 4). As the PrepSKA engineering design work progressed and it became clear that the design would not be "construction-ready" at the end of PrepSKA in 2011, the funding agencies' focus turned towards the governance and funding required for a four-year post-PrepSKA "Pre-

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[48] hba.skao.int/SKAHB-71. Minutes of the 3rd meeting of the SSEC, October 2009.

[49] Fanaroff noted that the term had been used in the formal Multi-party Negotiating Process in the 1990s leading to the South African Constitution—delegates should seek consensus but, if that proved impossible, the chair would decide whether there was sufficient agreement to allow negotiations to proceed.

Construction Phase" starting in 2012. To this end, the ASG formed a Pre-Construction Phase Resourcing and Governance Working Group (the Pre-Construction WG) in October 2009 led by Simon Berry to examine the policy issues and present viable recommendations to allow the project to progress to the next phase in time for implementation before 1 January 2012 when the then current governance arrangements would expire. Use of input from PrepSKA Work Packages 4 (Governance) and 6 (Funding) and from the ASG Schedule and Timeline Tiger Team (see later in this section) would be central to this effort.

A year later at the October 2010 ASG-SSEC meeting, the Pre-Construction WG was able to report progress on both fronts. A Project Execution Plan (PEP) had been developed including an estimate of resources required (see Sect. 4.5.2), and a pathway to the implementation of a legal entity-based governance structure including selection of a host for the SKA Project Office, had been outlined.

Two options were on the table to implement the new governance structure by mid-2011. The first, create a Founding Board governed by MoU to replace the ASG and manage the transition from the ASG and SSEC to the new legal entity. And second, on a short timescale, go straight to the creation of a legal entity, bypassing the Founding Board stage, to provide a decision-making body with the ability to approve and implement the PEP. The second option was not regarded as feasible in the time available, and not pursued by the ASG.

The Founding Board MoU became separate Letters of Intent (LoI) with a stronger mandate for action than the MoU. These were signed by nine countries (see Fig. 4.11) on 2 April 2011 in Rome following a landmark meeting of the SSEC and ASG in the final days of March 2011. The Founding Board was now a reality, with the tasks of "developing a legally constituted governance structure and an adequately resourced SKA Organisation for the pre-construction phase from 2012 to 2015".[50]

Each LoI signatory nominated two members to the Founding Board, a "scientist with relevant expertise" and a "representative of the signatory with appropriate financial authority". John Womersley was elected Chair, and Patricia Vogel from the Netherlands Organisation for Scientific Research (NWO), vice-Chair. Neither Canada nor the USA signed an LoI, Canada because there were issues with the wording of the LoI, and the US because it was not likely they could participate in the SKA given the Decadal Survey report, and the then current economic climate. However, Canada along with India, Japan, the Republic of Korea, the European Commission and ESO became non-voting "Observers" on the Founding Board while US delegates (Vernon Pankonin and successive US Consortium Chairs, Jim Cordes and Patricia Henning) were Invited Participants at Founding Board meetings.

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[50] hba.skao.int/SKAHB-72. Letter of Intent on a Global Partnership Concerning the Square Kilometre Array, April 2011.

**Fig. 4.11** Signatories to the Letters of Intent establishing the SKA Founding Board on 2 April 2011 at the Osservatorio e Museo Astronomico in Rome, Italy. Left to right: Jinxin Hao (China), Franz-Josef Zickgraf (Germany), Patricia Vogel (The Netherlands), Jean-Marie Hameury (France), Patricia Kelly (Australia), Jonathan Kings (New Zealand), John Womersley (UK), Gabriele Villa (Italy) and Valanathan Munsami (South Africa) (Credit: National Institute for Astrophysics, INAF, Italy)

Supplementary material SKASUP4-5[51] lists the Financial Authority representatives and Science representatives on the Founding Board.

Signing the LoI did not commit the signatories to any participation beyond the Founding Board, and to demonstrate their initial commitment, the signatories noted their intention to contribute up to € 50,000 per signatory to cover the cost of the Founding Board activities. As with the ASG, the Founding Board would make decisions by means of sufficient consensus but if that was not possible, decisions required a two-thirds majority vote.

How the Founding Board went about its business of completing the transition to a legal entity to take the project into the Pre-Construction Phase is described in Sect. 4.7.

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[51] hba.skao.int/SKASUP4-5. *Members of the Founding Board of the SKA Organisation.*

#### 4.4.2.4 PrepSKA Board and Officers

The third pillar of governance in the Transition Era was the PrepSKA Board, broadly charged with oversight of the project and reporting to the European Commission. Its membership included representatives of the organisations that signed the PrepSKA contract.[52] These were the funding agencies able to formally participate in the PrepSKA project, and the astronomical research organisations and universities who played key technical, managerial or political roles within PrepSKA. Work-Package Leaders and Observers also attended Board meetings and attendance numbers at meetings grew to more than 30.

The principal responsibilities of the Board were to oversee the activities defined in the work programme, approve allocation of resources, and maintain control of the project contingency and allocate contingency funds when appropriate.

Colin Vincent (STFC, UK) chaired the Board throughout its existence from 2008 to 2012. Phil Diamond (University of Manchester) was the first PrepSKA Coordinator (2008–2010), followed by Steve Rawlings (University of Oxford, 2010–2012), and finally by Paul Alexander (University of Cambridge, 2012). Althea Wilkinson (University of Manchester) was PrepSKA Programme Manager throughout the whole period.

### *4.4.3 PrepSKA Outcomes: Post-2012 Governance and Funding Models*

The original aim of PrepSKA WP7 was to provide the final consolidated implementation plan and signature-ready agreement for the next phase of the SKA project based on the work carried out in WPs 2 to 6. Multiple parallel work-streams were thus set in motion, as we have seen, to contribute to the plan, creating a complex enterprise with many interconnections and dependencies: SKA design, telescope operations, site selection process, HQ location, costs and funding model, procurement model and governance model. The work on resourcing, governance and legal structure carried out by the funding agencies created the framework into which the other activities found their place. Here we discuss the outcomes of WPs 4 and 6 on Governance and Funding models respectively. Outcomes of the other Work packages are discussed in Chap. 6 (WP 2 on Design), Sect. 8.4 (WP 3 on Site Selection), and Chap. 10 (WP5 on Industry Engagement and Procurement). The process of drawing the Implementation Plan (WP 7) together is discussed later in this chapter (Sect. 4.6).

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[52] hba.skao.int/SKASUP4-3. *Participating Organisations in PrepSKA.*

#### 4.4.3.1 Governance Options in the Pre-Construction Phase and on the Long-Term

PrepSKA Work Package 4 (WP4) was intended to study options for viable models of governance and a legal framework for the SKA project during its construction and operational phase. Detailed discussions on governance began in earnest during a PrepSKA Workshop in November 2008 in Washington DC and continued throughout the Transition Era with the focus changing in 2009 to the immediate post-PrepSKA period as part of the Joint Implementation Agreement. This would lead in December 2011 to the Articles of Association and Members Agreement for the UK Company Limited by Guarantee, the legal entity that would govern the SKA project for the next 9 years.

Crucial to the context for the Washington discussions was the equal top priority for ground-based astronomy given to SKA and the European ELT (E-ELT) in the European ASTRONET roadmap[53] published a month earlier. The Washington workshop was remarkable for its breadth of discussion and innovative ideas on governance and the future legal framework.

Patricia Vogel and Miriam Roelofs, both from the Netherlands Organisation for Scientific Research (NWO), coordinated the WP4 work. A thorough multi-step process to collect information on the governance and legal frameworks of existing international mega-science facilities as well as their best practices and lessons learned,[54] led to a shortlist of possible models for the full SKA that included CERN, ESO, ITER, ESRF, XFEL and ALMA (see Box 4.5).

**Box 4.5 Potential Models for the SKA Legal Entity**

*Treaty-based*
CERN (Conseil Européen pour la Recherche Nucléaire, European Council for Nuclear Research)
ESO (European Southern Observatory)
ITER (International Thermonuclear Experimental Reactor)

*National legal entity governed by international Convention*
ESRF (European Synchrotron Research Facility), *Société civile* (France)

(continued)

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[53] *The ASTRONET Infrastructure Roadmap: A Strategic Plan for European Astronomy* Editors: Michael F. Bode, Maria J. Cruz & Frank J. Molster (2008), ISBN: 978-3-923524-63-1, published by ASTRONET, www.ASTRONET-eu.org/

[54] hba.skao.int/SKAHB-71. Notes on the SSEC-ASG meeting in the Minutes of the 3rd SSEC meeting, October 2009.

**Box 4.5** (continued)
*National Legal Entity*
XFEL (European Free Electron Laser), GmbH (Germany)
*International Agreement (Europe-USA-Japan)*
ALMA (Atacama Large Millimetre/submillimetre Array) located in Chile

The initial conclusion[55,56] was that a treaty-based model for the SKA held many advantages for a facility that expected to operate for 50 years, but one significant disadvantage. The main advantages included a robust long-term structure supported by national commitments at governmental level that safeguarded the initial investments, a large degree of autonomy providing independence of the national law of SKA member states, and the capacity to operate in all member states of the SKA Organisation.

The clear disadvantage was the expected time to negotiate the Convention underlying the Treaty, typically 5 years.[57] Intergovernmental agreements are subject to parliamentary or other governmental control with lengthy formal steps to be taken before approval of the obligations on participating member states.

In contrast, the short timescale to establish a national legal entity like the German GmbH for XFEL was attractive, but such an entity would be subject to any changes in domestic legislation and therefore vulnerable with respect to long-term duration. A combination of the two models, a treaty-like Convention governing a national entity such as the ESRF, became the option of choice for the construction and operation of the SKA. The start-up process would still be lengthy, but it would create a flexible organisation with a guaranteed long-term commitment.

However, the more immediate problem in June 2010 was what legal structure could be put in place for the Pre-Construction Phase by the end of 2011 when the current MoUs governing the SSEC and SPDO expired. A national legal entity was the obvious short-term solution. Attention in the PrepSKA WP4 group turned to this question as part of the ASG Pre-Construction Resource and Governance WG and, with advice from legal consultants, Vogel and colleagues drew up a list of potential national legal entities to be considered. In addition, the WP4 group gave some thought to a new European legal entity construct, a European Research Infrastructure Consortium (ERIC), but rejected this as being too European-centric to serve a global project like the SKA.[58]

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[55] hba.skao.int/SKAHB-73. *Report on viable governance options for the SKA Organisation*, P. Vogel, M. Roelofs, M. Damen, PrepSKA Work Package 4, Deliverable 2, July 2011.

[56] hba.skao.int/SKAHB-74. *Viable options for SKA Governance& Legal Framework: Preparatory phase work (2008–2012)*, P. Vogel and M. Roelofs, presentation at SKAHistory2019 Conference, April 2019.

[57] It is interesting to note that the Australian Minister of Science, Senator Kim Carr, was more optimistic about treaty negotiation timescales during a lunch with Schilizzi in Manchester in October 2009. Senator Carr felt that a treaty organisation would only take a couple of years to establish if government ministers sat down together at the start.

[58] hba.skao.int/SKAHB-75. PrepSKA Work Package 4 on SKA Governance Options, Final Report, July 2012.

Three national legal entities were identified for further study: a UK Company Limited by Guarantee, a Dutch Scientific Foundation (Stichting), and a US not-for-profit Corporation. Choosing a host country for the SKA headquarters would automatically determine the form of the legal entity. That selection process was initiated at the June 2010 ASG meeting under the coordination of Simon Berry, as discussed in Sect. 9.2. The choice of the UK as host for the Headquarters is discussed in Sects. 4.7.1 and 9.2.

#### 4.4.3.2 SKA and ESO, Part 2: 2008–2009

As we have seen, at the WP4 Washington meeting in November 2008, and with the ASTRONET roadmap outcomes in mind, the approach to SKA governance and procurement specifically in Europe came under scrutiny. It was obvious that the approach should be Europe-wide rather than a set of independent national voices.[59] One option was to return to the idea of ESO as the institutional home for SKA in Europe, first mooted in early 2006 (Sect. 3.4.2). A side discussion at the Washington meeting between Phil Diamond and Bruno Murano (Italian delegate in the Council of the European Southern Observatory, representing ESO) came to the conclusion that a new information exchange would be useful. Murano's view of such a discussion was cautiously positive, as expressed in an email to Diamond[60]:

> Both EELT [European Extremely Large Telescope] and SKA are very ambitious programs, requiring the best use of our forces. ESO capabilities will be saturated in the next years by ALMA and EELT construction. At the same time it is felt that ESO shall act for the best positioning of ground based astronomy in Europe and of European astronomy in worldwide collaborations. Its institutional stability on the long term and international positioning can be a value for everybody, whatever the wavelength is.

In April 2009, Thijs van der Hulst, Steve Rawlings, and Wim van Driel (all members of the European SKA Consortium Executive Committee), Mike Garrett (SSEC, RadioNet Coordinator), and Diamond (SSEC, PrepSKA Coordinator) met a high-level delegation from ESO, including Tim de Zeeuw (Director General), members of the ESO Council and of the ESO Strategy Working Group chaired by Marano. The main discussion points[61] echoed those from the 2006 meeting (see Sect. 3.4.2). Did ESO Council have a view on how European SKA efforts should be organised? If ESO was to become involved in SKA efforts, what would be the status of SKA

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[59] hba.skao.int/SKAHB-76. *SKA-ESO Connections,* Note from P. Diamond to the European SKA Consortium Board, 15 January 2009.

[60] hba.skao.int/SKAHB-76. *SKA-ESO Connections,* Note from P. Diamond to the European SKA Consortium Board, 15 January 2009.

[61] hba.skao.int/SKAHB-76. *SKA-ESO Connections,* Note from P. Diamond to the European SKA Consortium Board, 15 January 2009.

within ESO? And how could the current strong role of the European radio astronomy institutes be preserved within any new European organisation?

Both parties agreed to identify the most important issues in moving forward but no commitments were made. In fact, the idea did not gain traction and was dropped without further substantial discussion.[62]

### 4.4.3.3 PrepSKA Outcomes: Estimated Costs and Funding Models

#### 4.4.3.3.1 Estimated Costs

From the earliest days of the SKA in the 1990s, estimates of the total cost for the SKA were made. It is fair to say these first estimates were naïve extrapolations of the cost of current state of the art radio telescopes scaled up for the much larger number of antennas and associated equipment and reduced by some factor to try to take account of innovation and economies of scale. As time went on, thoughts about "what the market would bear" came into play as well; what were equivalent astronomical projects under construction in other wavelength regimes expected to cost and what levels of funding were funding agencies prepared to contemplate.

It took many years before these estimates became reliable indicators of the true construction costs of Phase 1 of the SKA, let alone the full SKA. SKA experience shows that this occurred only when procurement processes were well underway. Along the way, the target construction costs served a useful function in setting bench-mark goals for the cost per sq. m of the telescope. This drove many design innovations, most of which were shown not to be feasible for an acceptable cost or on an acceptable timescale.

In these discussions on cost, the ISSC, and later the SSEC, assumed that the burden would fall equally on Europe, USA and the Rest of the World. This concept had been introduced by Ekers in an ISSC meeting in 2000 as a pragmatic way to avoid detailed cost sharing discussions at too early a stage. The "by-thirds" share assumption remained in place until 2009 when the PrepSKA WP6 studies on possible financial models began to examine share arrangements based on return on investment.

The first prediction of the cost of the full SKA, 300 million US dollars, or USD 300 per sq. m., was made by Peter Wilkinson in his 1991 paper on "The Hydrogen Array" (see Sect. 2.4.1.2). The cost per sq. m. was a factor ten or more less than the then state of the art.[63] By the time the PrepSKA period began in 2008, the internal target for the capital cost had burgeoned to €1.5 billion as a result of (i) the

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[62] hba.skao.int/SKAHB-77. Minutes of the SSEC Mid-term Teleconference, May 2009.

[63] hba.skao.int/SKAHB-78. Independent comments in 1993 by Rick Fisher on the possible fundamental changes in telescope design needed to reach a goal of USD 100 per sq. m for the telescope structure costs. This goal was about 40 times lower than the then current state of the art realised by the Green Bank Telescope.

**Table 4.4** Evolution of internal estimates of total design and construction costs as a function of time. Where both SKA1 and SKA2 capital costs are provided, the SKA2 costs include SKA1

| Year | Pre-Construction Phase | SKA1 capital cost | SKA2 capital cost | References |
|---|---|---|---|---|
| 1991 | | | USD 300M | Wilkinson (1991) |
| 1997 | | | USD 600M | [a]Large Telescope WG meeting, December 1997 |
| 2001 | | | USD 500M | hba.skao.int/SKAHB-79, Australian Decadal Survey Mid-term Review, B. Boyle, L. Webster et al. (2001) |
| 2003 | | | €1000M | hba.skao.int/SKAHB-80, The Down-selection Process for the SKA, R. Preston, R. Schilizzi et al., Discussion paper for the 15th meeting of the ISSC, August 2003 |
| 2004 | | | €1000M | Schilizzi (2004) |
| 2007 | €97M (2007–2011) | €250M | €1500M | hba.skao.int/SKAHB-57, PrepSKA proposal, April 2007 |
| 2007 | | | €1900M | hba.skao.int/SKAMEM-92, SKAcost: a Tool for SKA Cost and Performance Estimation, A. Chippendale, T. Colegate, J. D. O'Sullivan, June 2007, SKA Memo 92 |
| 2007 | | €300M | €1500M | hba.skao.int/SKAHB-82, Preliminary specifications for the SKA, Schilizzi et al. Nov 2007 |
| 2009 | | | USD 1670M (SKA-mid only) | hba.skao.int/SKAHB-83, Proposal to US Decadal Survey Committee. See hba.skao.int/SKASUP4-6 for a preliminary breakdown of the estimated total costs for SKA2-mid. |
| 2010 | €91M (2012–2017) | €350M | €1500M | hba.skao.int/SKAHB-115, SKA Project Execution Plan |
| 2011 | | €518M | | hba.skao.int/SKAHB-118, SKA Business Plan |
| 2016 | | €650M | | European Strategy Forum for Research Infrastructures (ESFRI) Roadmap 2016; www.esfri.eu |
| 2021 | (2012–2020)<br>€82M (SKAO)<br>>€250M (national) | €963M | | Pre-Construction Phase Costs (Phil Diamond, private communication);<br>SKA 1 capital costs (Simon Berry, private communication) |

[a] *Closing remarks,* Wim Brouw, Large Telescope WG meeting, Sydney, December 1997, http://www.atnf.csiro.au/research/conferences/SKA1997/index.html, accessed November 2022

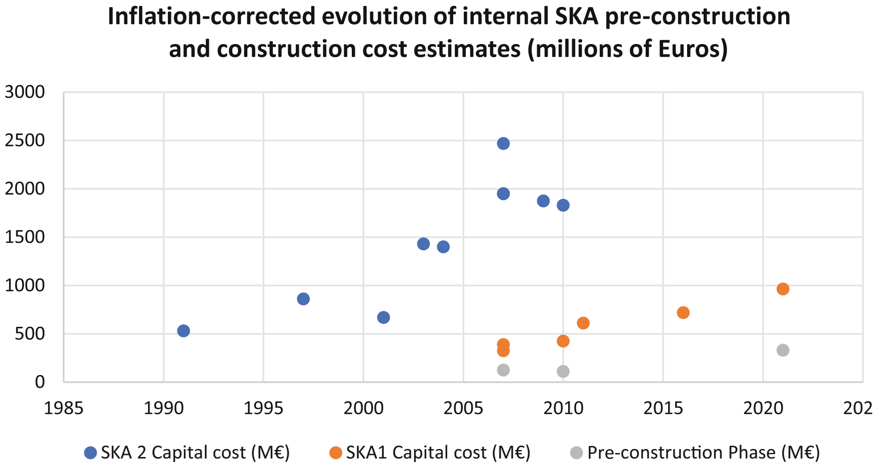

**Fig. 4.12** Evolution of SKA construction cost estimates by the SKA Project in millions of Euros as a function of year, from Table 4.4 and corrected for inflation to 2021 units. Where both SKA1 (orange) and SKA2 (blue) capital costs are provided, the SKA2 costs include SKA1. SKA Pre-Construction costs (grey) are also provided; the 2007 and 2010 numbers were estimates, the 2021 number is the money spent from 2012 to 2020. USD values in Table 4.4 have been converted to Euros at a nominal exchange rate of USD 1.1 = €1. Inflation correction factors for the years shown were the average of US, EU and UK values

intervening 15 years of engineering work in which the concept of using innovative technology to decrease costs slowly made way for lower risk, higher cost technologies with more predictable timescales, (ii) a substantial increase in scientific scope, (iii) the availability of far more detailed cost estimations such as the 2007 SKA cost study and (iv) comparisons with the Atacama Large Millimetre and sub-millimetre Array (ALMA) as an example of a comparably large radio astronomy telescope project. Table 4.4 provides the estimates of costs as "published" and Fig. 4.12 displays the same information with costs in 2021 Euros, corrected for inflation.

In 2007, the 10% Phase 1 was "guesstimated" to cost €250–300 million, the extra factor of two in cost per square metre compared with earlier estimates for the full SKA included start-up costs. Annual operations costs were taken as 10% of the capital costs, a standard number for modern radio telescopes that included a 2–3% allowance for upgrades to the telescope. By the time of the SKA1 de-scope (see Sect. 4.5.2) following the 2010 System Conceptual Design Review, the costs of SKA1 had increased to between €350 and 500M (2010 units) depending on the costs of the site infrastructure. At the start of construction of SKA1 10 years later in 2021, the costs had further escalated to €963M capital costs and an equivalent amount for the first 10 years of operation. The major factor in this increase in capital costs was a factor of four to five increase in the estimate of the cost of dishes, as discussed in detail in Sect. 6.4.6.

Table 4.4 and Figure 4.12 show that, at the time when the Transition Era began in 2006, the SKA was already a potential “big-science” project in terms of its cost estimate, and the subsequent equal top priority with the European Extremely Large Telescope in the ASTRONET European roadmap in 2008 (see Sect. 4.3.2.2.2) cemented its position among the other contenders. In the USA, SKA’s status would be determined by the 2010 Decadal Survey on Astronomy.

The funding agencies and project representatives discussed the funding cycles of US and European funding agencies in a meeting on the PrepSKA policy work-packages in Washington in November 2008. It was noted there that the US National Science Foundation (NSF) would be unlikely to provide early funding for the SKA from its Major Research Equipment and Facilities Construction (MREFC*)* account even with a positive recommendation by the Decadal Survey Committee. There was general concurrence amongst funding agency members that Europe could perhaps fund about 60% of SKA Phase 1 construction, with little or no contribution by the USA until Phase 2. This would remove the need to prepare a detailed SKA Phase 1 science case for the US Decadal Survey, which would focus on the Phase 2 science case instead. The US would need to fund about 40% of SKA Phase 2 construction costs to maintain its overall one-third share of SKA construction costs.[64] However, the eventual lack of sufficient support from the Decadal Survey signalled the gradual end of direct US involvement in the SKA. The estimate for SKA2 costs made by Aerospace Corporation, USD 5.9 billion, as part of its evaluation of all large proposals to the Decadal Survey Committee was a major factor in the lack of support in the Committee report, as we discuss more fully in Sect. 4.5.3.

As the SKA design matured in the Pre-Construction Phase, more confidence could be placed in the cost estimates of the system elements, and the estimated total capital costs rose substantially. This was also the lesson from ALMA.

> The difficulty of estimating costs for technically complex and sophisticated new instruments requires careful assessment of the level of technological readiness. Traditional cost estimating by scientists and engineers based on their previous experience, especially if based on smaller-scale projects, should be supplemented by professionals with cost estimating experience in comparable domains.[65]

This increase in total capital costs led the SKAO Board to impose a cost-cap in 2013 of €650 million for SKA1. By 2021, the cost estimates had further increased to the point that in the formal SKA1 Construction Proposal the SKA1 capital costs were €963M (see Table 4.4).[66]

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[64] hba.skao.int/SKAHB-84. Minutes of the SSEC teleconference, comment by K. I. Kellermann, December 2008.

[65] hba.skao.int/SKAHB-85. *Lessons Learned from ALMA*, Schreier, E. J., Webber, J., Paper submitted to the US National Science Foundation Sub-Committee of the Business & Operations Advisory Committee on Funding and Governance of Future Major Multi-User Facilities, September 2010.

[66] hba.skao.int/SKAHB-86. *SKA: Lessons Learned*, P. Diamond and J. McMullin 2019, SKAHistory2019 Conference.

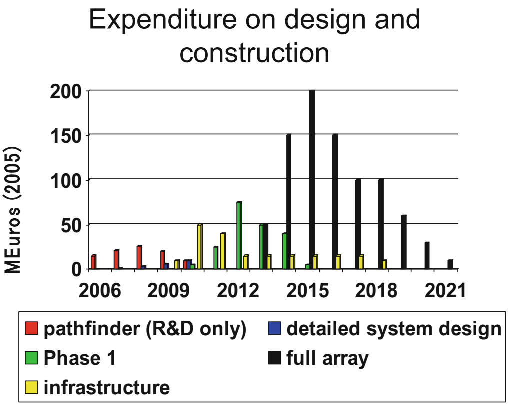

**Fig. 4.13** 2007 estimates of expenditure on SKA design and construction. In early 2007, the PrepSKA proposal foresaw a total expenditure on SKA design and construction of €1350M from 2006 to 2021. This comprised €100M on Pathfinder R&D to be integrated into the final design, €200M on SKA Phase 1 (10%) construction, a further €850M to expand to the full array (SKA2), and €200M on infrastructure costs

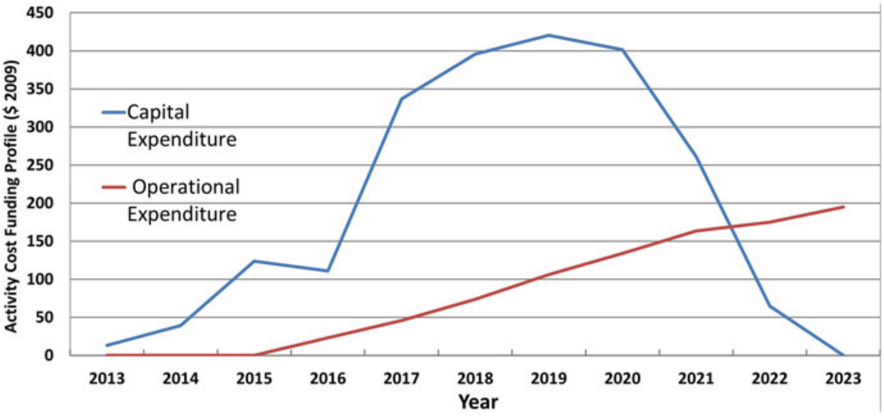

**Fig. 4.14** Total capital and operations expenditures for SKA-mid in FY2009 $million (from the submission by J. Cordes et al. in 2009 to the US Decadal Survey Committee). Estimated total spend on Phase 1 and Phase 2 construction of the SKA at mid-frequencies was USD 1670 million, peaking in 2019

#### 4.4.3.3.2 Spend Profiles in 2007 and 2009

As part of the planning process, spending profiles for the construction phases were constructed on two occasions, the first in 2007 for the PrepSKA proposal to the European Commission,[67] and the second, in 2009, in one of the submissions on

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[67] hba.skao.int/SKAHB-57. *Preparatory phase proposal for the Square Kilometre Array*, P. Diamond et al., May 2007.

SKA-mid to the Radio-Millimetre-Sub-millimetre (RMS) Panel of the US Decadal Survey Committee.[68]

Figure 4.13 shows the spending profile in the PrepSKA proposal for what was seen in 2007 as the pre-construction activities as well as Phase 1 and Phase 2 SKA activities. The peak in the construction spending was forecast in 2015.

Figure 4.14 shows the expected spending profile for the mid-frequency component of the SKA (300 MHz to 10 GHz, SKA-mid) 2 years later, in 2009, in the Decadal Survey submission based on the PrepSKA engineering work. The peak in SKA-mid construction spending was shown occurring in 2019, 4 years later than in the PrepSKA proposal.

At the start of the construction phase in 2021, the peak spend was expected in 2026.

#### 4.4.3.3.3 Funding Models: PrepSKA WP6

The original goal of WP6 was to look into all aspects of the financial model required to ensure the construction, operation and, ultimately, the decommissioning of the SKA. However, as the overall project schedule developed to cope with the constraints that emerged during detailed studies of the design and site selection process, it became clear that the post-preparatory, pre-construction phase would play a more significant role than earlier thought. It was then that the focus of the Work Package 6 team led by Simon Berry (STFC, UK) moved from SKA construction and operations funding models to pre-construction funding and governance issues. It is instructive to follow the lines of argument made in this study[69] since it led to a funding model that is being applied for SKA Phase 1 construction.

***SKA Construction and Operations*** The initial funding model for construction and operations followed the original simple ‘by thirds’ split implied by the equal representation for Europe, USA, and the Rest-of-the-world in the Grass-roots Era governance structures. The model also incorporated funding-phasing assumptions for SKA that minimised conflict with the construction funding profile for the European Extremely Large Telescope project (see Sect. 4.3.2.2). Recognising the mismatch in European-USA funding cycles, the ASTRONET Infrastructure Roadmap process in 2008 had Europe contributing about 60% of the SKA Phase 1 funding and the remainder from the rest-of-world bloc. The US would then come in at the end of the 2010–2020 decade with funding for their one-third share of the construction costs of SKA Phase 2. However, in 2010, this was seen as an unrealistic model in terms of matching the known and likely engagement timelines from the major investor countries particularly as the potential for US engagement in the project diminished with the outcome of the ASTRO2010 review process.

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[68] hba.skao.int/SKAHB-83. *The Square Kilometre Array, Project Description for Astro2010 Response to Program Prioritization Panels,* J. Cordes et al., April 2009.

[69] hba.skao.int/SKAHB-87. PrepSKA WP6 Final Report, July 2012.

Attention then shifted to other, non-fixed share arrangements, which in turn required more detailed discussion of questions of ‘return on investment’ than previously. Potential arrangements encompassed:

- Facility access and science return (for example, encompassing discussion of the continuation of an ‘open skies’ approach versus reserved access for contributors)
- Industrial and/or contractual return
- Operational participation (for example through allocation of regional data or science centres)
- Managerial or other governance influence.

The question of a ‘host premium’ contribution—the ‘value’ attached to a country’s hosting of a facility—was raised. However, with the site decision process going on throughout the PrepSKA era, it was not possible to consider this question in any adequate level of detail, except to note the presumption on all sides that some level of ‘premium’ would be in place in the project.[70]

Two other potential models looked at using clearly defined metrics to determine contribution levels. One was national economic strength measured by the Gross Domestic Product (GDP) such as underpinned contributions to ESA and ESO. The other was ‘community strength’, using the size of the astronomy community measured by membership levels in the International Astronomical Union. Neither were found to be concepts on which to base a viable and generally acceptable funding model.[71]

Another original objective of the study was to investigate the possibility of obtaining a loan from the European Investment Bank (EIB) and other similar national and/or regional bodies to provide a smooth funding profile for the construction phase of the project. A meeting with EIB officials in 2012 led to an understanding that the EIB Risk Sharing Finance Facility mechanism could provide an important mechanism for supporting the SKA project, primarily through balancing shortfalls in funding due to inconsistent commitment timelines from Members. This would smooth the funding profile of the construction phases of the project, particularly SKA Phase 2. A requirement would be a legal structure for SKAO that maximised stability and certainty such as an International Organisation and backing at sovereign government level.[72,73] That was not the case in 2012 and the opportunity was not followed up in the Pre-Construction Phase.

A further line of enquiry was to investigate the potential for private or non-governmental funding for SKA. The WP 6 team consulted individuals

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[70] In Australia, it was noted that the host country was at somewhat of a disadvantage because the premium would be primarily the low technology site development contracts.

[71] hba.skao.int/SKAHB-87. PrepSKA WP6 Final Report, July 2012.

[72] hba.skao.int/SKAHB-88. *Options for Private or Corporate Funding*, PrepSKA WP6 Deliverable 2 Report, 2012.

[73] hba.skao.int/SKAHB-87. PrepSKA WP6 Final Report, 2012.

experienced in the area but concluded that detailed discussion was premature at that stage. This was also not followed up in later years.

***Pre-construction Phase*** The funding model for the pre-construction phase used the detailed plan of activity with estimates of costs provided in the Project Execution Plan (PEP). This was more straightforward than for the later construction phase in that there was a clear understanding of the cost and scope of the planned programme, as well as the relationship with the chosen governance and 'procurement' arrangements, and the impact these would have on the overall structure of the project. In addition, there was an understanding of national positions and requirements from funders—what they expected to receive in return for their participation.

There was no willingness or desire among agencies and funders to move to an entirely centrally funded project structure. In contrast, there was strong support for maintaining local funding control over technical activities, albeit under the control of a strong central project office with overall design authority. This led to a two-part funding model for this phase: (i) an SKA Project Office (SPO) funded by contributions from member organisations to a centralised budget, and (ii) locally funded technical activities where a Member would through their own mechanisms provide support for work in their own country or to another country working in the same area through a consortium set up to deliver that work-package.[74]

The general conclusion drawn by Simon Berry and the WP6 working group in 2012 was that the route forward for funding the pre-construction phase could stand as a model for SKA1 construction provided a reasonably well understood work program, scope and schedule could be developed.

In the event, SKA1 construction and operations funding in the Inter-Governmental Organisation Era from 2021 onwards was based on a negotiated funding contribution structure which saw the three "host" countries—Australia, South Africa, and the UK—each commit to 14% of the budget. The levels of commitment by other countries were roughly in line with scientific capacity in the community, with countries with well-established astronomical communities paying more than the less well-established. This funding key also governs the telescope access rights.

## 4.5 Bumps in the Road

Here three key project issues are described that caused a re-think of the approach being taken—the phased implementation of the SKA; defining the scope of SKA Phase 1; and the failure to achieve sufficient backing for the SKA in the US Decadal

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[74] This was, in effect, a cartel-like risk management approach on the basis that, if each nation kept a large part of their funding under their control, ensured a sovereign Return on Investment. In practice, this approach hobbles a project like the SKA by adding complexity to the contractual phase.

Survey, Astro2010. A fourth key issue, the so-called "mask issue" affecting the placement of antennas in South Africa, is described in Sect. 8.4.4.

### 4.5.1 Phased Implementation of the SKA: A Decision with Lasting Consequences

At the time of writing, the SKA Observatory has formally embarked on construction of the first phase of the SKA, nominally 10% of the expected full SKA capability. The question is: why 10% and not the full array?

In the earliest conception of a phased construction process, a relatively small proof-of-concept demonstrator was seen as a prudent first step on the way to the full SKA, to convince funding agencies and community alike that the large radio telescope idea was feasible in practice. At the time this was discussed at the ISSC meeting in Sydney in August 2003,[75] Schilizzi sounded a note of caution that large demonstrators in excess of what is required to demonstrate technology to carry out science programs would drain resources from the SKA project itself. This particular question returned in 2006 when each candidate hosting-site initiated large national SKA Pathfinder projects to optimise the chance of being selected to host the SKA and as a substantial fall-back instrument in case they were unsuccessful in their site bid.

The note of caution notwithstanding, a year later in 2004, at the 12th ISSC meeting in Penticton, Canada, opinion had moved on and a "scientifically"-sized demonstrator (5%), the International SKA Pathfinder (ISKAP), was deemed essential to be built between 2009 and 2012 at the SKA site (then to be chosen in 2006). This was to be the first phase of a three-phase continuous construction process, where Phase 2 was the full SKA at low and mid frequencies and Phase 3 was an extension to high frequencies (20+ GHz).

Following the first exchange of views with the funding agencies at Heathrow in June 2005, it was clear that the Agencies were enamoured of the phased approach to construction put forward by the Project since it allowed them to contemplate a smaller tranche of SKA construction funding in parallel with full ELT construction funding. SKA funding would ramp up as ELT funding wound down. The ability of an interferometer to be constructed in phases allowed different partners to contribute at different times depending on their funding circumstances. Taking the remarks of the US representative and co-chair, Wayne van Citters, at the Heathrow meeting at face value, the US was unlikely to contribute substantial funds earlier than 2015. But that would interface well with the start of Phase 2 construction following the first phase of construction for part of the frequency range, funded primarily by Europe, Australia and South Africa.[76]

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[75] hba.skao.int/SKAHB-89. Minutes of the 10th meeting of the ISSC, August 2003.

[76] hba.skao.int/SKAHB-38. Post-Heathrow discussion on 12 July 2005 on SKA involving Richard Wade, Phil Diamond and Richard Schilizzi. Summary of the main points by Schilizzi, 15 July 2005.

The Heathrow meeting, and the subsequent descope of the then current seven telescope designs to the Reference Design[77] (Sect. 3.4.1) at the end of 2005, led to the SKA project plan being updated. Now included was a Phase 1 that was not just a demonstrator but a 10% instrument with capabilities surpassing then current instruments by at least a factor of two. This was a "foot in the door" approach that took account of the reality that the ESO ELT project was viewed by the funding agencies and the wider astronomy community at that time as having considerably higher priority than the SKA. This was not because there was a scientific reason for the ELTs to be ahead of the SKA, rather the perception that it was the turn of the optical/IR community to build a large expensive project and its design was more advanced than SKA's. Phasing the SKA design and construction also played to one of the strengths of an interferometer, that an extremely science-capable instrument can be built as a sub-set of the full instrument. The ISSC and subsequently the SSEC viewed the phasing concept as a funding convenience to enable resources to flow to both SKA and the European ELT. They continued to assume that funding for SKA Phase 2 would be approved before SKA phase 1 construction was completed despite a general warning from Vernon Pankonin (US National Science Foundation and member of the Agencies SKA Group) that Phase 1 funding might be all the SKA ever received. In fact, the funding agencies saw the phased approach as affording a "bail-out" opportunity after Phase 1, if so needed.

Another important factor, at least in the minds of the funding agencies, was the cost. SKA Phase 1 costs could be estimated using existing prices, or so it was thought, while SKA Phase 2 would require large reductions in unit costs if it was to be affordable. Going ahead with SKA Phase 1 allowed time for these assumed cost reductions to take place without holding the project hostage to whether they were real or not.[78]

This led in March 2006 to the ISSC deciding to prepare an SKA-10% science case (see Sect. 5.9.5) for an instrument to operate with a limited frequency range from 0.3 to 10 GHz and baselines up to 50 km as proposed in the Reference Design.[79] This would address important but unanswered questions in physics, excite the broader public, and showcase the potential of the full SKA.[80]

A year later in March 2007, the ISSC approved a resolution on a Phased Implementation of the SKA[81] based on the Reference Design and the Phase 1 science case developed by the Project Scientist, Bryan Gaensler, and the SPDO Science Working Group. Phase 1 was defined as 10% of the full SKA, covering a

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[77] hba.skao.int/SKAHB-90. *Reference Design for the Square Kilometre Array*, Discussion Document for the 15th meeting of the ISSC, SKA Program Development Office, January 2006.

[78] John Womersley, private communication to Richard Schilizzi, October 2022.

[79] hba.skao.int/SKAHB-90. *Reference Design for the Square Kilometre Array*, Discussion Document for the 15th meeting of the ISSC, SKA Program Development Office, January 2006.

[80] hba.skao.int/SKAHB-47. Minutes of the 15th meeting of the ISSC, March 2006.

[81] hba.skao.int/SKAHB-91. A phased implementation of the SKA, ISSC Executive Committee, Supporting Paper for the 17th meeting of the ISSC, March 2007.

frequency range of 0.2–3 GHz, Phase 2 as the full SKA, covering 0.07–3 GHz, and Phase 3 as the full SKA, extending the high end of the frequency range to 25 GHz.[82]

More specifically, the ISSC resolution entailed (i) a phased development of the full SKA starting with regional pathfinders contributing design knowledge to SKA Phase 1 which would be constructed from 2012–2016 for 250 M€; (ii) a Phase 1 that focused on the low and mid-band frequencies (this required a change of the reference design); and (iii) using the Phase 1 results to guide the development and construction of the full SKA.

Further development of the phased approach during 2007 led to a concern in the ISSC Executive Committee that Phase 1 was receiving too much emphasis, particularly in the light of the equal top priority given to the science to be done with the full SKA at low and mid-frequencies and the E-ELT in the ASTRONET review (see Sect. 4.3.2.2.2). With Pankonin's earlier warning still fresh in their minds, ISSC members at their meeting in October 2007 transformed the concept of the 10% Phase 1 instrument into a "technical readiness milestone" when 5–10% of the collecting area had been deployed. However, at the SKA Forum meeting a day later, the funding agencies did not agree with Phase 1 being downgraded in importance, and required it be restored. John Womersley (FAWG Chair) cautioned that it could prove difficult to ask governments for large amounts of funding without clear breakpoints like Phase 1 with its own science output. Martin Gallagher (Australia) and Phil Mjwara (South Africa) agreed that from a government perspective, it would be difficult to sell the SKA without the phased approach. This pragmatic view that timelines needed to be mapped and packaged for politicians prevailed.

The ASG and SSEC returned to the question of the timing of Phase 2 with respect to Phase 1 in July 2009 as part of a discussion of the Schedule-Timeline Tiger Team report (see the Sect. 4.6.1). Pankonin stated that the SSEC/SPDO must clearly define whether SKA Phase 1 was a prototype to be evaluated prior to Phase 2. If yes, then it should be less than 10% SKA, and should include evaluation of dishes, aperture arrays, phased array feeds. If no, then Phase 1 is the first phase of construction which proceeds seamlessly into Phase 2, and there should be a system prototyping phase prior to Phase 1. Ken Kellermann spoke for the SSEC in saying that SKA Phase 1—Phase 2 transition was a funding concept and that specific system components would be prototyped early in SKA Phase 1.

It was agreed by the ASG and SSEC that SKA Phase 1 would run seamlessly into Phase 2, with part of the prototyping being carried out by the SKA Precursors. The Precursor role remained until a few months later in 2009 when a revised approach to PrepSKA Work package 2 on SKA design was adopted (see Sect. 6.2.2.2) which replaced prototyping via the SKA Precursors to centrally managed Verification Programs. Active planning of the transition to Phase 2 diminished in 2014 in the face of the mounting costs of Phase 1 and corresponding increased cost estimates for Phase 2.

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[82] hba.skao.int/SKAHB-92. *A Phased Science Plan for the SKA*, Bryan Gaensler and Joseph Lazio, Supporting Paper for the 18th meeting of the ISSC, October 2007.

SKA Phase 3—extending the frequency range above 10 GHz—had always been seen as an integral part of the SKA program and was an important requirement for the site short-list in 2006 (see Sect. 7.3.4). It remained a scientific priority for the US SKA community, and this led to sporadic discussion in SSEC meetings about whether Phase 3 should be located in the USA since it was felt that the Australian and South African sites were not at sufficiently high altitudes for optimal high frequency operation. In the end, it did have sufficient priority globally that a program of tropospheric monitoring at both candidate sites was carried out as part of the site characterisation process (see Sect. 7.3.4), on the recommendation of the International Engineering Advisory Committee in 2009. However, the measurements were severely delayed, and the results had little impact on the site decision in 2012. In the meantime, as mentioned in Sect. 4.5.3, Steve Myers (NRAO) and colleagues submitted a proposal for a North American Array, effectively SKA Phase 3, to the Decadal Survey Committee in 2008, in competition with the SKA Phase 2 mid-frequency proposal by Cordes and colleagues.

### 4.5.2 Telescope-Design Resource Issues and the Scope of SKA1: Pizza and Beer Come to the Rescue

Resource issues dogged PrepSKA Work Package 2 on telescope design for the first 2 years as the national institutes juggled local and international SKA priorities. From the central project office perspective, substantial central funding for the design would have made the task easier. But as it was, €2.8M funding for PrepSKA WP2 was leveraging more than €130M of community expenditure on SKA-related R&D including the local Precursor and Pathfinder telescopes (see introductory paragraphs to Sect. 4.4). In addition, planning had already begun for the post-PrepSKA period[83] which also gave rise to resource concerns on the longer term.

As 2009 progressed, it was clear that the Precursors, Pathfinders and Design Studies were making excellent progress in developing technologies for the SKA, but the challenge for the SKA as a whole was to capture the full benefit of the global R&D in a systematic way. In an attempt to highlight these issues for the SSEC and find a solution for the lack of sufficient manpower being provided specifically for WP2 SKA design activities in the institutes, Schilizzi summarised the roles of the SPDO and the lead institutes in March 2010 as follows.[84]

> The role of the SPDO is to lead the system engineering work and analysis, set out the boundary system constraints for work on the sub-systems, carry out an analysis of the risks

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[83] hba.skao.int/SKAHB-93. *Post-PrepSKA Phase: detailed engineering, production engineering and tooling, and Phase 1 construction, 2012-2017,* P. Dewdney et al., Supporting paper for the 2nd meeting of the SSEC, February 2009.

[84] hba.skao.int/SKAHB-94. *The State of the SKA Project and Considerations on Phase 1,* R. T. Schilizzi, Discussion paper for the 4th meeting of the SSEC, March 2010.

> throughout the project and initiate risk mitigation procedures where necessary, and integrate the sub-system design knowledge into the overall system.
>
> The role of the lead institutes is to manage the execution of the tasks for which they are responsible under the PrepSKA contract for WP2, and to ensure that they are carried out in a timely manner in order to meet the review deadlines and the associated PrepSKA deliverables. The lead institutes are also responsible for self-organising the contributing institutes assigned to each individual task.

However, his personal notes earlier in the year[85] show the level of frustration felt about the lack of resources.

Late in 2009, the SKA design process had reached a point where the SPDO felt it would be prudent to have a high-level external panel review the system design (see Sect. 6.2.2.7). This was premature in the sense that the design was not at the usual level of detail for a conceptual design review. But not premature in the sense that there was real concern in the SPDO, supported by the SSEC Chair, Ken Kellermann, that some SSEC members were not prepared to take hard decisions on which elements of the design to retain as top priority in order to match project scope and technical readiness to the funding potentially available. A review with every prospect of failing to meet external approval appeared the only way to bring this message home.

The Review Panel was convened in February 2010. Membership comprised Wolfgang Wild, Chair (ALMA), Jim Yeck (IceCube Neutrino Observatory), John Webber (Head of the NRAO Central Development Laboratory), Robin Sharpe (ex-Philips Semiconductors) and Lyndon Evans (CERN), all with considerable experience in the design and construction of major scientific infrastructure and in engineering enterprises where mass production (and associated economies of scale) were involved. The latter expertise was particularly relevant to the SKA—a machine of thousands/millions of the same parts. The Panel had two main conclusions, the first that the SKA timeline was over-ambitious and unrealistic for the current scope and cost, and second that the science case was too broad and pushing the project into impossible parameter space. They pointed out that, with technology being pushed dramatically on almost all fronts, the schedule was bound to be unrealistic given the low readiness levels of the new or unproven technologies. One of their recommendations was to form science and technical advisory groups to aid decision-making in the science-technology-cost trade-offs for the SKA and SKA1, in particular.

It was hard to ignore this advice. The SSEC, on the first day of its next meeting a month later in March, decided there was sufficient independent science and engineering expertise in the SSEC to form an internal SKA Phase 1 Definition Sub-committee. The mandate was to produce an SKA1 Concept Design consisting of (i) high-level targeted science goals, and (ii) the required technology mix per frequency range and baseline length. The Sub-Committee members were: Mike Garrett, Chair (SSEC Vice-Chair), Richard Schilizzi (SPDO Director), Steve Rawlings (ESKAC Chair), Jim Cordes (USSKAC Chair), Dave DeBoer (Engineering/Site Advisor) and Justin Jonas (Engineering/Site Advisor).

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[85] hba.skao.int/SKAHB-95. Not expressed publicly. R. Schilizzi, Personal Notebook 11, 22 and 29 January 2010.

**Fig. 4.15** The SSEC Sub-Committee in the process of defining SKA Phase 1, University of Manchester, March 2010. Left panel: Michael Garrett (Sub-Committee Chair). Right panel: l-r David DeBoer, Richard Schilizzi, Steve Rawlings, Jim Cordes, Justin Jonas (Credit: Michael Garrett)

Not wasting time, the Garrett Sub-Committee met the same evening in a small conference room in the Turing Building in the University of Manchester over pizza and beer, and came up with a draft plan (Fig. 4.15). The key scientific drivers were to be: (i) History of neutral hydrogen: Epoch of Re-ionisation (EoR) to now; (ii) Pulsars for Gravity (General Relativity and the detection of gravitational waves), and (iii) Transient Universe (new phenomena).

The technology mix was proposed to be (i) an Aperture Array ($10^5$ $m^2$; 70–450 MHz; baselines to about 100 km), and (ii) 200 single pixel feed dishes of 15 m diameter (0.45–3 GHz; (but with a surface accuracy capable of observing at 10 GHz as required for Phase 2; baseline lengths to about 100 km). The Aperture Array specification represented a ten-times increase in sensitivity over LOFAR, whilst the specification for dishes represented a three times improvement over the Extended VLA and GMRT. The innovative technologies including the Phased Array Feeds and the dense Aperture arrays were to be transferred to the upgrade path for Phase 2. Not all SSEC members agreed with the proposed restricted set of science goals. Russ Taylor noted that many in the radio astronomy community would feel disenfranchised from the SKA if continuum imaging and polarimetry were not listed as science goals.

As can be seen in Fig. 4.16, the Garrett Committee raised the estimated cost of SKA1 from €300M to €350M, including contingency but not operating costs.

Further iteration and discussion with the SSEC in May led to a reformulation of the science goals to focus on those that drove the technical specifications:

(i) understanding the history and role of neutral hydrogen in the Universe, and
(ii) detecting and timing binary pulsars and spin-stable milli-second pulsars.

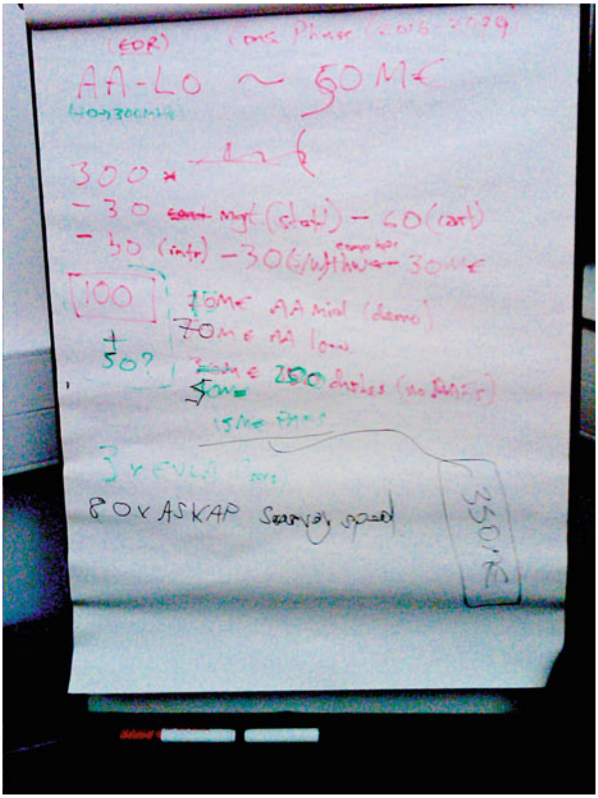

**Fig. 4.16** Flip-over sheet in Fig. 4.15 depicting the various options for SKA Phase 1 and their estimated costs. The estimated total cost (€350 million) is shown at the bottom right. (Credit: Michael Garrett)

The SSEC formally recognised that other science would be possible with the technical solutions proposed and with that, the remaining dissenters in the SSEC came into line. The resulting SKA Memos 125[86] and 130[87] became pivotal SKA documents.

These two goals remained the drivers for SKA1 technology development for the next 5 years until the new SKAO Director of Science, Robert Braun, and his colleagues enlarged the scope of science for SKA1.

The speed and decisiveness of the SSEC action on SKA 1 had a positive effect on the funding agencies as it demonstrated the astronomical community could focus on the larger task in hand when required.

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[86] hba.skao.int/SKAMEM-125. *A Concept Design for SKA Phase 1 (SKA1)*, M.A. Garrett, J.M. Cordes, D. de Boer, J.L. Jonas, S. Rawlings, R.T. Schilizzi SKA Memo 125, August 2010.

[87] hba.skao.int/SKAMEM-130. *SKA Phase 1: Preliminary System Description,* P. Dewdney, J-G Bij de Vaate, K. Cloete, A. Gunst, D. Hall, R. McCool, N. Roddis, W. Turner, SKA Memo 130, November 2010.

### *4.5.3 Why the US Is No Longer Directly Involved in the SKA*

The US was a major partner in the SKA from the time of the establishment of the Large Telescope Working Group in 1993 (see Sect. 2.5) until the end of 2011 when the US SKA Consortium dissolved itself following the failure to obtain a positive recommendation for construction funding in the National Academy of Sciences Decadal Survey in 2010 (Astro2010). This marked the end of active US involvement in the SKA at institutional level.

In this section, we summarise briefly the first decade and a half of US involvement in the SKA and follow with a description of the Astro2010 process, its outcome for SKA, and conclude with some reflections on this major bump in the road on the way to SKA.

#### 4.5.3.1 The 1990s

The Very Large Array (VLA) had come into operation at the start of the 1980s and the Very Long Baseline Array (VLBA) in the late 1980s. The Atacama Large Millimetre and sub-millimetre Array (ALMA) was the new radio astronomy project in prospect, and there was little enthusiasm in the National Radio Astronomy Observatory for a further large project like the SKA. But individual astronomers and engineers in the US including the NRAO made significant contributions to discussions of the science and potential engineering solutions for the large radio telescope concept in the 1990s. In October 1998, the US led the way in creating the first SKA Consortium in the world. Rick Fisher and Ken Kellermann (both NRAO) organised a meeting at Green Bank that led a few months later to an initiative from Yervant Terzian (Cornell University) and Jill Tarter (SETI Institute) to form a US Consortium for SKA (USSKAC). Jackie Hewitt (MIT) was elected Chair and Tarter vice-Chair. Tarter and colleagues coordinated the preparation of a position paper for the 2000 Decade Review, Astronomy and Astrophysics in the New Millennium (McKee & Taylor, 2001). This resulted in a recommendation for USD 22 million for SKA technology development in the Moderate Initiatives category (see also Sect. 3.3.3.8). The McKee and Taylor report lauded the significant nature of the international SKA collaboration (Kellermann et al., 2021).

#### 4.5.3.2 First SKA Funding

A National Science Foundation (NSF) Advanced Technology and Instrumentation grant of USD 1.5 million followed in 2002. This was used for developing the Large-N Small-D (LNSD) array concept that had grown out of a series of Workshops on the Search for Extra-Terrestrial Intelligence (SETI) held between 1997 and 1999 (Ekers et al., 2002) (see also Sect. 3.2.6.5). This led to a plan driven by Jill Tarter (SETI Institute), Sandy Weinreb (Caltech-JPL) and Jack Welch (University of California, Berkeley) for the Allen Telescope Array—built for SETI and radio astronomy—to function as an LNSD SKA Pathfinder (Kellermann et al., 2021). LNSD arrays were adopted in late 2005 as part of the reference design for the mid-frequency SKA as described in Sect. 6.2.1.3.

As far as the science case and technical requirements were concerned, the US ISSC delegation also promoted extending the high frequency limit of the SKA to 25 GHz to meet the low frequency limit of ALMA, reflecting the widespread local community interest in these wavebands. This led to the high-frequency SKA concept as Phase 3 of the SKA, a concept accepted by the remainder of the ISSC as a quid pro quo for US support for the lower frequencies. Later in the decade, in 2008, the USSKAC with Jim Cordes as Principal Investigator, received a USD 12 million NSF Technology Development Program (TDP) grant to develop further the dish aspects of the Large N-Small D concept. Originally expected in 2005, the delay in the TDP grant award was caused by an NSF Senior Review into astronomy funding. The TDP became a significant contribution to the global SKA design effort coordinated via PrepSKA (see Sect. 6.4.5). In addition, as we have seen in earlier sections, the US led the way on several recognised SKA Precursors and Pathfinders including the Allen Telescope Array, Long Wavelength Array, EVLA, and PAPER and were involved in the Murchison Widefield Array and MeerKAT, as well as the early stages of LOFAR.

With the largest delegation of any single country in the International SKA Steering Committee from its inception in 1999, US radio astronomers were a strong science, technical and governance presence throughout the 2000s. However, following the June 2005 Heathrow meeting of funding agencies (see Sect. 3.4.1), it was clear to ISSC members that, despite some positive words of support for the SKA concept at Heathrow by the NSF Director of Astronomy, Wayne van Citters, nothing could be decided on substantial long-term construction and operations funding until after the 2010 Decadal Survey. The three-year delay in funding the Technology Development Program added to the general uncertainty surrounding long-term construction funding from the USA and put the US in a position of relative weakness in the ISSC in terms of project leadership compared with the European countries, Australia and South Africa[88]. The latter were perceived to have prospects of significant funding in the near term and growing political will within their governments to move the SKA forward. Equivalent prospects in the US were seen as an essential element in funding the construction of the full SKA.

All eyes were therefore on the Decadal Survey.

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[88] The ISSC discussion in early 2006 on the formation of an SKA Board that included funding agency representatives (see Sect. 3.4.3) illustrates this point.

#### 4.5.3.3 Decadal Survey, Astro2010 New Worlds, New Horizons in Astronomy and Astrophysics

In 2006 attention in the US was already turning to preparations for submission of position papers in 2008 for the 2010 Decadal Survey which was to be carried out under the auspices of the National Academy of Sciences. An NSF Radio, Millimetre, Submillimetre (RMS) Planning Group chaired by Martha Haynes from Cornell University concluded in 2005 that “it is imperative for the future of meter to centimeter wave astronomy that the U.S. play a leadership role in the design and development of the SKA. To accomplish this, NSF must provide adequate support for the U.S. SKA technology development and demonstrator instrument programs” (Kellermann et al., 2021). In 2007, an Associated Universities Incorporated (AUI) committee on Future Prospects for US Radio, Millimetre, and Submillimetre Astronomy, chaired by Richard McCray from the University of Colorado, came to a similar but less US-centric conclusion to the Haynes RMS Planning Group: “Develop the technologies for the era of Square Kilometer Array science, Develop, test, prototype, and implement the technologies required to achieve SKA-class science, Review and assess the progress of the international SKA effort on a continuing basis.” (Kellermann et al., 2021). Several discussions on the future of radio astronomy in the US were also held under the banner of the “Chicago” meetings in 2006 and 2007 in which a number of initiatives were presented, including the international SKA. The USSKAC drew encouragement from these meetings that the SKA proposal was timely and strongly supported in the (radio) community.

By early 2008, the USSKAC had defined the two main principles to underpin the submission to the decadal committee[89]: (i) the project was an international collaboration. This was a position supported by the NSF, evidenced by informal participation in international funding agency discussions and by funding of two very significant SKA Technology Development Programs intimately linked with the international preparatory program of SKA development (PrepSKA). (ii) Following advice from the NSF, the proposal should be for the full range of science, and for all three phases of SKA construction including the high frequencies. In other words, a proposal for the full SKA.[90]

In the event, a single all-encompassing proposal was not submitted. SKA-mid (frequency range 300 MHz to 10 GHz) was singled out for the international SKA proposal submitted by Jim Cordes (Cornell University) on behalf of the USSKAC, while Don Backer at UC Berkeley submitted a separate proposal for development and construction funds for the Hydrogen Epoch of Reionisation Array (HERA) that was in effect SKA-Low, and Steve Myers at NRAO submitted a proposal for development funding for a North America Array (NAmA) that was in effect SKA-high (or SKA Phase 3, upper frequency limit 25 GHz). Of the three, the low and high frequency array concepts generated the greatest scientific enthusiasm in the

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[89] hba.skao.int/SKAHB-98. Minutes of the 1st SSEC meeting, April 2008.

[90] hba.skao.int/SKAHB-99. Minutes of the SSEC Mid-term Telecon, July 2008.

US.[91] A fourth proposal was submitted by Geoff Bowers at UC Berkeley for the Radio Sky Surveys Project which had as its goal the sky surveys aspect of SKA-mid.

This multi-pronged approach did not adhere to the NSF advice and made it clear that there were separated SKA interests in the US that were not well coordinated. We comment further on this in Sect. 4.5.3.8.

#### 4.5.3.4 Survey Structure

The mandate from the US Academy of Sciences for the 2010 Decadal Survey, New Worlds, New Horizons (Blandford, 2010) was to survey space and ground-based astronomy and astrophysics and recommend priorities for the most important scientific and technical activities of the decade 2010–2020. More specifically, the committee was to formulate a decadal research strategy with recommendations for initiatives in priority order within different categories related to the size of the activities and their home agencies. A new element of this survey compared to earlier ones was the inclusion of projects not yet out of the starting blocks despite recommendations in previous Surveys, together with new initiatives from the research community. The survey included analyses of the technical readiness and sources of risks of all projects, and independent estimates of the cost and schedule risks with help from an independent contractor, Aerospace Corporation. This was a major change in the Survey process and drove the preparation and execution of the Survey.

The Decadal Survey Committee was chaired by Roger Blandford from Stanford University. It was assisted by five Science Frontier Panels that defined the themes for the science case that underpinned the survey recommendations, and four Program Prioritisation Panels (PPP) that conducted in-depth studies of technical and programmatic issues in the different wavelength areas for the 100 or so proposals submitted. In the first phase of the Survey, the science panels identified themes that would define the research frontiers for the decade, and specific questions within each theme (see Blandford (2010) for details). In the second phase, the PPPs reviewed the proposed facilities, instruments and programs versus the key science questions and, using additional information from the Aerospace Corp analysis of technical readiness, cost and risk, drew conclusions that the Panel Chairs submitted to the Survey Committee. In the final phase of the Survey, the Survey Committee reviewed the PPP reports and drew up recommendations that took account of the PPP recommendations and the budgetary and schedule outlook for NASA, the Department of Energy, and NSF. As we discuss further in Sect. 4.5.3.8, the outlook in 2008 at the height of the global financial crisis was bleak and budgets were under very close scrutiny.

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[91] hba.skao.int/SKAHB-64. Report on the Roadmap and Strategy for the US Decadal Plan by Joe Lazio, Minutes of the 18th meeting of the ISSC, October 2007.

The specific questions for each of the science themes were not made known to the proposers to avoid tailoring of the responses to the questions.[92]

Following the call in late 2008 by the Decadal Review Committee for White Papers on Science and Technology, six SKA-relevant responses were submitted.[93,94] These included those mentioned earlier, SKA-mid, HERA, NAmA and the Radio Sky Surveys Project as well as papers by Fred Lo et al. on "The Impact of the National Radio Astronomy Observatory", and Rick Fisher (NRAO) et al. on "Large Instrument Development for Radio Astronomy".

Two Requests for Information were issued to selected proposers including Jim Cordes for the SKA-mid proposal. The first in February 2009 was for an overview of the science, engineering, costs, and programmatic issues, and the second in June 2009 to provide considerable additional detail for use primarily by Aerospace Corporation in its evaluation of technical readiness, costs and risks.

The relevant Program Prioritisation Panel for the SKA was the Radio, Millimetre, Submillimetre (RMS) panel chaired by Neal Evans from The University of Texas at Austin. One of the main considerations for the RMS Panel in each case was the scientific quality of the proposed facility and, in particular, its ability to address the key questions the Frontier Science Panels had formulated in a range of categories from being the only instrument to answer the question, to being of no help in answering the question. With this directed "key science" approach, an argument like "This instrument will open up new discovery space." carried little or no weight.[95] The potential for discovery, or "Exploration of the Unknown" , had always been a strong component of the SKA science case (see Sects. 5.3.7 and 5.10.9) and was included in the SKA-mid science case for the Decadal Survey submission using the time domain as an example of parameter space ripe for the exploration of dynamic cosmic phenomena. The discovery in 2007 and general acceptance in 2013 of the reality of the Fast Radio Bursts became a textbook example.

The other important consideration for the RMS Panel was technical readiness combined with a reasonable cost estimate, driven largely by the desire on the part of the National Academy of Sciences and the US funding agencies to find ways to quantify potential schedule and cost over-runs before project approval and thus attempt to avoid the issues that befell several large space-based astronomy projects.[96]

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[92] hba.skao.int/SKAHB-100. Interview with N. Evans, R. Schilizzi, 22 June 2018.

[93] hba.skao.int/SKAHB-101. Minutes of the 3rd meeting of the SSEC, October 2009.

[94] hba.skao.int/SKAHB-102. Minutes of the 4th meeting of the SSEC, March 2010.

[95] hba.skao.int/SKAHB-100. Interview with N. Evans, R. Schilizzi, 22 June 2018. It is true to say that the "serendipity" argument never has had much currency in the US proposal review system throughout the decades.

[96] The James Webb Space Telescope, one of the Great Observatories, is, at the time of writing shortly after the commissioning phase in 2022, already having significant scientific impact despite substantial cost over-runs and schedule delays during design and construction. The authors expect the same for the SKA.

#### 4.5.3.5 The SKA-Mid Proposal

Following an initial analysis of the SKA-mid response to the first RFI, the RMS Panel's preliminary conclusions[97] were that it was hard to find a single scientific question established by the Frontier Science panels that could *only* be answered by SKA-mid. It was clear that it would contribute important information to many questions but there was no "killer app". The Panel formulated a number of questions on the science, engineering and organisation to be answered before a face-to-face question and answer session between the SKA-mid proposal team and the Panel in Pasadena, California on 9 June 2009. As one of the questions they posed to Cordes et al. put it "In order to justify this amount of money, there'd better be some BIG (sic) science coming out of this."

There were also concerns about technical readiness particularly the perceived optimistic timeframe and technical issues concerning the correlation of the very large data rates envisaged. According to one of the Panel members a decade later, they felt "underwhelmed" after the question-and-answer session in Pasadena.

The Aerospace Corporation analysis only added to the misery. Their estimate of the capital cost of the full SKA-mid was USD 5.9 billion, meaning a US contribution of USD 2 billion. This was well above the total of €1.67 billion (USD 670 million for the US) estimated by the international SKA project for the full SKA-mid telescope. No estimate was provided for Phase 1 of SKA-mid by the Aerospace Corporation. The primary cause of this much higher estimate came, apparently, from large contingency factors applied to design elements with perceived low technical readiness. Details of the Aerospace Corporation analysis have never been made public, presumably for proprietary reasons, and to avoid endless arguments over the details. The cost estimate was dismissed at the time by the SKA scientific community as being over-cautious over-estimates. However, with knowledge of the current (2022) approved capital costs for Phase 1 of the SKA, approximately USD 1 billion, it is hard to argue with the overall outcome of the analysis.

#### 4.5.3.6 "Thumbs-Down" for SKA-Mid

In its report to Blandford's Committee, the Radio-Millimetre-Sub-millimetre Panel gave top priority in the "radio" area to the Hydrogen Epoch of Reionisation Array (HERA) proposed by Don Backer and colleagues while noting its reservations about large scale funding for SKA-mid in the coming decade from the "killer app" science and technology readiness points of view. The Panel concluded SKA-mid was not ready for the construction funding proposed by the US SKA Consortium and the international community. It recommended a continuing US role in the development of concepts for the international SKA mid and high components. No funding was recommended for the North American Array or the Radio Sky Surveys project.

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[97] hba.skao.int/SKAHB-100. Interview with N. Evans, R. Schilizzi, 22 June 2018.

The Blandford Committee's final report in 2010 noted the "enormous science potential and enthusiastic support [for SKA] around the globe" but concluded that "despite unqualified enthusiasm for the science the facility could deliver and the recognition that it represents the long-term future for radio astronomy, the Survey Committee encountered a major discrepancy between the schedule advertised by the international SKA community and the timescale on which the NSF could realistically make a significant contribution to SKA's construction and operations costs". Picking up on the Aerospace Corporation's view that the SKA technical readiness was low, the Committee also noted that the detailed path to construction of any of the three SKA facilities (low, mid and high) was not clear, as was the case for some of the other major projects in other areas of astronomy. In contrast, HERA offered a development pathway for SKA-low while it would be primarily through continued technology development that the US could remain an active partner in the next generation metre/centimetre radio facilities through the SKA collaboration including also the precursors and pathfinders. The Committee did not make a formal recommendation for any funding for such continued US participation in SKA development in either SKA-mid or the North American Array.

Without a formal recommendation from Astro2010, there was no mechanism for the NSF to allocate any funds to international SKA development or construction.

In recognition of the global character of the SKA project, the Committee did suggest that every 5 years or so "the international science community should come together in a forum to share scientific directions and strategic plans, and to look for opportunities for further collaboration and cooperation, especially on large projects". A mid-term review of US projects did take place in 2015, chaired by Jacqueline Hewitt from MIT, but this only discussed the status of approved projects and did not consider the SKA or any other new project.[98]

#### 4.5.3.7 Aftermath, 2010–2011

The SSEC meeting in October 2010 was a time of soul-searching for the global project.[99] Was the SKA vision too far out of line with reality? SSEC Chair, Mike Garrett, noted recent SKA developments, both positive and less so, including the European ASTRONET and US Astro2010 outcomes, the SKA1 Concept definition, and the Project Execution Plan (PEP, see Sect. 4.6.2), as well as the increasingly prominent role played by the Agencies SKA Group, and then raised questions about fundamental tenets of the SKA project. Should SKA1 focus on technology innovation or invest in one array/receptor technology? What was the role of SKA Precursors in SKA1? Was there a natural cycle of facility construction? Would it make sense to focus on low frequencies in SKA1 and dishes in SKA2? Should the

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[98] *New Worlds, New Horizons: A Midterm Assessment*, J. N. Hewitt et al., https://www.nap.edu/catalog/23560/new-worlds-new-horizons-a-midterm-assessment

[99] hba.skao.int/SKAHB-103. Minutes of the 5th meeting of the SSEC, October 2010.

**Fig. 4.17** Ethan Schreier, President of Associated Universities Incorporated (AUI) (Credit: Ethan Schreier)

Precursors be incorporated in SKA1 and 2? Was the project progressing too quickly? Should it wait for first science results from the Precursors?

In response, the Director pointed out that there were two courses of action: descope the project to SKA-low only or SKA-mid only <u>or</u> carry out the engineering work needed to design the SKA1 described in SKA Memo 125 and PEP before final costing. After lengthy discussion, the SSEC preferred to stay the course agreed in previous months, and not descope.

In their meeting held at the same time, the Agencies SKA Group noted[100] that "while the US Decadal Survey highlighted a view of the need for more technological development to be undertaken to enable viability of the program, the US would not substantially contribute towards this, and US construction funding would not be forthcoming during this decade. As a consequence, funding for the SKA project would essentially need to be provided within Europe and by the rest-of-world".

Several post-Astro2010 meetings took place in the USA to discuss the RMS Panel report and possible strategies for the future. At the time of the SSEC and ASG meetings in October 2010, a generally held view in the US reported by Joe Lazio (JPL, Caltech; SKA Project Scientist) was that the international SKA was the "long-term future for radio astronomy" and that HERA was a potential avenue for contributions to SKA-low while keeping the flame burning for SKA-high.[101] A roadmap group chaired by Lazio was established. Alignment between the Astro2010 science goals, various on-going U.S. projects, and SKA science goals was clear, and

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[100] hba.skao.int/SKAHB-104. Minutes of the closed session of the meeting of the Agencies SKA Group, October 2010.

[101] hba.skao.int/SKAHB-103. Minutes of the 5th SSEC meeting, October 2010.

**Fig. 4.18** Two early proponents for the SKA exchange views on the path forward for the project at the SSEC-ASG meeting at INAF, Rome, March 2011. Left: Ken Kellermann, right: Ron Ekers. (Credit: Anton Zensus)

there were interests in continuing relevant technology development. However, no obvious NSF funding path was available on the scale needed for significant contributions to international SKA activities. There was a perception in the US radio astronomy community voiced by Ken Kellermann that "the Astro2010 report damned the SKA project with faint praise".[102] An initial reaction from non-US members of the SSEC was to look for joint approaches to combine HERA and SKA-low, but there was also concern expressed about US commitment to the international projects.

The wind had gone out of the sails of the US SKA contingent by this time, but the US Consortium and Associated Universities Incorporated (AUI) President, Ethan Schreier (Fig. 4.17), mounted separate last-ditch attempts to alter the SKA course at the pivotal SSEC-ASG meeting in Rome at the end of March 2011. This was the meeting (Fig. 4.18) when the SKA Founding Board was established as a pre-cursor

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[102] hba.skao.int/SKAHB-103. Minutes of the 5th SSEC meeting, October 2010.

to the Pre-Construction Phase legal entity, the SKA Organisation (see Sect. 4.4.2.2), a clear indication that Europe and the rest of the world were prepared to move ahead without the USA, if necessary.

The US Consortium expressed the desire to remain involved in the SKA and to join the Founding Board but were concerned about the project schedule as well as the reality of the current funding situation with the NSF unable to fund any new direct SKA expenditure.[103] Bob Preston voiced the Consortium's concerns that the SKA was too ambitious and advocated a reorganisation of the project focused on Phase 1 to "attract whatever funding there may be".[104]

Associated Universities Incorporated (AUI) managed NRAO on behalf of the US Government. As AUI President, Ethan Schreier had long participated in ISSC and SSEC meetings as an Observer on the grounds that NRAO was not mandated by NSF to play a leading role in the SKA, but he could as AUI president since AUI was independent of the NSF. He also had long experience in large astronomy projects both space and ground. Schreier felt strongly that this gave him a mandate to find a way to allow US entry into the Founding Board provided the international project heeded the main messages from the Astro2010 report.

At the Rome meeting, Schreier presented his views to the ASG and SSEC on the relationship between the US radio astronomy priorities and international SKA planning. These views were not supported in a formal sense by the US SKA Consortium despite considerable similarities. He noted that, to many in the US, the current international process had overly optimistic funding expectations in view of higher funding priority for other facilities, and SKA design effort taking place prior to initial results from SKA Pathfinders. He questioned the underlying assumption that what was required to address the scientific goals was a single SKA facility too large for any single country to build. He also questioned whether SKA, especially Phase 1, needed to be one facility built at one site. And, bravely, he also questioned whether the proposed international project governance was appropriate to fiscal and programmatic reality, and was it cost effective. He proposed that the SKA should start with the existing Precursor and Pathfinder projects and the Astro2010 recommended HERA and NanoGrav (pulsar timing) projects, define or continue the necessary technology developments, and define science investigations needed to better specify the eventual full SKA. The requirements and path forward could be reevaluated as science discoveries and technology advances were achieved from investments already in hand.

Schreier's views did not meet with universal approval in the ASG or SSEC. SSEC member, Peter Quinn urged that the vision for the SKA not be lost. Phil Diamond interpreted the USSKAC position paper as a "wait and see" message but he felt, as he did in January 2006 (see Sect. 3.4.3), that the project would lose momentum if current global activities stopped. This view was supported by John

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[103] hba.skao.int/SKAHB-105. US SKA Position Paper, Supporting Paper for the 6th meeting of the SSEC, March 2011.

[104] hba.skao.int/SKAHB-106. Minutes of the 6th meeting of the SSEC, March 2011.

Womersley (ASG Chair) who felt that questions were being reopened that were long settled. On the other hand, Anton Zensus and Michael Garrett (SSEC Chair) felt it important for the project to continue to engage the US in the short and medium term.

This rearguard action by Schreier had the problem of not being backed by substantial funding in the US and was not sufficient to sway the international project, with the result that the US SKA Consortium dissolved itself, effective at the end of 2011.[105] There were some in Europe who were not unhappy that the US was not going to be so prominently involved, as it provided an opportunity for Europe to take the lead on a science mega-project.

The Technology Development Program limped on into 2012 with the aim of transferring the knowledge acquired to the Canadian arm of the SKA Dish Verification Program before its formal winding up later that year. However, the knowledge was not lost to the US community and was put to good use in the next generation Very Large Array (ngVLA) program started by Tony Beasley, Director of NRAO. This was effectively the SKA-high/Phase 3 concept (see Sect. 4.5.3.2), and it received a positive recommendation in the Astro2020 Decadal Survey report.[106,107]

#### 4.5.3.8 Why Did the SKA Fail to Tick All the Boxes in Astro2010?

The main factors in SKA's demise in the US were the political context of the Decadal Survey, the low state of readiness of the SKA as a project in 2009 resulting in the very high-cost estimate by the Aerospace Corporation, and the perceived lack of a science "killer app".

At the end of 2008 when the Survey Committee began its work, the Global Financial Crisis was in full swing. In the years prior to 2008, the US Agencies funding astronomy and astrophysics (National Science Foundation, NASA, and the Department of Energy) had received budget increases well above inflation, then the global financial crisis hit and funds available to science were much more tightly constrained than before. Agency briefings took place with the Survey Committee late in 2008 in which the National Science Foundation (NSF), NASA, and the Department of Energy described their ongoing projects, what senior reviews were in progress, and their extrapolated budgets. All these briefings emphasised that there was "no money".

There was also a widespread feeling, in the proverbial corridors, that with ALMA and NRAO still absorbing large amounts of funding following the 2000 Survey, it

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[105] As noted in Sect. 4.4.2.3.1, US delegates did continue to engage with the project. SKA Siting Group (see Chap. 8) Chair, Vern Pankonin, and successive US Consortium Chairs, Jim Cordes and Patricia Henning were Invited Participants at Founding Board meetings for the rest of 2011.

[106] National Academies of Sciences, Engineering, and Medicine 2021. Pathways to Discovery in Astronomy and Astrophysics for the 2020s. Washington, DC: The National Academies Press. https://doi.org/10.17226/26141

[107] At the time of writing, the SKA and ngVLA science communities have held their first joint meeting to discuss the complementarity and synergy of the two instruments.

was the “turn” of the Optical/Infra-Red community for major funding. It would be very hard to sell another major radio facility in the 2010–2020 decade and, in that sense, the deck was stacked against a positive recommendation for SKA construction funds even before the Decadal Survey began. As far as the NSF was concerned, ALMA construction was well underway and was regarded as a project success and evidence that the formal processes followed by NSF were similar to those followed by NASA for their projects. NSF wanted guidance on whether operations funding for US community users of the two big optical projects (TMT and GMT) should be high priority. The Large Synoptic Survey Telescope (LSST) was already the top priority for NSF internally and was seen to be much further along than other projects, despite concerns about the data analysis.

Other factors in play were noted by Ethan Schreier in his reflections in 2019.[108] These included the different research culture in the USA compared with other countries (see Sect. 1.5 on the complexities of global science projects), the lack of an adequate coordinated US astronomy community strategy in general, the lack of effective radio community strategy for Astro2010 in particular, and the lack of a comprehensive long-range NSF strategy in astronomy. On the final point, he noted that it was a traditional NSF position to react to community pressure rather than develop its own long-range strategy.

Schreier pointed out that there was no US ground-based astronomy culture of capitalising on economic drivers, and no political necessity of engaging industry, as there was in Europe, Australia and South Africa. He also contended that the international SKA project’s attention to governance issues and political considerations affected and delayed program decisions, and this “turned off” many in the US community. While this may be true, the different approval and funding cycles around the world all had different local requirements and the USA was no exception, for example the increased sensitivity in Astro2010 to full and verifiable cost accounting following the James Webb Space Telescope experience, among others. This was less evident in science cultures where the funding agencies became “partners” in the project at an earlier stage of project development than in the USA. There was also an underlying concern in the US astronomy community that international projects were time-consuming and to be avoided unless funding exigencies demanded it. In 2008, it was still the NSF view that international projects were encouraged, but others in the astronomy community pointed to the Gemini and ALMA projects as not being happy experiences for the US.

The other points raised by Schreier all played a role in the outcome of the Decadal Survey, but the primary issue, not mentioned by Schreier, was that the SKA project was, with hindsight, insufficiently mature to match the requirements of the new era in which large projects had to have a solid design and firm cost estimates at an earlier stage in the project cycle in order to avoid cost over-runs. The SKA could not withstand the scrutiny of the Aerospace Corporation. In essence, the SKA project

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[108] hba.skao.int/SKAHB-107. *Why isn’t the US involved in the SKA?*, presentation by Ethan Schreier at the SKAHistory2019 Conference, 2019.

development cycle did not match the US approval and funding cycle. Although the SKA was not in the construction phase, it was evaluated as such for the Astro2010 review because the schedule, in 2009 when the proposal was written, was to complete SKA Phase 2 by 2021. Hence, the cost of mitigating the risks to complete the project within this timescale were estimated by Aerospace Corporation to be USD 5.9 billion. Had this project maturity issue been recognised as sufficiently important, a different strategy could have been followed. The SKA had not even reached the Conceptual Design Review (CoDR) stage in 2009. These Design Reviews took place in 2010 and 2011, and the Preliminary Design Reviews in 2014 and 2015. As noted in Sect. 4.5.2, the System Conceptual Design Review in early 2010 led to a selection of technologies for Phase 1 and an Advanced Instrumentation Program (SKA Memo 125) which then formed the basis of the Project Execution Plan including schedule, timeline and cost estimates published later that year. It is possible that the SKA would have received a more favourable review in the ASTRO2010 report had the Phase 1 concept definition paper (SKA Memo 125) been completed a year earlier in time for review by the Radio-Millimetre-Sub-millimetre Panel and the main Decadal Survey Committee.[109,110]

Europe was 3 years ahead of the USA in the proposal/approval/funding cycle and followed a different approach in which the funding agencies were more engaged in the SKA than was possible with the carefully proscribed hands-off approach in the US. With the EC-funded SKA Design Study (SKADS) successfully underway in 2005,[111] inclusion of the SKA in the ESFRI roadmap in 2006 and equal top priority in the ASTRONET Survey in 2007–2008, there was sufficient community and political support for the SKA to allow the European Commission and other funding agencies and government departments around the world to participate in the PrepSKA policy work-packages and work towards the establishment of SKAO as a legal entity in 2011. However, the NSF could not be engaged in the SKA in any formal way before completion of the Decadal review process although Vernon Pankonin was a leading figure in the FAWG and the ASG, chairing the SKA Siting Group and a Tiger Team on Scheduling and Timeline.

In both Australia and South Africa, the governments were fully committed in the battle to win the right to host the SKA. In Australia, a mid-term review of the 2006–2015 Decadal Plan (see Sect. 4.3.2.4) in 2011 prepared by a sub-committee of the National Committee for Astronomy chaired by Elaine Sadler (University of Sydney), listed SKA as highest priority, followed by ELT access. Noteworthy was that participation in the SKA should not be conditional on hosting the telescope even though this was a major selling point to government.

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[109] hba.skao.int/SKAHB-103. Minutes of the closed session of the Agencies SKA Group, October 2010.

[110] hba.skao.int/SKAHB-108. Email comment to Schilizzi by an RMS panel member, 31 August 2010.

[111] *Wide Field Astronomy & Technology for the Square Kilometre Array,* 2011, Proceedings of Science, https://pos.sissa.it/132

Despite this engagement with funding agencies and governments in Europe and the rest of the world apart from the US, it remained a fragile time for the project. It was uncharted territory, building a global project from scratch without the backing of an already existing institution. The international project was intent on riding the European wave and maintaining the momentum generated earlier by ASTRONET recognition and the mobilisation of European technical and scientific effort via the SKADS project. The SKA project felt it could not afford to slow down to match the US cycle and run the risk of losing momentum. The European and other agencies were content that they had mitigated the major risks by focusing on the phased approach and leaving the details of the construction to the post-PrepSKA Pre-Construction Phase from 2012 onwards. The estimated Phase 1 construction costs (€350M) appeared manageable.

What could the international project including the US partners have done to keep the US involved?

A more successful approach in the Decadal Survey submission may have been to seek US technology development funds in the 2010–2016 period and propose Europe and the Rest of the World fund Phase 1 construction starting in 2017. During Phase 2 construction, the USA would bear a larger share of the Phase 2 construction costs so that the funding share was equalised. Technology development funding for SKA was in fact the RMS panel recommendation and mentioned by the Blandford Committee, but not as a formal Recommendation. This particular approach had been extensively discussed at the Washington meeting of the Funding Agencies Working Group in November 2008 (see Sect. 4.4.3.3.1) but was not followed up in the SKA submission. The reasons for this have not been recorded.

This pragmatic approach would have accommodated Schreier's point that insufficient account was taken of the priority for the LSST and GSMT. There is no doubt that a point of concern in the Radio-Millimetre-Sub-millimetre Panel was the advice from NSF to the US SKA Consortium in the early 2000s that SKA activities in the US should be community driven with the universities in charge, not the NRAO in view of the latter's responsibilities in ALMA and the Expanded Very Large Array. The SKA was seen by the Panel as too large a project for the universities—the required project management experience and resources, as well as experience in coordinating design effort across the country, were not readily available in the university environment. In reality, only NRAO could have provided this.

Another likely contributing factor was that the USSKAC did not think it had the ability to significantly affect the SKA program. Individual members like Ken Kellermann regularly voiced concerns about timescales and costs but not in a way to change the course of the project. The US SKA Consortium was not a monolithic entity; different groups pursued or advocated different segments of the science case. In some ways, it resembled the European SKA Consortium without the over-riding sociological-scientific driver of the European Research Area with its focus on the value of regional collaboration.

Long-term US participation in the SKA would have required NRAO leadership, but not only that. The NSF would have been the only funding agency to fund the SKA, but it already had major projects on its books for construction and operations in the 2010–2020 decade in the form of the Large Synoptic Survey Telescope (LSST) and the Daniel K. Inouye Solar Telescope (DKIST). There was no room for a major investment in the SKA in the decade.

## 4.6 SKA Implementation Plan

The first discussion on the implementation plan was initiated by Martin Gallagher on behalf of the Australian Government, at the meeting in Washington of the funding agencies representatives involved in the PrepSKA policy work-packages in November 2008. A draft discussion paper on a possible SKA Phase 1 decision process to the Funding Agencies Group proposed the establishment of a high-level negotiation group to co-ordinate the detailed arrangements for the implementation of SKA Phase 1. This was the start of a concerted effort by both the funding agencies and project to develop the signature-ready implementation agreement required by the PrepSKA contract, and the subject of Work Package 7 (see Sect. 4.4.1). And as has already been mentioned, this culminated in the establishment in November 2011 of a UK legal entity, the SKA Organisation (SKAO), to govern the SKA project in the post-PrepSKA pre-construction phase rather than Phase 1 construction itself.

Key elements supporting the Implementation Plan were a Project Timeline, Project Execution Plan, and Business Plan for the new SKAO, as well as a Work Breakdown structure for the Pre-Construction Phase. The trajectory towards the site decision was managed separately, as described in Chaps. 7 and 8. In the following pages, we outline two of the key elements—the Project Timeline and Project Execution Plan, the former a key component of the latter. The Business Plan and Work Package Consortia formed in response to the Work Breakdown Structure are covered briefly in Sect. 4.7.

### *4.6.1 Telescope Design and Construction: Schedules, Timelines, and Project Plans*

One of the key roles of the ISSC and SSEC as steering committees was to create and maintain a “vision” of the SKA that would provide a cohering force internally in the project and a stimulus for the greater involvement of the wider astronomy community, as well as funding agencies and governments.

This vision matured with time as opportunities and constraints came into better focus. Underpinning the vision was a series of multi-year project plans initially created by ISSC members, and the SPDO from 2004 onwards, which drove the project forward at the practical level. These plans were based on schedules and timelines. Forward planning became a recurring theme in ISSC and SSEC meetings, and in meetings with the funding agencies from 2005 onwards.

Estimating the time to completion for a large project like the SKA is not an exact science, especially one that breaks new ground in size and project management experience for the community as well as in the scale of international collaboration. Success-oriented thinking and sociology played a substantial role in the SKA project for much longer than might be expected. This is a cautionary but instructive tale and provides an example of the difficulties of generating an accurate timeline until late in the project development cycle. The first project plan in 1999 foresaw start of construction 11 years later in 2010; reality proved this was an underestimation by factor of two.

In the following, we use definitions of "schedule" and "timeline" described by Vernon Pankonin (US delegate to the SKA funding agencies groups from 2007 to 2011, National Science Foundation) in 2009 at the start of work by a Funding Agency-SPDO/SSEC "Timeline Tiger Team".[112] A "schedule" is a procedural plan that indicates the time and sequence of a series of operations and events, and that accounts for interdependencies of the operations and events. A "timeline" is a visual presentation of a series of operations and events. The goal of the Timeline Tiger Team was to prepare a credible overall SKA timeline, but for the timeline to be credible it must be built on a viable schedule.

For the SKA, four stages of "reality" can be discerned regarding the schedule and timeline to start of construction and completion.

1. *Early science and engineering stage 1993–1998*

In the initial discussions of the science and engineering of the SKA in the early 1990s described in Sect. 3.2.1, there was no explicit international project plan. The individuals and institutes represented in the Large Telescope Working Group (LTWG) were more concerned with assembling the science case and pursuing technical solutions and funds via national sources.

The first mention of a timeline for the SKA was in August 1996 by Robert Braun (then at ASTRON, The Netherlands) in an International Union of Radio Science (URSI) Commission J (Radio Astronomy) session on Next Generation Centimetre/Decimetre Radio Telescopes held at the URSI General Assembly in Lille, France. Braun spoke of the expectation that a proposal for the SKA would be submitted by 1998. The abstract of the talk is all that survives, and no further details were given.

Harvey Butcher spoke about organisational issues at the fifth meeting of the LTWG in Sydney in December 1997 and set out the first milestones for the SKA. These were: a broader and deeper science case by 2000, technical R&D completed by 2000/2001, and a possible funding window for SKA from 2005/2006 between ALMA and the next optical telescopes. In 1997, there was a substantial feeling of optimism about the SKA generated by the first grants for SKA innovative technologies in The Netherlands, Australia and Canada (see Sect. 3.2.6), and recognition of SKA as a potential large project in a number of countries. The timescales put forward

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[112] hba.skao.int/SKAHB-101. Minutes of the joint SSEC-ASG meeting on 29 Oct 2009 included in the Minutes of the 3rd meeting of the SSEC, October 2009.

reflected this optimism but were no more than “guesstimates” or aspirations based on previous experience in proposing funding for national radio telescopes. However, a broader/deeper science case was generated in May 1998 2 years earlier than Butcher’s 2000 milestone by the LTWG under the leadership of Robert Braun.[113] This was refined and expanded in an international SKA science meeting in Calgary, Canada in 1998 and the resulting publication[114] is now recognised as the first SKA Science Book (see Chap. 5 for a discussion of the science case and its evolution).

It is worth commenting that a relatively short projected time to potential funding and, beyond that, to start of construction is almost universally found embedded in large project plans and is a well-known sociological phenomenon.[115] In astronomy, an initial timescale with a distant milestone for funding approval runs the risk of the wider community turning its attention to shorter-term projects with more immediate scientific and reputational returns. A shorter projected timescale to funding approval gives institutes and individual colleagues the feeling it would be useful to engage with the project sooner rather than later in order to get an inside edge on technology development and a seat at the table when design decisions are being made as well as decisions on access rights to the telescope when operational.

In 1999, the nearest project in scale to SKA, ALMA had just signed a Memorandum of Understanding between ESO and NRAO to carry out a joint project. Japan joined the collaboration in 2001. All three partners had their own separate advanced plans for a millimetre array but given the scale of these ambitious projects there was pressure on them to join forces.[116] Unlike SKA, ALMA was not born global. In view of the lead-time of ALMA over SKA, it is somewhat surprising in hindsight that the SKA Director and ISSC members did not seek advice from ALMA on expected timescales in projects of this size and complexity until 2006.[117]

### 2. *Schedules take shape but timescales are still optimistic, 1999–2005*

Shortly after the ISSC was created in 1999, a Long-Term Planning Committee jointly chaired by Harvey Butcher and Bob Preston (Jet Propulsion Laboratory, USA) was formed, and rolling five-year plans became a regular agenda point for the Steering Committee.[118] In the years to 2004, Preston led these discussions until Schilizzi as the new Director took over that responsibility.

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[113] hba.skao.int/SKAHB-124. SKA Science Case, R. Braun and the LTWG, May 1998.

[114] hba.skao.int/SKAHB-7. Science with the Square Kilometer Array, A.R. Taylor and R. Braun (Eds), March 1999.

[115] hba.skao.int/SKAHB-109. US National Audit Office, “Over-optimism in government projects, December 2013. See also Chap. 11.

[116] https://www.almaobservatory.org

[117] hba.skao.int/SKAHB-47. Ethan Schreier presentation at the 15th Meeting of the ISSC, March 2006. In 2007, the SKA Operations Working Group chaired by Ken Kellermann solicited the views of Tony Beasley (then ALMA Project Manager) on operations planning in ALMA.

[118] In general, these project plans add value within an organisation but in the early stages of a project with multiple independent national and institutional parties like the SKA in the 1990s-early 2000s, they had little external impact.

**Table 4.5** Initial timeline and schedule elements (1999)

| Year | Schedule element |
|---|---|
| 2002 | Complete a [project] framework and plan to converge on a technical solution |
| 2005 | Converge on the technical description of the SKA |
| 2008 | Complete a scientific and technical proposal for the SKA |
| 2010 | Start construction |

At the inaugural meeting of the ISSC in April 1999, a "tentative sequence of the events for the international project" was set out. These events or activities included: (i) refine specifications; (ii) reduce choice of technology to one or two options; (iii) construct one or two prototypes; (iv) operate and refine prototypes, make a selection and write proposal; and (v) full construction.[119]

The final sentence on this topic in the meeting Minutes provided the only project milestone: "Full construction should begin around 2010". This was taken up as the project mantra to the extent that the password for ISSC members to access on-line meeting documents was "SKA2010". As mentioned in the introduction to this section, this reflected the optimism and lack of experience in the ISSC regarding the amount of time and effort preparation for a mega-project like the SKA would demand. Interestingly, the password was maintained for several years after the goal for start of construction had moved beyond 2010 for inertia reasons more than anything else.

At the second meeting of the ISSC later in 1999, Dewdney led a discussion on the goals and timeline for the international project taking plans for prototypes by 2005 in several countries into account.[120] The rudimentary timeline and schedule elements were as set out in Table 4.5.

The decision on the SKA technology in 2005 was to be informed by the national prototypes then under development or discussion.[121] These included the 1 hT (one-hectare Telescope)/Allen Telescope Array, USA), a multi-beaming telescope operating at 21 cm (Australia), FAST (Five hundred metre Aperture Spherical Telescope, China), THEA++ (Thousand Element Array, NL), LAR (Large Adaptive Reflector, Canada), and LOFAR (Low Frequency Array, NL).

As time went on, the ISSC added site selection in 2005 to the timeline and more detailed milestones on the way to the decisions on technology and site with the result that by the Heathrow meeting of funding agencies in mid-2005, the timeline to start of construction had slipped by 2 years to 2012. This was mostly the result of reviews of the national prototyping activities coordinated by the International Engineering Management Team and the ISPO Engineering Working Group, both led by the Project Engineer, Peter Hall. These showed that a down-selection of technology would be feasible in 2007 rather than 2005. Despite this, the funding agencies regarded the timeline as unrealistic in view of the lack of focus in receptor

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[119] hba.skao.int/SKAHB-21. Minutes of the 1st meeting of the ISSC, April 1999.

[120] hba.skao.int/SKAHB-110. Minutes of the 2nd meeting of the ISSC, August 1999.

[121] hba.skao.int/SKAHB-110. Minutes of the 2nd meeting of the ISSC, August 1999.

**Table 4.6** Timeline and Schedule elements (2006)

| Period | Schedule element |
|---|---|
| 2000–2007 | Preliminary design and technology development-prototyping of antenna technologies and design studies of all other aspects of the SKA architecture including general site dependencies |
| 2005–2009 | Advanced design and prototype arrays-construction of regional and national technology demonstrators and science-capable 1% SKA pathfinder telescopes |
| 2008–2011 | Full system design including production verification unit, leading to SKA Phase 1 construction |
| 2011–2014 | SKA Phase 1 construction leading to an initial operations capability and full array design fine-tuning |
| 2014–2018 | Complete construction of SKA Phase 2 leading to the final operations capability |

technology development, and they regarded the project as a whole not yet mature enough for adoption into national or regional roadmaps (see further discussion in Sect. 3.4.1).

After the second meeting of the funding agencies in February 2006, the ISPO put forward the first more detailed schedule.[122] For the first time, this included a phased implementation for the SKA with construction of Phase 1 (10%) starting in 2011 (see Table 4.6).

3. *A formal approach to schedule and timescale is taken, 2006–2012: the Pre-Construction Phase is born*

As the funding agencies became more involved in the SKA from February 2006 onwards, it became regular practice for the ISSC and its successor, the SSEC, to inform the Funding Agencies Working Group and its successor, the Agencies SKA Group (ASG), of changes in SKA schedule elements and project timelines. These emerged as details of the engineering design and site characterisation matured.

In July 2009, the ASG became concerned that the political and financial aspects of the timeline for a project as complex as SKA were not yet being taken into account appropriately and, as noted earlier, it formed a Timeline Tiger Team[123] to jointly develop the timeline together with the Project. It was already clear at the outset of the Tiger Team's work that the telescope design would not have progressed sufficiently far by the end of PrepSKA in March 2012 to enable SKA1 construction to commence. This meant that a post-PrepSKA phase needed to be included in the schedule with attendant thought given to interim governance and funding issues in that period. Not only was additional funding needed for the continuation of the engineering

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[122] hba.skao.int/SKAHB-111. SKA Project Plan, ISPO, Supporting paper for the 16th meeting of the ISSC, August 2006.

[123] Members of the Tiger Team were Vernon Pankonin (NSF, chair), Simon Berry (STFC), Bernie Fanaroff (SKA SA), Martin Gallagher (Australian Government DIISR), Jean-Marie Hameury (CNRS), Sherrie-Lee Samuel (STFC), Ken Kellermann (SSEC), Jim Ulvestad (SSEC), and Richard Schilizzi (SPDO).

**Table 4.7** Technical and Programmatic Timeline—June 2010

| Technical timeline | Schedule element | Programmatic timeline | Schedule element |
|---|---|---|---|
| 2008–2012 | Technology development and telescope system design and cost | 2011 | Establish SKA organisation as a legal entity |
| 2013–2015 | Detailed design & pre-construction phase | 2012 | Site selection |
| 2016 | Select advanced technology | 2014 | Construction funding approved for SKA Phase 1 |
| 2016–2019 | SKA Phase 1 construction | 2017 | Construction funding approved for SKA Phase 2 |
| 2018–2023 | SKA Phase 2 construction | | |
| 2020 | Full science operations with SKA Phase 1 begins | | |
| 2024 | Full science operations with SKA Phase 2 begins | | |

design, but funding of the SPDO to pay for staff costs was a concern, as well as extending the MoU with the University of Manchester on hosting the SPDO which also expired at the end of 2011. The post-PrepSKA phase became known as the Pre-Construction Phase.

For several SSEC members, the Tiger Team formation raised the fear that the ASG had begun the long-feared "takeover" of the project.[124] However, the Director[125] interpreted the ASG's request to take ownership of the SKA schedule as evidence of a long-term commitment to the project. In the event, it was agreed that the SSEC would approve changes to scientific and technical components of the schedule, while the ASG would approve programmatic changes.

The primary goal of the Tiger Team was to prepare a "credible overall SKA timeline that incorporated siting, funding, and governance considerations". The starting points were to identify a clear technical readiness baseline as input into the technical component of the schedule of activities, and the 'political/resource' risks and issues. The Tiger Team was not "mandated to validate any schedules or timelines, and any experts consulted would not be asked to validate or critically review any of the schedules or timelines". In hindsight, this latter statement made it less likely that the output would be "credible".

The resulting technical and programmatic timeline shown in Table 4.7[126] was presented at the Agencies SKA Group meeting in Assen in June 2010.[127] The work

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[124] hba.skao.int/SKAHB-112. Minutes of the SSEC teleconference, September 2009.

[125] hba.skao.int/SKAHB-112. Minutes of the SSEC teleconference, September 2009.

[126] hba.skao.int/SKAHB-113. SKA Timeline, Supporting paper for the SSEC teleconference, July 2010, SPDO.

[127] hba.skao.int/SKAHB-114. Minutes of the open session of the meeting of the Agencies SKA Group, June 2010.

**Fig. 4.19** Technical timeline for the SKA included in the 2011 Business Plan (Credit: Kobus Cloete)

of the Tiger Team was deemed finished at that point, and ownership handed back to SPDO. Any further changes in the project schedule timeline were to be approved by the SSEC with the concurrence of the ASG. The initial findings of the Tiger team suggested that "the technical systems schedule would define the critical path. Having a credible overall timeline would be dependent on having a credible technical system timeline. The credible technical system timeline would be dependent on having a credible schedule with the interdependencies shown." Not exactly a ringing endorsement of the timeline presented. Box 4.6 notes some of the authors' thoughts on the complexities and caveats in generating a timeline for a project like the SKA.

### Box 4.6 SKA Challenges and Risks, and Timeline

The SKA challenge was to establish a new global organisation at the same time as designing a telescope on a scale never before attempted by the radio astronomy community. Not only was the scale well beyond the experience of the community at that time but the starting premise was that as much innovation as possible, both self-developed and external, would be utilised to create unique astronomical capabilities, reduce cost, and maximise Return on Investment for national governments. In addition, the site choice had strong political overtones, involving as it did a choice between a first-world country with a long history of leadership in radio astronomy, and a country emerging from a long period of political darkness and cultural oppression, with great ambitions in radio astronomy but little experience.

The schedule risks of this enterprise were hard to fully comprehend, and no meaningful analysis was carried out. It was no wonder that a "credible timeline" was not forthcoming.

A more detailed timeline[128] was published in the Project Execution Plan (PEP) later in 2010. The related SKAO Business Plan (see Sect. 4.7.3) prepared for the new

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[128] See hba.skao.int/SKASUP4-7. *High-level SKA timeline and schedule elements from the Project Execution Plan.*

**Table 4.8** The SKA project timeline in reality, 2012–2020

| | |
|---|---|
| 2012 | Formation of the design consortia for the pre-construction phase |
| 2014 | Preliminary design reviews for system elements and system as a whole |
| 2014–2015 | Telescope re-baselining (de-scope) process |
| 2016 | Cost control process |
| 2017–2020 | Critical design reviews |
| 2015–2021 | Process leading to the establishment of the inter-governmental organisation |
| 2021 | Start of SKA Phase 1 construction |

legal entity in 2011, included the visualisation of the technical timeline shown in Fig. 4.19.

In March 2011, the external PEP Review Panel recommended a Work Breakdown Structure (WBS) basis for planning rather than the Work-package approach taken in the PEP (see next section). The Panel expected that developing the WBS approach would take 18 months and would delay the start of SKA1 construction by a year to 2017. This was reflected in the timeline noted in the final PrepSKA reports in 2012.

4. *What actually happened between 2012 and start of construction in 2021*

Although formally outside the scope of the book, it is worthwhile to briefly review the timeline from 2012 to the start of construction in 2021. As we have noted, the timeline in the final PrepSKA report had Phase 1 construction starting in 2017. Even the entry for SKA in the 2016 ESFRI roadmap had Phase 1 construction taking place from 2018 to 2023 with early science starting in 2020.

What actually happened in the project between 2012 and 2021 is shown in Table 4.8 without going into any detail.

What caused the additional delay to construction start in 2021?

There were three separate periods when project momentum slowed considerably and delays were incurred. The latter were caused by: (i) the reduced level of engineering development in 2012 caused by difficulties in acquiring additional SKA Project Office staff, (ii) the re-baselining process in 2014–15 when it became clear that the cost of Phase 1 exceeded projected funding by a considerable margin, and (iii) an additional cost control process in 2016 that took the best part of a year. In addition, the differing levels of system engineering rigour across the design consortia caused tension and delay.[129]

It is fair to say that in the light of the long delays that have eventuated in the SKA and in ESO's Extremely Large (optical) Telescope (ELT),[130] funding agencies as

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[129] hba.skao.int/SKAHB-86. *SKA: Lessons Learned*, P. Diamond and J. McMullin, 2019, SKAHistory2019 Conference.

[130] Initial science operations for SKA Phase 1 are expected in 2029–2030. Construction of the ELT in Chile began in 2014 and "first light" is expected in 2027. At the time of the ASTRONET road-mapping exercise in 2007–2008, ELT construction was expected to start in 2010 (see Sect. 4.3.2.2.2).

well as the projects themselves could benefit from independent estimates of time-scales and costs or, in their absence, include substantial time and cost contingencies in their planning.[131]

### 4.6.2 Project Execution Plan for the Pre-Construction Phase

As mentioned earlier in Sect. 4.4.3.1, the funding agencies began to discuss the ramifications of a phased implementation plan in the PrepSKA Work Package 4 Washington meeting in November 2008, and the necessity to plan for a post-PrepSKA Phase starting in 2012 in more detail. A Discussion Paper on "Post-PrepSKA Phase: detailed engineering, production engineering and tooling, and Phase 1 construction, 2012-2017" from the SPDO in early 2009 began this process.

During the course of 2009 and 2010, the project matured substantially in the eyes of the ASG members. Before this, the radio astronomy community was somewhat of an unknown quantity on the world stage (see Box 4.7). The change came about as a result of (i) work done together with the SSEC and SPDO on the Joint Implementation Plan and the policy work-packages in PrepSKA, (ii) the growing ownership of the site selection process by the ASG (Chap. 8), (iii) the development of the Precursors in Australia and South Africa and the financial commitment involved in the site infrastructure and telescope design, prototyping and construction, (iv) the buildup of organised global collaboration on the telescope design (Chap. 6), and (v) the ability of the SSEC and SPDO to respond rapidly to the criticisms in the System Conceptual Design Review report (see Sect. 4.5.2).

**Box 4.7 The View of the SKA Project from the Perspective of the Funding Agencies Early in the Transition Era**

Initial strong support for the SKA project came from the candidate host countries, Australia and South Africa, as they had invested time, energy and money in the site short-listing process in 2006 and were committed to the final stage of the competition. In Europe, the SKA star began to rise with the inclusion of the project in the ESFRI Roadmap (1996) and the subsequent European Commission Call for Preparatory Phase studies (2007), as well the equal highest scientific priority for ground-based astronomy in the ASTRONET Roadmap (2007–2008).

(continued)

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[131] In the case of the SKA, it is fair to say that a majority in the SSEC regarded the Aerospace Corp. cost estimates in the US Decadal Survey process (see Sect. 4.5.3) as being over-cautious. In part this was due to these estimates not being released for public scrutiny.

**Box 4.7** (continued)

Despite this support, in 2008 the radio astronomy community was an unknown quantity for the funding agencies in terms of its capacity to carry out the telescope design and site selection processes on a global stage. There was doubt that the radio astronomers really knew what they were doing at this level and industry-led project management for the SKA project was discussed privately by the Agencies SKA Group (ASG), but never recommended. The view of the ASG Secretariat was that they should "keep the faith, hold their nerve, and drive the momentum where possible".

The SKA's growing maturity was reflected in an upbeat speech on the project and the Agencies SKA Group activities by John Womersley at the International SKA Forum meeting in Assen, The Netherlands, in June 2010. He concluded by saying:

> I strongly believe that projects like SKA are needed if we are to address the problems facing our society and our planet. Nonetheless, to successfully convey this message, in a time of great pressure on public finances across the world, will be a challenge for all of us. It will require that we combine our visionary thinking about the future with a more rigorous approach to the realities of strategic planning, setting priorities, implementation of projects and good practice in project governance. Yesterday's agreement by the agencies group to move to set up a new legal entity to manage the next phase of SKA is an important step in this direction.

However, considerable scepticism about the details of the SKA1 definition and costing was voiced by the US and Canadian representatives in the ASG (Vernon Pankonin and Greg Fahlman (National Research Council, Canada) respectively). As a way forward, the ASG initiated a discussion of the funding needed in the post-PrepSKA Pre-Construction Phase, with the intention of determining the detailed costing for the construction phase post-2011. What was needed was a Project Execution Plan (PEP) that set out a budget and a resource-loaded schedule for the Pre-Construction Phase.

The inevitable Tiger Team to generate the PEP was formed in August 2010, led by the Director with senior engineers and astronomers from the SPDO, SSEC and the wider community as members. The PEP[132] duly appeared in time for the October 2010 ASG meeting, much to the surprise of some of the ASG members. It became the blueprint document of the tasks required to deliver the pre-construction phase of the SKA project, and one of the fundamental pillars underpinning the future development of the SKA. It influenced the project's progress for much of the following decade.

The top-level goals of the Pre-Construction Phase foreseen in the PEP were to: (i) progress the SKA design to completion of Production Readiness Reviews and the letting of contracts for construction of major sub-systems; (ii) advance the infrastructure rollout on the selected site to the point where sub-systems could be

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[132] hba.skao.int/SKAHB-115. *Project Execution Plan for the Pre-construction Phase for the Square Kilometre Array (SKA)*, R. T. Schilizzi et al., January 2011.

deployed; and (iii) mature the SKA legal entity into an organisation capable of carrying out the construction, verification and operation of the telescope.[133]

A key part of the PEP was to implement the Memo 125 recommendation on a reduced astronomical scope for Phase 1 into the engineering part of the project plan. An accompanying major decision was to select known technologies for SKA-mid (dishes) and SKA-low (dipole arrays) on the grounds that these were well-tried concepts and could be costed accurately, in principle. The innovative technologies (phased array feeds, PAFs, see Sect. 6.4.7) for dishes and dense aperture arrays (AAs, see Sect. 6.5) were transferred to an "Advanced Instrumentation Program" to be matured in time for the SKA Phase 2 technology decision in 2016.

This decision was not made without internal debates in the PEP Tiger Team led by Phil Diamond (then Director of CSIRO Astronomy and Space Science in Australia) on behalf of Phased Array Feeds and Arnold van Ardenne (ASTRON, The Netheralnds)on behalf of Aperture Arrays. Eventually, the argument that carried the day was that the funding agencies and governments were more likely to buy into a project plan whose technical costs were bounded by practical experience than into one with innovative technologies as yet unproven.

A prominent role was foreseen for the SKA Project Office. It would have management and design authority, something that had taken time to be accepted by the institutes in the PrepSKA period. It would have responsibility for contracting the work on major sub-systems to a small number of work package contractors comprising consortia of participating organisations and industrial partners but could also be individual companies or participating organisations. The Project Office would also be the executive arm of the SKA Organisation and report to the governing Board of Directors.

The PEP team had access to the work being done in PrepSKA WP4 described Sect. 4.4.3.1, in particular the emerging conclusion that the most suitable legal entity in the Pre-Construction Phase would be some form of not-for-profit company dependent on where the host institute for the SPO was located. The Board of the new legal entity would replace the tri-partite governance provided by the SSEC, ASG and PrepSKA Board. The PEP work would be carried out under formal contracts under the overall authority of the SPO instead of the current "best-efforts" basis.

The estimated resources required for this work totaled €90.1M for the four-year period covering 2012 to 2016. This entailed €62.6M for work package contracts and €27.5M for the costs of the central project Office. Staff costs dominated the Project Office costs with 92 staff proposed at the end of the 4 years, up from 18 in 2011.

An early version of the staffing plan in the PEP foresaw growth to 120 staff members by 2015, but this was beaten back to 62, primarily by Diamond and Justin Jonas (South Africa), to reduce SKA HQ project office costs. Interesting to note is that staff numbers grew to 130 in the Pre-Construction Phase that ended in 2020 under the leadership of Diamond who had become SKAO Director-General in late

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[133] hba.skao.int/SKAHB-115. *Project Execution Plan for the Pre-construction Phase for the Square Kilometre Array (SKA)*, R. T. Schilizzi et al., January 2011.

2012. This reflected the growing maturity of the project and its need for staff to handle the many pre-construction activities in parallel.

The Pre-Construction Working Group organised a formal review of the PEP in March 2011 by a high-level international panel[134] chaired by Gary Sanders, Project Manager of the optical Thirty-Meter Telescope project and a well-respected expert in managing large scientific projects. This resulted in overall endorsement of the SKA PEP.[135] In particular, the Panel stated that the SKA project was ‘ripe to transition from a “science project” into a “big project”’. But to achieve this transition in a complex global project with multiple interested parties, it would be important that the Project Office and its related governing bodies were afforded financial and operational management autonomy.

The two main practical recommendations from the Panel were taken up by the SPO in subsequent years. The first was that the work of the Pre-Construction and Construction phases should be reorganised into a product tree/deliverable-oriented Work Breakdown Structure (WBS) and all subsequent work should be managed according to this WBS, rather than the PEP-proposed organisation by work packages. Work packages could be redefined later under the deliverable-oriented WBS.

The second recommendation was that suitable cost estimation tools be acquired with the aim of reviewing and redefining the scope of the construction project and the pre-construction phase, if necessary, to create realistic, affordable phases for SKA.

It is beyond the scope of this book to enter into further detail here.

## 4.7 Transition to the Pre-Construction Phase, 2011–2012

Four tasks awaited the Founding Board after its establishment on 2 April 2011 (see Sect. 4.4.2.3.1) as it moved to complete the Joint Implementation Plan and create the SKA legal entity. The first was to work towards a legally constituted governance structure and an adequately resourced SKA Organisation for the Pre-Construction Phase. The second to decide on the location of the SPO for the Pre-Construction Phase after considering the recommendation of the ASG at the Rome meeting at the end of March 2011. The third to finalise a commonly agreed resourced execution plan for the pre-construction phase of the SKA. And finally, to oversee the preparation of the recruitment process for the Director of the SKA Project Office in consultation with the SSEC.

With these four tasks completed, the Founding Board would cease to exist and the SKAO Board of Directors would take over as the governing body of the SKA pre-construction legal entity. At the time of its establishment, the Founding Board only expected a four-month existence since the choice of legal entity had been made

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[134] hba.skao.int/SKASUP4-8. *Members of the Review Panel for the Project Execution Plan, March 2011.*

[135] hba.skao.int/SKAHB-116. *Report on the Review of the Project Execution Plan*, G. Sanders et al., March 2011.

and the existing PEP and Business Plan were well on the way to being able to serve as a “resourced execution plan” for the Pre-Construction Phase. However, it took until November, 8 months after starting, to complete all the preparations for the new legal entity.

### 4.7.1 UK Company Limited by Guarantee

As described in Sect. 9.3, the ASG decided in late-2010 to call for proposals for hosting the SKAO Headquarters during the Pre-Construction Phase. The final set of candidates for hosting were: ASTRON in Dwingeloo, The Netherlands, the Max-Planck-Institute for Radioastronomy in Bonn, Germany, and the University of Manchester, UK (then the current location for the SPDO). A review of the proposals by an external panel led to a recommendation that Manchester would be the location for the SKAO HQ. A fuller discussion of the selection process and outcome is given in Sect. 9.3.

The Founding Board accepted the Review Panel recommendation that Manchester host the new SKAO headquarters operation at its first meeting on 2 April 2011. This carried with it the decision that the legal entity for SKAO would be a UK Company Limited by Guarantee (CLG). That left 9 months to establish the new organisation including the administrative transfer of SPDO staff from the University of Manchester to the new SKA Organisation, a task that was accomplished with a month to spare.

We now discuss the legal requirements for establishing the “SKA Organisation” as a CLG in the UK, the accompanying Business Plan, and then elaborate briefly on its management structure and the convoluted recruitment process of the new Director-General which included the appointment of an Interim Director-General for a nine-month bridging period.

### 4.7.2 SKA Organisation (SKAO): Articles of Association and Members Agreement

Establishing the Company Limited by Guarantee required *Articles of Association (AoA)* and a *Members* (of the Company) *Agreement* to be lodged with Companies House in the UK. The Founding Board Legal Working Group worked with a consulting legal company, Clifford Chance LLP, on the detailed aspects of the AoA and Members Agreement for SKA and used the Project Execution Plan and Business Plan as the working documents underpinning the resourced execution plan.

Under UK law, the Articles are a public document that set out the detailed administrative and governing clauses governing day-to-day management of the SKAO Company.[136] The “objects” for which the SKA Organisation was established

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[136] hba.skao.int/SKAHB-117. Articles of Association for SKAO, SKAO Archive/SKA History Book Archive/Ch4/Founding Board\/Articles of Association].

were to carry out the Business Plan; select a preferred site for the SKA Facility in accordance with the Articles; and to develop an organisational framework for the construction and operation of the SKA Facility. Interesting to note is the word "preferred" referring to the site selection. This was added at the very last minute as a recognition that the Board of Directors were only empowered to make a recommendation of the preferred site since the Members of the Company, in their Agreement, had reserved the right to actually make the site decision.

A Members Agreement for a Company Limited by Guarantee, on the other hand, is a private document setting out a simple contract between all or some of the members and therefore can deal with all or some of the aspects of the relationship between the parties, if required.

### *4.7.3 Business Plan*

The Business Plan[137] set out the work to be undertaken in the pre-construction era of the SKA project in order to achieve construction readiness. It described the operation of a new, stronger SKA Project Office, the governance of that Office within the wider technical project, and the relationship of the Office with global efforts towards a common aim. The Plan also presented two investment plans, one for a conservative starting position, the other for an expanded partnership in the future. The Business Plan and the Project Execution Plan were seen by the SKA community (funding Agencies and scientists and engineers) as the two most important project documents underpinning the work to be done by the new legal entity.

The overall goals for the pre-construction phase set out in the Business Plan, updating those in the Project Execution Plan, were fivefold: (i) progress the SKA design and prototyping to the point of completion of production readiness reviews; (ii) establish industry participation strategies, procurement processes, and protocols governing the work package consortia; (iii) work towards identifying funding commitments for SKA1 construction and operations; (iv) prepare the long term SKA organisational structure and arrangements for the construction, verification and operation of the SKA; and (v) build relationships with relevant national and international astronomy organisations to ensure SKA 1 science and opportunities were fully integrated into a global astronomy perspective.

The Business Plan also set out the organisation structure to be adopted by the SKAO as a UK Company Limited by Guarantee (CLG):

*Members of the Company*—oversight of the overall strategic direction, governance and progress of the project.

The Members are the ultimate "governing body" of the CLG and can decide upon crucial matters involving the CLG which relate to member-specific issues such as any increase in minimum membership dues, amending the Articles of the Members

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[137] hba.skao.int/SKAHB-118. SKA Business Plan, November 2011.

Agreement etc. It is up to the Members to decide which matters are to be decided by Members and which by the Board of Directors. Members can in this manner exercise control over the CLG in matters that could potentially affect their rights. For the SKA, the Members reserved the right to make the site decision.

*Board of Directors*—The Board represents the Members; and is responsible for the project and the activities of the company, with various areas of responsibility delegated to the Director General. It has oversight of the technical activities being undertaken globally via nationally- and regionally- funded Work Package Consortia (WPCs). Board members are appointed by the Company Members.

The Board of Directors is the main operational body for the CLG which is by UK Company law responsible for day-to-day management for the CLG. The Articles of Association govern its composition, the procedures for its meetings and the rules on decision-making including the voting procedure.[138]

*Director-General*—reports to the Board; provides overall leadership of the SKA project and its progress through the pre-construction phase; leads the SPO; and exercises management and system design authority for the whole project.

*SKA Project Office* (SPO) —executes those work packages within the Project Execution Plan for which it is directly responsible; defines and manages all interactions with WPCs; receives and integrates work done by WPCs and other sub-contractors; and coordinates the wider SKA project.

*Work Package Consortia* (WPC)—are self-organised consortia of Participating Organisations and Industry that have been assigned by the Board of Directors to deliver the sub-system work packages. Funded directly from (multiple) national sources but report to the SPO, and have the responsibility to deliver production-ready subsystems according to requirements defined by the SPO.

The specific tasks of the SPO and WPC foreseen for the pre-construction phase in the Business Plan are listed in Box 4.8.

### Box 4.8 Proposed Specific Tasks of the SKA Project Office and Work Package Consortia in the Pre-construction Phase

| SKA Project Office | Work Package Consortia |
|---|---|
| Overall technical development and procurement management | Dish Array |
| Science drivers and science breadth | Aperture Arrays |
| System design, and system engineering | Signal Transport & Networks |
| Maintenance & support and operations | Central Signal Processing |
| Site engineering | Software & Computing |

(continued)

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[138] hba.skao.int/SKAHB-119. Summary note by Clifford Chance LLP explaining the Articles of Association and Members Agreement for the UK Company Limited by Guarantee.

| | |
|---|---|
| | Power |
| | Telescope Monitoring and Control (added in 2013) |

The Business Plan also laid out the resources required for the pre-construction phase and a potential resourcing plan for SPO and WPC activities on a per-country basis. The resources required were estimated to be a total of €90.9 million over the four-year period, comprising €63.4 million for Work Package Consortia and €27.5 million for SPO costs. In November 2011 just before the legal entity was established, pledges from eight countries had been made for €69M of the €91 million required (€16.7 million for the SPO and €52.5 million for the WPC). The eight countries were Australia, Canada, China, Italy, Netherlands, New Zealand, South Africa and the UK. Scenarios were developed for a reduced version of the work plan if no further funds were forthcoming, but the total pledged was deemed sufficient to go ahead and establish the legal entity. By the end of the Pre-construction phase in early 2021, €82 million had been spent on SPO activities and more than €250 million on the national efforts on all aspects of the project (see Table 4.4).

With completion of these preparatory activities, the pre-construction phase governed by the new legal entity began on 23 November 2011.

### 4.7.4 SKAO Established at Last

The SKA Organisation (SKAO) formally came into being as a UK Company Limited by Guarantee when the Articles of Association were signed at a ceremony held in conjunction with the first Board of Directors meeting at Heathrow Airport on 23 November 2011. This marked the start of the Pre-Construction Phase and was a major milestone in the transition of the SKA to a science mega-project. It also marks the end of the period of SKA history that we deal with in this book, apart from the telescope site decision in 2012 which we describe in Chap. 8.

Seven national parties signed the Articles of Association and Membership Agreement to establish the SKA Organisation and became Full Members of the company (Fig. 4.20 and SKASUP4-9[139]). These parties were: Australia (the Department of Innovation, Industry, Science and Research), China, (National Astronomical Observatories, Chinese Academy of Sciences), Italy (Istituto Nazionale di Astrofisica), The Netherlands (Nederlandse Organisatie voor Wetenschappelijk Onderzoek), New Zealand (the Ministry of Economic Development), South Africa (National Research Foundation), and the United Kingdom (Science and Technology Facilities Council). In March 2012, Canada (National Research Council of Canada)

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[139] hba.skao.int/SKASUP4-9. *SKA Organisation: Signatories, Members and Directors, 19 Dec 2011.*

**Fig. 4.20** The signatories to the Articles of Association of the SKA Organisation as a UK Company Limited by Guarantee at the first meeting of the SKAO Board of Directors at Heathrow airport on 23 November 2011. Left to right: John Womersley (UK, Chair), Bernie Fanaroff (South Africa), Belinda Brown (New Zealand), Jos Engelen (The Netherlands), Corrado Perna (Italy), Patricia Kelly (Australia). Jun Yan (China) was unable to attend in person. (Credit: SKA Observatory)

joined as Full Member of the SKA Organisation, and in April 2012 India (National Centre for Radio Astrophysics) joined as Associate Member.

John Womersley (UK) was elected Chair of the Board (and of the Company Members), and Colin Greenwood was appointed Company Secretary. Subsequent Chairs of the Board were Giovanni Bignami (2015–2017) and Catherine Cesarsky (2017–2021) who played equally active roles in the SKA project as Womersley had. Cesarsky was subsequently appointed the first chair of the SKAO Observatory Council in 2021.

The SSEC formally dissolved itself at the end of 2011 with several of its members being invited to take up Scientific Director non-voting positions on the Board of Directors (see hba.skao.int/SKASUP4-9). The Agencies SKA Group had dissolved itself on the establishment of the Founding Board earlier in the year, in April.

#### 4.7.4.1 SKAO Management

The initial management structure for the SKA Organisation is shown in Fig. 4.21. Once the site decision had been made formally in November 2012, the management structure evolved into a more simplified form in which the Policy Advisory Committee and the Industry Participation Advisory Committee were combined into the

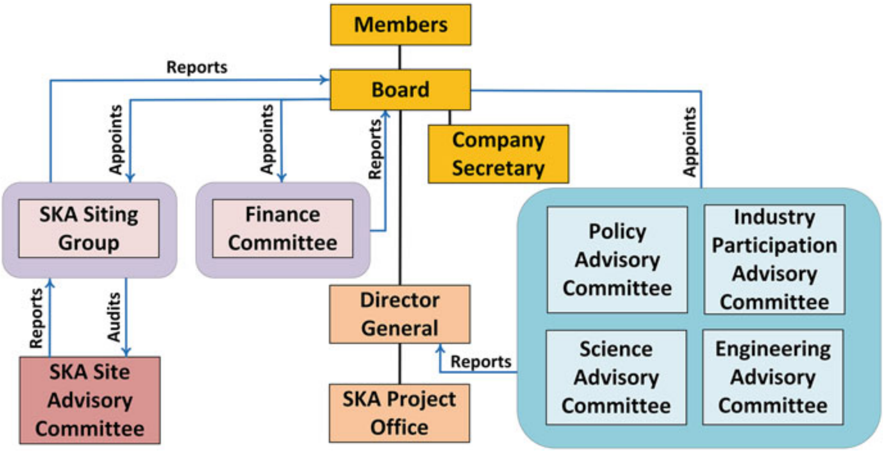

**Fig. 4.21** Initial management structure of the SKA Organisation in 2012 (Credit: SKA Observatory)

Strategy and Business Development Committee, and the separate Science and Engineering Advisory Committees were combined into one. This remained so until the transition into an inter-governmental organisation in 2021.

#### 4.7.4.2 Director-General Recruitment

As mentioned earlier, the decision in mid-2010[140] to focus on the pre-construction phase in the Joint Implementation Agreement was strongly influenced by the fact that the Memorandum of Agreement with the University of Manchester on SPDO employment arrangements would come to a close by the end of 2011. To ensure that the SPDO activities and staff conditions would continue smoothly into the pre-construction phase and to maintain the momentum that was built up during PrepSKA, a legal entity for the project was needed before the end of 2011.

While it proved possible to establish the legal entity on that timescale, it was not possible to appoint a new Director of the SKA Project to succeed Schilizzi immediately after he stepped down from the position at the end of 2011 after 9 years in the job. This was despite the ASG/Founding Board having more than a year's notice of his decision to do so. Two reasons emerged for this. The first was the concern on the part of the South African delegation that at least two of the potential candidates for the position were located in Australia and, if either were appointed, this might lead to an unconscious bias in advice given to the various entities involved in the site decision process. The second was rather more concrete. It became clear in

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[140] hba.skao.int/SKAHB-114. Minutes of the open session of the meeting of the Agencies SKA Group, June 2010.

**Fig. 4.22** The three Directors of the SKA at the ASKAP site in 2014. From left to right: Michiel van Haarlem (Interim SKAO Director-General, 2011–2012), Phil Diamond (SKAO Director-General, 2012–ongoing), and Richard Schilizzi (International SKA Director, 2003–2011) (credit: Michiel van Haarlem)

discussions held in mid-2011 by Patricia Vogel and her team working on the legal aspects of the Joint Implementation Agreement with the consultant legal firm, Clifford Chance LLP, that the new Director-General could only be appointed by the new legal entity once it was formally in place. An earlier appointment would have had to be, initially, as a University of Manchester employee, with a transfer some months later to the UK Company Limited by Guarantee. A potentially time-consuming and uncertain (for the candidate) process.

This led to the appointment of an Interim Director-General (IDG) until the new Director-General was in post.

#### 4.7.4.2.1 Interim Director-General, December 2011–October 2012

The choice for Interim Director-General fell on Michiel van Haarlem from ASTRON in The Netherlands (see Fig. 4.22). He had been appointed as Founding Board Executive Secretary in August 2011 and took over as Interim Director-General 4 months later in December. He had been a member of the Dutch SKA team in the late-1990s and organised the Amsterdam and Dwingeloo “Perspectives in Radio Astronomy” conferences in 1999 (see Sect. 3.2.4.2) before moving to LOFAR in

1999 soon after that project began to ramp up. Prior to his appointment as Founding Board Executive Secretary and SKA Interim D-G, van Haarlem had been the Managing Director of LOFAR.

The main tasks for van Haarlem were establishing the SPO as the new operational arm of the SKA and, in particular, completion of the staff transition formalities from the University of Manchester to the new company and, in addition, managing the continuing activities of the project in accordance with the PEP. Chief among the latter were completion of the detailed WBS for the pre-construction phase required for the Business Plan and the final PrepSKA deliverable, as well as making preparations for establishing work package consortia to carry out the pre-construction design work.

The newly formed Board of Directors of the SKA Organisation had one major decision on its plate in the initial 6 months—the site decision—which we cover in detail in Sect. 8.6. However, the Interim Director-General had little involvement in this decision process in the final stages, apart from being an ex-officio member of the Site Options Working Group formed by the Board in April 2012 to generate options for a dual site solution (see Sect. 8.6.3.2). It is not obvious why the Board did not ask van Haarlem and the SPO for comments on the SKA Site Advisory Committee (SSAC) recommendation in view of the considerable technical expertise among SPO staff (previously SPDO staff) on many aspects of the site process. They were also not asked to help assess the feasibility of the dual site solution prior to the decision and it was only after the site decision had been taken that the SPO staff were asked to examine how it might all be done and how MeerKAT and ASKAP could be integrated into the SKA. Box 4.9 touches on the lessons to be learned about appointing an Interim Director-General.

Van Haarlem did not put himself forward as a candidate for SKA Director-General and returned to ASTRON in October 2012 becoming Head of the Netherlands SKA Office in March 2013. He continued his involvement in international SKA affairs for several years on the invitation of the newly appointed Director-General leading discussions with Australia and South Africa on SKA hosting agreements.

**Box 4.9 The Timing of Director-General Appointments**

A lesson to be learned here is to avoid the situation where a long-serving Director plans to step down at the same time as a new legal entity is established. In SKA's case, the transition from a collaboration-based governance structure to a legal entity caused a substantial discontinuity. In addition, even for a transition from one legal entity to another, it is usually the case that only the new legal entity will have the power to appoint a new Director.

Any interim Director appointed to fill the gap before the new Director is in place will have little power to do anything other than manage the transition situation as the new legal entity is brought up to speed, while keeping the show on the road and not taking any far-reaching decisions. It is almost inevitable that a hiatus is created, and project momentum suffers.

(continued)

**Box 4.9** (continued)

If this is a likely event in the life of a project, it represents a project risk, and deserves to be included as a schedule element, and time allocated in any project timeline. There are parallels, but on a much grander scale, with the political hiatus following elections in some countries where it takes time to form a coalition of parties to govern the country.

It should be said for the SKA that lessons were learned such that, 10 years later in 2021, the transition from the UK Company Limited by Guarantee to an Inter-Governmental Organisation went far more smoothly than the earlier experience, partly because the Director-General remained in post.

#### 4.7.4.2.2 Director-General

Phil Diamond (see Fig. 4.22) was appointed Director-General in May 2012 and took up his position a few months later in October. As related in these pages, he had a long involvement in the global SKA endeavour as a member of the ISSC and SSEC from 1999 to 2011 and as ISSC chair at a critical time in 2005 and 2006 during the first formal interactions with the Funding Agencies Plenary Group and the 2006 site short-listing decision. In parallel, he had held senior management positions in the University of Manchester (Director of MERLIN,[141] and the Jodrell Bank Centre for Astrophysics) and in the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia as Chief of what is now the Astronomy and Space Science Division.

At the time of writing, Diamond continues as Director-General of the SKA Observatory, and has led the project through some turbulent times including the re-baselining (de-scope) of the design, a substantial cost control exercise, and the choice to continue with Manchester as location of SKAO headquarters in the construction and operations phases. He, and the Chairs of the Board of Directors, have also guided SKA towards its transition to an Inter-Governmental Organisation (IGO) and the start of construction. Relating the stories of the turbulent times is beyond the scope of this book, but we will spend a few words on the transition to an IGO.

### 4.7.4.3 Transition to an Inter-Governmental Organisation

It had always been recognised that a UK Company Limited by Guarantee was a temporary solution for the SKA legal entity during the pre-construction phase. For a global project, a European Research Infrastructure Consortium (ERIC) was regarded[142] as too Europe-centric, and as the pre-construction phase gathered pace, attention focused on an Inter-Governmental Organisation (IGO).

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[141] MERLIN stands for Multi-Element Radio-Linked INterferometer.

[142] See Sect. 4.4.3.1 for the discussion of potential governance entities for the SKA carried out in PrepSKA Work Package 4.

**Fig. 4.23** Signatories to the SKA Convention in Rome on 12 March 2019. From left to right: Jill Morris, UK Ambassador to Italy; Zhang Jianguo, Vice-Minister of Science and Technology, China; Manuel Heitor, Minister for Science, Technology and Higher Education, Portugal; Marco Bussetti, Minister of Education Universities and Research, Italy; Mmamoloko Kubayi-Ngubane, Minister of Science and Technology, South Africa; Oscar Delnooz, Deputy Director, Department for Science and Research Policy at the Ministry of Education, Culture and Science, The Netherlands; Gregory French, Australian Ambassador to Italy (Credit: SKA Observatory)

This was stimulated by the successor project to PrepSKA called GO-SKA[143] (see Fig. 4.1), also funded by the European Commission from December 2011 to January 2015. Led by Patricia Vogel (Netherlands Organisation for Scientific Research), GO-SKA's primary aim was to provide guidance at policy-level to the SKA Organisation in the pre-construction phase. Specifically, this involved broadening and strengthening the engagement of funding agencies and governments around the globe and preparing the establishment of global governance for SKA. It is credited with being instrumental in enabling the decision to start the process of establishing SKAO as an IGO.

Discussions towards this end began in earnest in 2015 led by the Italian Ministry of Foreign Affairs with the aim of negotiating the core texts of agreements and supporting concepts relevant to the agreements or supporting policies. All SKAO members (Australia, China, India, Italy, Netherlands, New Zealand, South Africa, Sweden, and UK) were involved, with the majority as 'negotiating parties'. A year later, a Convention Task Force was formed to finalise the text of the Convention, Privileges & Immunities and Financial Protocols, and in 2018 government representatives initialled the documents in Rome. The formal Convention Signing Ceremony took place on 12 March 2019 in the magnificent Ministers' Hall in the Italian Ministry of Education, Universities and Research (see Fig. 4.23). During the process

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[143] A Global Organisation for SKA, https://goska.skatelescope.org/, accessed 1 November 2022.

of ratification of the Convention by individual governments, a Council Preparatory Task Force of government representatives worked closely with the SKAO Board of Directors to prepare the transition to the IGO.

The SKA IGO Treaty finally came into force on 21 January 2021 after five nations had ratified the Convention (Australia, Italy, The Netherlands, South Africa and the United Kingdom), and the SKA Observatory was born, 28 years after the first global SKA Working Group had been formed in 1993.

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# Chapter 5
# Evolution of the SKA Science Case

The dominant components of the science case involve the evolution of the universe as it is traced by neutral hydrogen, understanding the dark ages when the first stars are changing the state of the primordial hydrogen (the so-called Epoch of Reionisation) and the effect of the super massive black holes in the nuclei of galaxies. Radio observations are identified which provide unique and complementary information about the universe. These include magnetic fields, transient radio signals from pulsars and fast radio bursts (FRBs) and tests of general relativity.

The chapter includes a discussion of the way the case for building an SKA was adapted to meet the aspirations of the different stakeholders in a global collaboration and concludes with a description of the scientific advances already being made by the SKA pathfinders.

## 5.1 Introduction

By looking at the science proposed for the SKA over three decades, in various talks and reports, the way in which the emphases changed as the SKA concept was developed can be traced. Chapter 2 shows how the historical development of designs for a range of radio telescopes influenced the ideas behind the SKA. This chapter focuses on the role of the science case in shaping the final SKA design and discusses how it has evolved over time, reflecting the transition from the initial broad scientific opportunities through to more focussed key science projects and finally to the detailed and comprehensive science requirements that were needed to refine design options as the construction stage approached.

New scientific ideas emerged, and priorities have changed throughout this period. These changes will continue in the future, and it will be a challenge for the SKA project to adapt as new scientific opportunities arise. Unlike space projects which are fixed after launch, terrestrial telescopes are never finished.

R. T. Schilizzi et al., *The Square Kilometre Array*, Historical & Cultural Astronomy,
https://doi.org/10.1007/978-3-031-51374-9_5

The introduction chapter discussed the difference between astronomy which is an observational science and experimental sciences. These differences have influenced the ways the SKA developed into a global mega-science project. The tension between emphasis on a small number of key questions (experimental physics approach) and exploring a broader parameter space (observational astronomy approach) has affected the formulation of the science case.

## 5.2 The Context in 1990

The state of radio astronomy in the 1990s when the first ideas of a future SKA-scale radio telescope emerged shaped the scientific drivers for some of the specific pre-SKA projects discussed in Chap. 2.

By 1990, the Very Large Array (VLA) had been in operation for a decade. Radio astronomy was a very active area of research and had been in a privileged position from the 1950s through to the 1980s, making significant impact as the first astronomy outside the optical wavelength band. But then, quite dramatically, astronomy started to develop rapidly in many other wavebands (Infra-red, Ultra-Violet, X-ray, $\gamma$ -ray) as observations from space became possible. Radio astronomy developments plateaued with relatively few new facilities being built for many years after completion of the VLA in 1980.

The possibility of measuring the epoch of reionisation in the early universe—now a major part of the SKA science case—was not yet being discussed. Detection of gravitational waves was only an aspirational dream. There was no accelerating universe to explain and no case yet for dark energy. At this time, observations of the cosmic microwave background and the big optical surveys measuring galaxy distances (redshifts) were making a significant impact on our understanding of the evolution and large-scale structure in the universe. The most distant objects in the universe had been pushed out to redshifts of five or six[1] and the hot topic was how galaxies formed and how they evolved. The case for dark matter had already been around for 30-plus years but the nature of dark matter was unknown then and is still unknown at the time of writing.

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[1] Redshift is the apparent increase in wavelength due to motion of the source away from the observer, and hence can be used to measure the expansion of the universe. Redshift increases with greater distance, which corresponds to further back in time (Hubble's Law). A redshift of five or six corresponds to galaxies which are about 90% of the age of the universe.

## 5.3 Pre-1990 Science Cases for a Large Collecting Area Radio Telescope

As recounted above, and in Sect. 2.4.2, the VLA meeting in Socorro in 1990 was the point at which a number of independent ideas and concepts for a very large telescope came together for the first time. Science goals that could only be achieved with a major increase in sensitivity were being discussed in different groups around the world. These initial science goals are described in more or less chronological order as an introduction to a discussion of the broader SKA science case and its evolution in the remainder of this chapter.

### *5.3.1 SETI and Project Cyclops: 1971*

Cocconi and Morrison (1959) published an article in Nature suggesting the feasibility of interstellar signalling using radio, saying "*The probability of success is difficult to estimate, but if we never search, the chance of success is zero*." As was described in Sect. 2.2.2.2, the 1971 NASA-AMES Cyclops design study led by Barney Oliver (Hewlett-Packard, USA) and John Billingham (NASA)[2] looked at the requirements for a radio telescope with the sensitivity needed to detect radio signals emanating from other civilisations spread throughout the galaxy, which would be extremely weak when they arrived at Earth. The final version of this inspirational report proposed an array of 1000 100-metre dishes. The Search for Extra-Terrestrial Intelligence (SETI) has been included as one of the SKA goals from the earliest days.

### *5.3.2 Govind Swarup's Vision for the Next Generation Radio Telescope, 1978–1991*

Govind Swarup (TIFR, India) had a very well-defined scientific project in mind in 1970 when he built the large cylindrical Ooty Radio Telescope discussed in Sect. 2.2.2.5. The lunar occultation observations of the radio source 3C273, with the Parkes radio telescope in 1963, led to the discovery of quasars[3] by Maarten Schmidt (1963) and the first evidence for the existence of black holes. Swarup wanted to build a telescope with enough sensitivity to observe occultations of weaker radio sources to use as high redshift probes for cosmology studies. His innovative equatorially-mounted cylindrical telescope was a great success,

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[2] See Oliver and Billingham (1972).

[3] Quasars are now known to be galaxies with accreting black holes in their nuclei which generate optical (and other wavelength) emission brighter than all the stars in the galaxy. Discovered serendipitously in 1963 (Kellermann & Bouton, 2023).

providing high sensitivity at relatively low cost. As discussed in Chap. 2, Swarup went on to plan and build a succession of radio telescopes using innovative technology and always focussed on clear scientific objectives.

In 1988, he wrote a paper on the idea of building 1000 GMRT 45-m antennas (1 million $m^2$) primarily for SETI observations (Swarup, 1988) and during GMRT construction, in 1991, he published another article on a concept for a 700,000 $m^2$ telescope comprising 160 × 75-m dishes (Swarup, 1991). A primary motivation was to understand how galaxies form, and what the gas was doing before it formed into galaxies. This had been the basic aim of the earlier Giant Equatorial Radio Telescope (GERT) , see Sects. 2.2.1.6 and 2.4.1.1. To do this there had to be enough sensitivity to see neutral hydrogen[4] in the early universe before the first stars formed, something that would require a significantly scaled-up version of the GMRT. In the proposed science case for the 160 × 75-m telescope Swarup also mentioned observing pulsars[5] and using the pulsar timing for gravitational wave detection, as well as for SETI. All these goals were prominent aspects of what became the SKA science case.

### 5.3.3 Soviet Union Square Kilometre Telescope, 1982–1990

As mentioned in Sect. 2.4.1.4, discussions of large collecting area radio telescopes go back to Semyon Khaikin and Yuri Pariiskii in the 1960s. By the 1980s the USSR Academy of Sciences had established a working group to explore the science case for a Square Kilometre Telescope (SKT) (Gurvits, 2019). The main science cases for the SKT included studies of the statistics of extragalactic sources (log *N*–log *S*[6]), pulsars, and extra-galactic radio recombination lines.[7] Neutral hydrogen in our own galaxy and other galaxies, and the search for extra-terrestrial intelligence were also part of the science case. Pariiskii complemented this activity with his diagram (see Fig. 2.20) displaying the exponential increase in collecting area of radio telescopes over time and noting that the largest radio telescopes would reach 1 million square metres collecting area by 2000 if the trend from the first few five decades of radio astronomy continued.

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[4] Neutral hydrogen has a spin-flip transition that makes it detectable in either absorption or emission in the radio at a frequency of 1.4 GHz (21 cm wavelength). First detected in 1951 following up on a theoretical prediction (Kellermann & Bouton, 2023).

[5] Pulsars are rapidly spinning neutron stars that produce periodic radio pulses. Discovered serendipitously in 1968, see Kellermann and Bouton (2023).

[6] log *N*–log *S* refers to the number of radio sources (N) as a function of flux density (S). This statistic can be used to infer how radio sources are distributed with distance and time going back in the Universe.

[7] Radio recombination lines are the emission lines caused by the radio wavelength series of transitions as ionized hydrogen recombines to its ground state. First detected in 1962 following up on a theoretical prediction, see Kellermann and Bouton (2023).

### *5.3.4 UK, Hydrogen Array, Peter Wilkinson, 1985*

Following a visit to the VLA in 1984, Peter Wilkinson.[8] (U. Manchester, UK) made a proposal to the "Priorities for Astronomy in the United Kingdom" study group for a Large Radio Flux Collector. This proposal was based on the case for high angular resolution imaging and hence determining the velocity distribution and column density of atomic neutral hydrogen in nearby galaxies.[9] This would require a collecting area 100 times larger than the VLA, and ten times larger than Arecibo (see Sect. 2.4.1.2). There was no UK support for this proposal and the idea lapsed until Wilkinson came to Socorro in October 1990 to attend IAU Colloquium 131 as discussed in Sect. 5.4.1.

### *5.3.5 The Netherlands Large Telescope: Robert Braun, Ger de Bruyn and Jan Noordam*

After Robert Braun left the VLA in the late 1980s and went to the Netherlands Foundation for Research in Astronomy (NFRA) he was thinking about how to get sufficient sensitivity in a radio telescope to do extragalactic HI (see Sect. 2.4.1.3). Braun used Ger de Bruyn's cosmological HI signal strength calculation code and it was apparent to him that a square kilometre collecting area would be needed to get galaxy HI emission detections out to cosmologically interesting distances.[10] After extensive discussion with de Bruyn and Jan Noordam at NFRA on how to build such a telescope, they proposed an array of large collectors with a total collecting area of 1 $\text{km}^2$. This was later named Euro-16[11] It was similar in scale to the Swarup proposals and made a similar science case, but also emphasised the study of interstellar HI in extragalactic systems with sufficient sensitivity and resolution to observe the HI structure with a level of detail previously only possible in our own galaxy. Their science case also included: pulsars, transient radio sources and galaxy clusters, studying both thermal and non-thermal radio emission. They also envisaged this as the core of an incredibly sensitive very long baseline (VLBI) array.

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[8] hba.skao.int/SKAHB-2. *What stuck in my memory. . .*, Peter Wilkinson (2019), presentation at SKA History 2019 Conference.

[9] Neutral hydrogen comprises ~90% of the (observable) matter in the universe.

[10] Email from Robert Braun 9 Jan 2023.

[11] hba.skao.int/SKAHB-5. *EURO16: Proposal for an Array of Low Cost 100 Meter Radio Telescopes*, J. E. Noordam et al., 1991.

### 5.3.6 Penticton Meeting “Radio Schmidt Telescope” 1989

In 1989 a meeting was held in Penticton to discuss an early initiative in Canada, led by Peter Dewdney (DRAO, Canada), to build the equivalent of a radio Schmidt telescope, a survey telescope but focusing on wide field-of-view science rather than higher sensitivity. This workshop was well attended by the international community and many of the technical topics raised were important for the SKA instrumental developments discussed in Chap. 6. For example, the Canadian proposal for an array of 100 small 12 m dishes (see Sect. 2.2.2.4) to maximise the field of view was the forerunner of the “large N—small D” design concept[12] that has played a major role throughout the development of the SKA. Small D increases the field of view and large N improves the imaging dynamic range and sensitivity.

Because the focus for this meeting was wide field of view and brightness sensitivity, galactic astronomy applications dominated the science case with both spectral line and continuum proposals to trace the large-scale structures in the galactic interstellar medium (ISM) and to measure nearby. The proposed array of small dishes was also well suited to radio imaging of the active sun. However, these goals did not require higher sensitivity and they did not get much emphasis in the future SKA science case. Extreme scattering events (ESEs) had just been discovered (Fiedler et al., 1987) and these made a strong case for surveys of transient radio sources, but even though this phenomenon has never been fully understood it did not re-appear in the SKA science case! Extragalactic astronomy requiring observations of large-scale structures such as the distribution and dynamics of HI in relatively nearby galaxies was included, as were the continuum observations of low brightness features in galaxy clusters. Observations of structure in the radio continuum emission from the cosmic microwave background (CMB) and the Sunyaev-Zeldovitch effect were considered. Multiwavelength astronomy had become popular so there was a general case for large radio surveys to match those being made at infrared and X-rays wavelengths.

### 5.3.7 Unexpected Discoveries

As discussed in Chap. 1, De Solla Price (1963) reached the conclusion that most scientific advances follow laboratory experiments and that the normal mode of growth of science is exponential. Subsequently, Harwit (1981) analysed discoveries in astronomy and concluded that most important astronomical discoveries were a result of technical innovation. De Solla Price (1984) pointed out that practitioners using new technology apply it to “everything in sight” often leading to the discovery of novel and surprising phenomena and this led to a recognition of the importance of

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[12] As discussed in Sect. 2.2.2.4 and in Chap. 6, n is the number of elements of diameter d. The total area is proportional to $n \times d^2$.

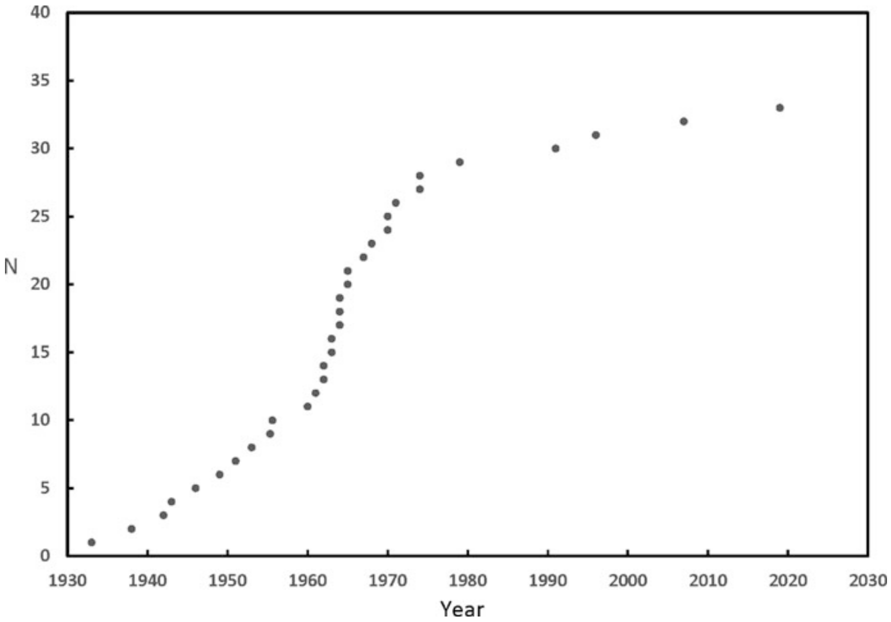

**Fig. 5.1** Cumulative number of discoveries at radio wavelengths vs time. (Credit: K. I. Kellermann, NRAO)

exploration of the unknown when discussing the design of new facilities (Wilkinson et al., 2004). Some discoveries are predicted new phenomena which are either confirmed by an observation or are observed accidentally but still confirm an existing prediction. In radio astronomy there had been a very large number of serendipitous discoveries of the unexpected and this was the theme for a meeting on the 50th anniversary of Jansky's discovery of radio emission coming from outside the earth (Kellermann & Sheets, 1984). The "Serendipity pattern" and its broader role in the nature of scientific discoveries is discussed by Merton and Barber (2004). It was well known in the radio astronomy community that while successful telescopes were built by visionaries, these telescopes often became best known for their unexpected discoveries, not for the reason they were built. There have now been a great many unexpected discoveries in radio astronomy; as summarised in a new book on the discoveries in radio astronomy (Kellermann & Bouton, 2023). Their Chap. 12 includes a dramatic discovery rate plot (Fig. 5.1)—with peak discovery rate between 1960 and 1980. These discoveries include many of the constituents of modern radio astronomy; radio galaxies, quasars, the cosmic microwave background, pulsars, masers, blackholes and many others.

## 5.4 Convergence of Visions: VLA Tenth Anniversary, 8 Oct 1990

The IAU colloquium 131 celebrated the 10-year birthday of the VLA. A meeting was held in Socorro, New Mexico, 8–12 October 1990. The VLA had been operating for a decade and was having a huge impact in astronomy, as is discussed in Chap. 1.

This meeting is generally recognised by the radio astronomy community as where the birth of the global SKA concept took place. The ideas of a next generation radio astronomy facility with a square kilometre of collecting area at centimetre wavelengths, which were discussed at this meeting, had arisen spontaneously in four different countries (as described above) and led to the "born global" concept.

### *5.4.1 Hydrogen Array: Peter Wilkinson*

During a break at the Socorro meeting, Jan Noordam talked to Peter Wilkinson about the Dutch proposal to build 16 100-m dishes. For a number of years Peter Wilkinson had also been thinking about the sensitivity requirements needed to observe HI in distant galaxies (see Sect. 2.4.1.2), so it was agreed that a talk on this topic be included in the meeting. Wilkinson agreed to give the talk and made the case for a square-kilometre collecting area array, which he called the Hydrogen Array (Wilkinson, 1991). Figure 5.2 shows an optical and an HI picture of the nearby grand design spiral galaxy, M81. These two pictures have some similarities but are also dramatically different. Wilkinson's concept was that there is a universe of stars and a universe of gas. So, in addition to looking at the universe in the light of stars, there is huge value in looking at the universe in the light of hydrogen gas, the gas from which the stars and first galaxies formed. Wilkinson penned this often-quoted comment, "*The encyclopaedia of the universe is written in very small typescript and to read it requires a very sensitive telescope*."

### *5.4.2 Exponential Growth of Radio Telescope Sensitivity: Yuri Parijskii*

Yuri Pariiskii (Pulkovo Observatory, Russia) also gave a talk at the Socorro meeting and showed the exponential increase in sensitivity of radio telescopes vs time (see Fig. 5.3). Ekers had shown a similar plot at the Prague URSI General Assembly in September 1990. The exponential growth curves have been discussed in Sect. 1.2.3 and the sensitivity plot for some of the major radio telescopes v time is plotted in Fig. 1.1. Kellermann (NRAO, USA) may have been the first to describe this exponential improvement in sensitivity with time and his plot is included in Sullivan

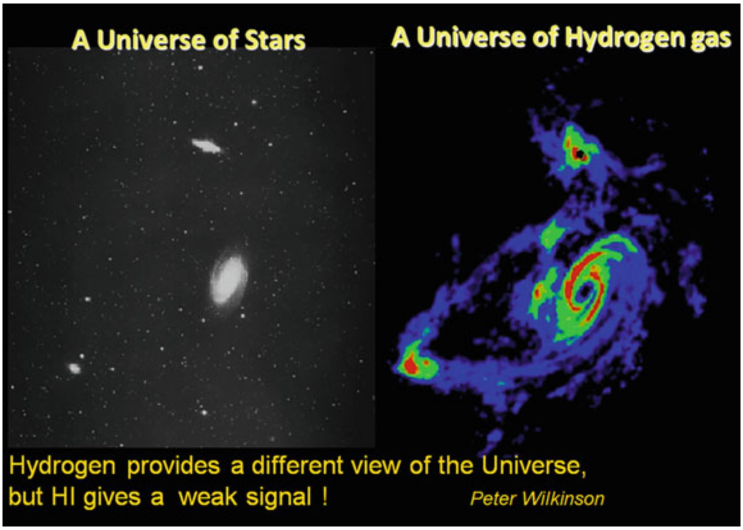

**Fig. 5.2** Peter Wilkinson's comparison of a Universe of Stars and of Hydrogen gas. The M81-M82-NGC 3077 group. (Left) Palomar Sky Survey Image. (Right) VLA image of the 21 cm line of HI. Yun et al. (1994). Credit: NRAO/AUI/NSF

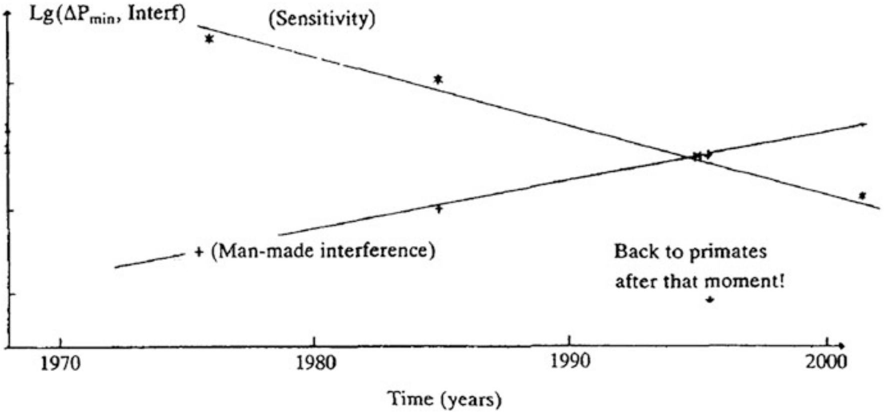

**Fig. 5.3** Interference and sensitivity versus time. (Credit: Fig. 10 from Pariiskii, Y. (1992), "Radio astronomy of the next century". *Astronomical and Astrophysical Transactions,* 1(2), 85–106. Reprinted with permission from the Eurasian Astronomical Society)

(1984, Preface p. x). Pariiskii's version of this plot (Fig. 5.3) is a measure of sensitivity (which improves as you go down in this plot) versus time. It is a log-linear plot so, again, there is the exponential trend, and the black dot in Pariiskii's plot at the year 2000 would correspond to something like an SKA. When Pariiskii gave this talk in Socorro he added a fascinating twist to the story. In Fig. 5.3 the sensitivity is improving exponentially but the world's man-made radio frequency interference (RFI) environment is getting exponentially worse as more RFI generating technology develops. His key message was that human ability to observe the universe at radio wavelengths is shrinking with time and therefore the next generation radio telescope must be built before these lines cross. Experience with radio observatories all around the world demonstrate that we are indeed running out of time! The impact of RFI, and the procedures needed to avoid this fate, are discussed in Sect. 5.8.2. By being clever, we may be able to suppress RFI by using adaptive RFI excision.[13] We can also select radio quiet sites,[14] however the increasing threat from low earth orbiting satellites (LEOs) will affect all sites on earth. Pariiskii did not publish his talk in the IAU Colloquium Series, but it was published a year later (Parijskij, 1992).

## 5.5 The Evolving Science Case

It is interesting to see how the science case evolved over the 30 years that have elapsed since the story started to be written in 1990. We have used four major sources of information:

i. hard copies of presentations including the science case made at meetings involving the SKA in various countries over this period,
ii. summaries of the science case included in the minutes of SKA meetings,
iii. reports included in the SKA memo series and newsletter articles and
iv. the SKA science books.

The first SKA science book was based on the Calgary meeting in July 1998 (Taylor & Braun, 1999), this was followed by the summary of the 7–9 April 1999 Amsterdam meeting "Perspectives on Radio Astronomy: Science with Large Antenna Arrays" (van Haarlem, 2000). Then a complete revision of the science case, edited by Chris Carilli (NRAO) and Steve Rawlings (Oxford, UK) was published in 2004. Finally, there is the massive two-volume edifice on the current science case published by SKAO in 2015.

The historical sequence of developments is given in the following sections and includes summaries of the actual presentation text in the boxes. We discuss the evolution of the different individual science areas in Sect. 5.10 and we have prepared a retrospective over-view of the evolving science case in the form of a matrix (Fig. 5.4). To simplify these comparisons, we have used a consistent terminology in the matrix but the text in the boxes is kept close to that used in the presentations at

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[13] hba.skao.int/SKAMEM-34. *Spatial Nulling for Attenuation of Interfering Signals, A. R.* Thompson: 7 Aug 2003.

[14] hba.skao.int/SKAMEM-37. *RFI Measurement Protocol for Candidate SKA Sites*, R. Ambrosini, R. Beresford, A. -J. Boonstra, S. Ellingson, K. Tapping, 23 May 2003.

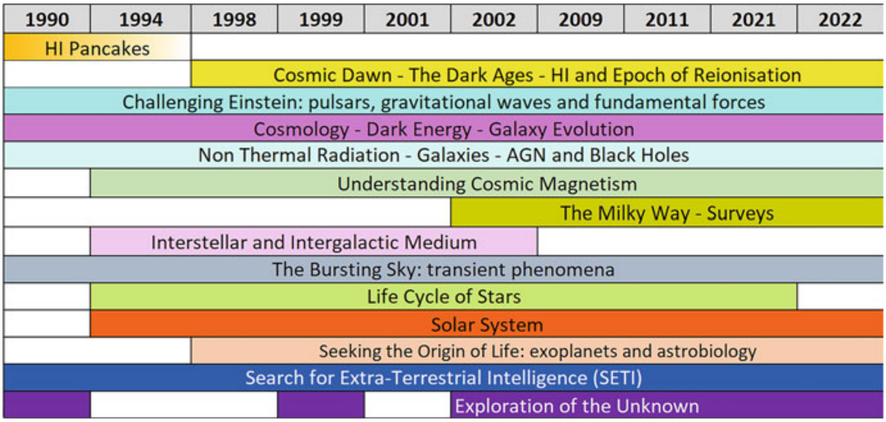

**Fig. 5.4** An overview of the evolving science case. Blank regions are included in periods when a particular case was not emphasised

the time. This has been prepared from a much more detailed matrix with all the sub-categories included. Finally, we comment on how the science case impacted the development of the SKA concept in Sect. 5.11.

### *5.5.1 SKA Science Case in 1990*

Box 5.1 is a composite science case from Swarup, Braun and Wilkinson presentations in the early-1990s. Note that the concept of the key science drivers did not materialise until well after 1990.

**Box 5.1 1990 Science Case**

- 21 cm HI from pancakes of gas before galaxy formation
  - Zel'dovich pancakes [the case for EoR had not yet been recognised]
- HI in high redshift galaxies
  - Surveys, large scale structure
  - Dynamical dark matter estimates
  - The "Great Attractor" debate
- Pulsars
  - Using pulsar timing for gravitational wave detection
  - Extragalactic pulsars detections
- Non-thermal radio continuum

(continued)

**Box 5.1** (continued)

  - The low luminosity emission from normal galaxies and weaker AGN at significant cosmological distances
  - New classes of stellar radio emission from stars in our galaxy

- Radio transients

  - The evolution of the radio emission from extra-galactic supernovae remnants

- Search for Extra-Terrestrial Intelligence (SETI)

The case for detecting the Epoch of Reionisation (EoR) had not yet been made but it was already clear that galaxies formed out of collapsing gas clouds. Ya Zel'dovich (Sternberg Institute, Russia) had proposed that to get rid of angular momentum, the gas would first collapse into flat pancakes and, after that, galaxies of stars would form (Zel'dovich, 1970). There were unsuccessful efforts at that time to try and detect these HI pancakes which would be the predecessors of the first galaxies with stars. Uson et al. (1991) claimed a VLA detection, but this was not confirmed by de Bruyn using the Westerbork Synthesis Radio Telescope (WSRT) or by Subramanyan and Swarup using the GMRT.

There was a case for measuring hydrogen over a large range of redshifts, to complement the big galaxy surveys of large-scale structure. HI observations to measure the velocity distribution could also provide mass estimates of galaxies including their dark matter. In 1990 the "Great Attractor" was a very hot topic. This was a large-scale gravitational anomaly traced by galaxy peculiar motions in the relatively nearby universe. Where was all the missing mass in the local universe causing these peculiar motions falling towards the Great Attractor?

From the very beginning, there was a clear science case for pulsars research which has become stronger over time. In 1993 the Nobel Prize in Physics[15] was awarded jointly to Russell A. Hulse and Joseph H. Taylor Jr. (U. Massachusetts, USA) "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation." This was a pulsar in a binary neutron star system discovered using the Arecibo radio telescope (Hulse & Taylor, 1975). The circumstances leading up to this discovery are described by (Kellermann & Bouton, 2023) Chap. 7. The observation of the orbital decay of the binary pulsar confirmed the existence of gravitational waves (Taylor & Weisberg, 1982). Gravitational waves have now been detected directly [see Sect. 5.10.3] making this an even more active area of research. Already in 1990 it was also understood that pulsar timing could be used for detecting the predicted very long wavelength cosmological gravitational waves generated in the early universe. The possible detection of extragalactic pulsars was also considered at this time.

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[15] https://www.nobelprize.org/prizes/physics/1993/summary/

The ability to detect supernovae[16] at great distance by observing non-thermal radio emission was considered important and radio continuum observations of the normal galaxies and weaker Active Galactic Nuclei (AGN) was included but with no specific additional goals.

There was some emphasis on finding new classes of stellar radio sources that might be detected, a topic which then disappeared out of the science case and has only re-appeared in the last few years as part of the search for radio transients and possibly transient radio emission from exoplanets.

The science cases nearly always included the evolution of life in the universe as one of the big questions. The emphasis on this varies between Searching for Extra-Terrestrial Intelligence (SETI) transmissions or other evidence for technology ("technosignatures") and looking for markers for planetary formation and other evidence for living organisms ("biosignatures").

### 5.5.2 Utrecht Meeting and the Euro-16 Proposal

On 27 September 1990 a "brainstorming" meeting was held in Utrecht[17] to discuss future developments in Dutch radio astronomy following the huge success of the Westerbork Synthesis Radio Telescope which had been in operation since the 1970s. This brainstorming meeting led to the proposal[18] for the "Euro-16" array with a total collecting area of 1 km$^2$ to provide enough sensitivity to detect neutral atomic hydrogen (HI) at cosmological distances, as already discussed in Sect. 5.3.5.

### 5.5.3 SKA Science Case 1994 and the URSI Large Telescope Working Group (LTWG)

One of the terms of reference for the URSI Large Telescope Working Group, the LTWG (Sect. 3.2.1), was to produce a concrete proposal supported by a well-defined scientific case. They did this at their first meeting,[19] which was held at Jodrell Bank on March 21 and 22, 1994. They decided the major scientific drivers should be defined by assessing what science could be envisaged with a 100-fold improvement

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[16] Strong synchrotron radio emission is generated by high energy particles accelerated in the remnants of a supernova explosion. First detected serendipitously in 1949 using WWII radar equipment, see Sullivan (2009) and Goss et al. (2023).

[17] "*National Astronomical Brainstorm*", Utrecht, Netherlands, 27 Sep 1990. We have been unable to recover the documentation for this meeting.

[18] hba.skao.int/SKAHB-5. *EURO16: Proposal for an Array of Low Cost 100 Meter Radio Telescopes*, J. E. Noordam et al., 1991.

[19] hba.skao.int/SKAHB-123. Minutes of the first meeting of the URSI Large Telescope Working Group, Robert Braun, March 1994.

in telescope performance, and then seeing how this would influence the instrumental specifications. Box 5.2 is a summary of the science case which emerged from the Large Telescope Working Group study, together with items from hard copies of the overhead projector presentations made in this period.

**Box 5.2 1994 Science Case**

- Cosmology
  - HI detections of galaxies at cosmologically interesting distances
  - Statistics of emission from powerful radio galaxies and quasars
- Galaxy evolution, dark matter and large scale structure
  - Galaxy evolution between $z = 0$ and 5 using radio continuum and neutral hydrogen
  - Proto-galaxy and proto-cluster evolution at red-shifts of 1 to 10 via HI emission
  - Weak gravitational lensing to probe the distribution of dark matter
- Interstellar medium
  - Deuterium emission imaging in the Galaxy
  - Recombination line imaging in H, He, C and S
  - Magnetic fields
- Galaxies
  - Extend galaxy rotation curves to measure dark matter content
  - The power source for quasars and active galactic nuclei (AGN)
  - Extragalactic SN and SNR
  - Magnetic fields
- Pulsars
  - Using pulsars to find rare objects such as black-hole binaries
  - Detecting extragalactic pulsars
  - Pulsar timing to Test General Relativity
  - Pulsar timing to detect gravitational radiation
- Stars
  - Many research areas discussed; mass loss, planetary companions, protostellar discs and jets, solar flares.
- Solar system
  - Imaging planets
  - Planetary radar
  - Detecting asteroids

(continued)

**Box 5.2** (continued)
- SETI
  - Detecting extra solar system planets
  - ETI communication detection (SETI)

This report included some insightful additional suggestions. They asked how will the study of proto-galaxy evolution be impacted by the new competition with observations of the much stronger CO emission at mm wavelengths? They included the possibility of detecting the primordial recombination lines of $H_{\text{n-alpha}}$ for $n = 20$ to 40 transitions from the cosmological recombination epoch in the very early universe (redshift $z=1500$) when the plasma from the big bang first combined. This is a very surprising inclusion which was not discussed further at the time but it would have had a big impact. It is now considered an exceptionally important opportunity for a specialised future telescope (Rao et al., 2015). The case for searching for Zel'dovich pancakes was fading away as the possible detections (see Sect. 5.5.1) were never confirmed. Magnetic field measurements using the Zeeman splitting of right and left circularly polarised HI emission or absorption were discussed, and the use of Faraday rotation was analysed, setting requirements on the frequency range and frequency resolutions. As a consequence of the recent discovery of exoplanets,[20] pulsar timing now includes searches for exoplanets as well as general relativity theory tests.

## 5.5.4 Pesek Lecture 1995

Ekers (1995) gave the Pesek Lecture, "*SETI and the One Square Kilometre Radio Telescope*" on 2 October 1995 at the 48th International Astronautical Congress in Oslo, Norway. The SKA telescope could be considered a significant step towards the realisation of project Cyclops for SETI (see Sect. 2.2.2.2). The SKA would provide a sensitivity 400 times that of the recently completed Project Phoenix survey using the Parkes radio telescope in Australia.[21]

In addition to summarising the SKA Science case and the exponential growth in sensitivity of radio telescopes, the lecture included the first discussion with the space community of SKA opportunities for solar system astronomy. Radar and thermal imaging would be possible for the more distant planets and for many of the planetary satellites. Radar observations of near-earth asteroids were crucial to make orbit

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[20] The confusing story of the first exoplanet detection (Wolszczan & Frail, 1992) is discussed in detail by Kellermann and Bouton (2023, Chap. 9).

[21] https://www.seti.org/seti-institute/project/details/parkes-australia-1996

determination possible at significantly greater range, an essential requirement for any asteroid collision avoidance program.

If the SKA were used as a communication ground station for deep space missions, high band width communication would be possible with extremely modest spacecraft communication antenna and power requirements. For example, the SKA would have had adequate sensitivity to achieve the original communication objectives of the Galileo spacecraft mission to Jupiter in 1995 even when using its low gain omnidirectional antenna.[22]

### 5.5.5 *Oort Workshop 1997*

On 2 June 1997 the topic of the Oort workshop in Leiden was *Scientific Drivers for the Next Generation Radio Telescope.*[23] This was a small workshop with 16 international experts from 7 different countries discussing the range of science that could be done with a next generation centimetre wavelength radio telescope. It was assumed that such a telescope should be capable of making high angular resolution high dynamic range images with at least a factor of 10 more sensitivity than existing arrays such as Westerbork and the VLA. The focus of the workshop was on the science, but Harvey Butcher (ASTRON, Netherlands) provided an insightful overview of the technical, political and social issues involved in such a major global project. Science topics included for discussion covered the full range of topics identified by the Large Telescope Working Group (Sect. 5.5.3). It also included, for the first time, a presentation by Piero Madau on the possibility of using the spectral signature of the 21 cm line to probe the epoch of reionisation (EoR) and heating in the early universe (EoR). This is the first presentation of a science case which over time became the most important driver for SKA-low (Sects. 5.5.20 and 5.10.2).

Following that meeting, George Miley (U. Leiden, Netherlands) made a proposal to ASTRON in July 1997 for a design study of a simpler high sensitivity low frequency array that could be built on a much shorter time scale than was projected for the SKA (see also Sect. 3.2.6.1). Miley was concerned that interest in radio astronomy would decline without such a focussed mission. There was an obvious need for different technologies at lower and higher frequencies (transition at about 300 MHz) and this led to the beginning of LOFAR (see Sects. 3.2.6.1 and 3.3.3.4.1) and the technology-based split of the SKA into separate lower and higher frequency solutions. However, the overlapping science cases were not split, and they continued to be discussed jointly under the one SKA umbrella.

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[22] This was relevant at the time because the high gain Galileo antenna did not unfurl, and significant mission objectives were compromised.

[23] hba.skao.int/SKASUP5-1. *Oort Workshop*, is a copy of all the presentations.

### 5.5.6 Science with the SKA 1998

URSI had established the LTWG in September 1993. The six subsequent meetings of this working group were a forum for mobilising a broad scientific community to discuss the technical requirements and to cooperate in establishing the science objectives. In December 1997 the 1kT workshop[24] in Sydney included a half-day meeting of the LTWG to discuss the science drivers.[25] The May 1998 report developed from these discussions[26] represents the first international effort to document some of the many science goals that will be addressed by the SKA. They drew attention to a particularly noteworthy aspect. "This will be the world's premier astronomical imaging instrument. No other existing or planned instrument in any wavelength regime can provide simultaneously: spatial resolution better than the Hubble Space Telescope (<0.1"), a field of view significantly larger than the full moon (1 square degree), the spectral coverage of more than 50% ($\gamma/\Delta\gamma < 2$) and a spectral resolution sufficient for kinematic studies ($\gamma/d\gamma > 10^4$) and all at a sensitivity which is about 100 times that currently achievable."

**Box 5.3 1998 Science Case**

- The Dark Ages
- Large-scale Structure and Galaxy Evolution
  - HI surveys out to $z = 3$
- Very Deep Fields
- Probing Dark Matter with Gravitational Lensing
- Circum-nuclear masers
  - $H_2O$ megamasers
  - 0H megamasers
- Synchrotron Ageing and Evolutionary Studies of Radio Galaxies
- Fossil galaxies
- Halo Emission
- Parsec-scale radio structure in Active Galactic Nuclei
- Interstellar Processes
  - Cosmic Ray Origin
  - Supernova Remnants

(continued)

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[24] At this time the SKA was known as the 1kT in Australia.

[25] An almost complete set of presentations put together by Wim Brouw are still accessible at https://www.atnf.csiro.au/research/conferences/SKA1997/index.html

[26] hba.skao.int/SKAHB-124. *Square Kilometer Array Radio Telescope - The Science Case*, edited R. Braun, May 1998.

**Box 5.3** (continued)

  - HII Regions
  - Interstellar Propagation Effects
  - Carbon Recombination Lines

- Magnetic Fields
- Formation and Evolution of Stars
  - Detection of Stellar Radio Continuum Emission
  - Circumstellar Environments
  - Stellar Astrometry
- Transient Phenomena
  - Supernovae and Gamma-ray Bursts
  - Coherent Processes
  - Extra Solar System Planets (exoplanets)
  - Flare Stars
- Gravitational Radiation and General Relativity
  - Pulsar timing and searches
- Formation and Evolution of Life
  - Solar System Science
  - SETI

The summary of this very extensive science case is given in Box 5.3. It now included many topics not previously discussed and for each topic they included considerable detail on the value of the science and the technical requirements. They did not restrict the list to new science areas which will only be possible with the SKA. For the first time the "Dark Ages" were included as a major component of the science case. They explored the observable effects of the various possible sources of ionising radiation on the neutral hydrogen gas. The frequency range of interest now extended from 20 GHz down to 30 MHz but it was noted that different antenna technologies would be needed to cover this frequency range (see Sect. 5.7.3 and Chap. 6). Weak Gravitational Lensing (Kaiser & Squires, 1993) was another field which had opened up since the initial science discussions and SKA, with its well defined point spread function (PSF), as a very promising observational technique.

These topics were the basis for discussions at the International SKA Science meeting in Calgary, 17 July 1998. An interesting presentation[27] made at this meeting was "missing items" which identified new ideas that had emerged since the last URSI LTWG discussions. These included highly redshifted CO where the 3 mm

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[27] Ekers, personal records.

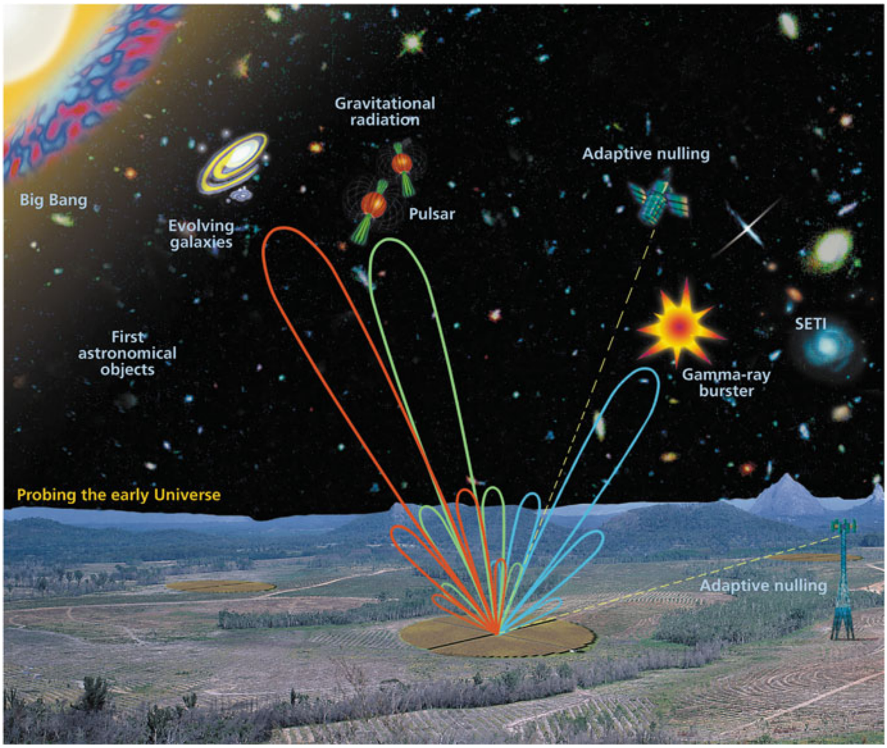

**Fig. 5.5** SKA multibeam concept prepared for a brochure in 2003. Design: H. Sim, Credit: CSIRO Radio Astronomy Image Archive CRAIA-SKA006

lines were redshifted into the 1.5 cm SKA band, Sunyaev-Zel'dovich effects, gravitationally lensed HI, fast (msec) transients[28] and deep space communications.

### 5.5.7 Impact of a Multibeam Design on the Science Case: 1998

At the 1998 Calgary meeting the use of simultaneous multiple beams pointing in many different directions was being discussed. This was analogous to the multiple high energy projects sharing particle accelerator beams. This concept had quite an impact on the science case as is illustrated in Fig. 5.5. The multibeam concept emerged as an innovative new technology development, first as a natural option

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[28] Note that this is 20 years before the Lorimer Burst, the first extragalactic fast transient, was discovered.

for an aperture array and later also as a driver for the Luneberg lens proposals—see Chap. 6. Note that the possibility of splitting the signal and forming multiple beams with no loss in S/N is only possible at radio wavelengths and is a fundamental quantum effect, see Radhakrishnan (1999), that dramatically changes design and observational strategies possible at radio wavelengths.[29]

In 2002 the International Science Advisory Committees (ISAC) Radio Transient Working Group[30] suggested at least 10 simultaneous beams were needed to monitor multiple sources simultaneously. They also pointed out that the concept of simultaneously doing many different observations at the same time opened up the opportunity for high-risk science which can be done commensally. For example, SETI was often included in the science case but rarely given much emphasis until the multibeam option opened more opportunities for such high-risk observations. The ISAC also pointed out that the multiple-beaming capability would make it possible to identify terrestrial radio-frequency interference in one beam in order to remove it from other beams.

### *5.5.8 SKA Science Book (Eds Taylor and Braun) 1999*

As discussed in Sect. 3.2.4.2 a major international meeting focused on SKA science was held in Amsterdam in March 1999 (van Haarlem, 1999) and this raised greater awareness of the SKA in the wider astrophysics' community. The detailed science case discussions which now included the broader astronomy community together with the science case developed by the LTWG led to the first publication of the SKA science case: *Science with the Square Kilometre Array: a next generation world radio observatory* (Taylor & Braun, 1999). This was published by the Netherlands Foundation for Radio Astronomy but not widely distributed outside the SKA community. *Science with the SKA* included material from 67 contributors. These were largely based on presentations made at the SKA Science Workshop held in Calgary, Canada, in July 1998 and in Amsterdam the following year. Planning for a next generation facility had led to the conclusion that a revolutionary new instrument at radio wavelengths was needed, one with an effective collecting area 30 times greater than the largest telescope ever built.

Taylor and Braun (1999) expressed the view that "With a spatial resolution better than the Hubble Space Telescope, a field-of-view (FoV) larger than the full Moon, and the ability to simultaneously image a wide range of red shifts (as many objects at high redshift in one long integration as the whole Las Campanas redshift survey of

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[29] In the Raleigh-Jeans part of the spectrum there are many photons for every possible state in the system so multiple identical copies of an undetected signal stream can be made and signal amplification is possible. These techniques are not possible with the photon limited data streams observed at higher frequencies.

[30] hba.skao.int/SKAMEM-6. *Radio Transients, Stellar End Products, and SETI*, J. Lazio, March 2002.

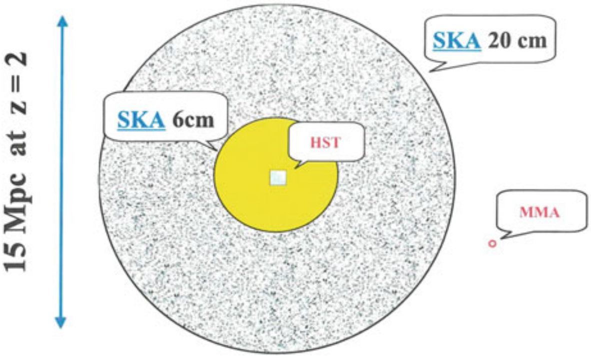

**Fig. 5.6** Comparison of the fields of view of the SKA (1 square degree at 20 cm) with those of the Hubble Deep Field and the MMA the proposed MilliMetre Array, which evolved into the Atacama Large Millimetre/sub-millimetre wave Array (ALMA). Credit: CSIRO Radio Astronomy Image Archive CRAIA-SKA002

galaxies!), the SKA will be a discovery instrument to rival the NGST [Next Generation Space Telescope][31]". They summarised the main goals of SKA with a focus on the evolution of structure in the Universe on all scales.

- Probe the structure and kinematics of the Universe before the dawn of galaxies to understand the physics of the early Universe and how galaxies arose.
- To chart the formation and evolution of galaxies from the epoch of formation. To measure the evolution of the properties of galaxies, including dark matter halos, trace the star formation history of the Universe, and explore the origin of cosmic magnetic fields and their role in galaxy evolution.
- To understand key astrophysical processes relating to the process of star formation and the physical and chemical evolution of galaxies by studies of the local Universe.
- To trace the physical mechanisms that give rise to planetary systems, to understand the evolution of our own solar system, and to engage in definitive experiments to answer the question, "Are we alone?"
- To detect long-period gravitational waves, conduct exhaustive tests of general relativity, and explore the properties of nuclear matter within neutron stars.

Taylor and Braun optimistically assumed the SKA would need to be completed by 2010 to complement developments at other wavelengths. But they also noted that while the SKA had been born global, there was no international vehicle such as ESO or CERN to develop this concept.

The value of a very wide FoV had already been identified by the discussion of the Radio Schmidt telescope in Penticton in 1989 (see Sect. 2.2.2.4). Figure 5.6 compares the wide FoV of the SKA (Table 5.1) with that of the Hubble Deep Field and the MMA (Milli-Meter Array).[32] By combining interferometry and phased-array receiver technology, the SKA will image a FoV of one degree at λ21 cm with angular

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[31] Later renamed the James Webb Space Telescope.

[32] The MMA was the US mm array proposal now the Atacama Large Millimetre Array (ALMA) after merging with the European LMDA proposal. Both have a similar very small field of view.

**Table 5.1** SKA design goals[a]

| Parameter | Design goal |
|---|---|
| Aeff/Tsys | $2 \times 10^4$ $m^2/K$ |
| Total frequency range | 0.03–20 GHz |
| Imaging field of view | 1 square deg. @ 1.4 GHz |
| Number of instantaneous pencil beams | 100 |
| Maximum primary beam separation | |
| Low frequency | 100 deg. |
| High frequency | 1 deg. @ 1.4 GHz |
| Number of spatial pixels | $10^8$ |
| Angular resolution | 0.1 arcsec@ 1.4 GHz |
| Surface brightness sensitivity | 1 K @ 0.1 arcsec (continuum) |
| Instantaneous bandwidth | $0.5 + \nu /5$ GHz |
| Number of spectral channels | $10^4$ |
| Number of simultaneous frequency bands | 2 |
| Clean beam dynamic range | $10^6$ @ 1.4 GHz |
| Polarisation purity | −40 dB |

[a]This table from the SKA technical workshop in Sydney Dec 1997, is reproduced in Taylor and Braun (1999, p. 17)

resolution of 0.1”. Taylor and Braun again emphasised this advantage compared to any other existing or planned instrument in any wavelength regime.

This science case was used to develop the first quantitative set of SKA design goals which have not changed significantly since then.

The potential to study the epoch of reionisation (EoR) was clearly emerging as can be seen in the following quote from Taylor and Braun (1999, p. 23):

> Prior to the epoch of full reionization, the intergalactic medium and gravitationally collapsed systems will be detectable in 21-cm radiation. Physical mechanisms that would produce a 21-cm signature are Lyα coupling of the hydrogen spin temperature to the kinetic temperature of the gas resulting from the radiation by an early generation of stars, preheating by soft x-rays from collapsing dark matter halos, and preheating by ambient Lyα photons. A patchwork of either 21-cm emission, or absorption against the Cosmic Microwave Background, will result. The Square Kilometre Array offers the prospect of measuring this signature, and so detecting the transitional epoch from a dark universe to one with light.

Dark Ages refer to a time before light existed in the Universe. As the first stars and galaxies formed, their light re-ionised the surrounding neutral intergalactic medium. This ended the Dark Ages and brought us the nearly completely ionised, light-filled Universe in which we live today. Figure 5.7 illustrates the Dark Ages and the reionisation era in the context of the cosmic history of the evolving universe.

At that time, the most distant quasar known had $z = 5$ (corresponding to redshifted HI at 200 MHz) so there was much speculation about the observability of this “epoch of first light” at low radio frequencies, a dream which has still not been realised more than 20 years later. The physics of the 21 cm HI emission and

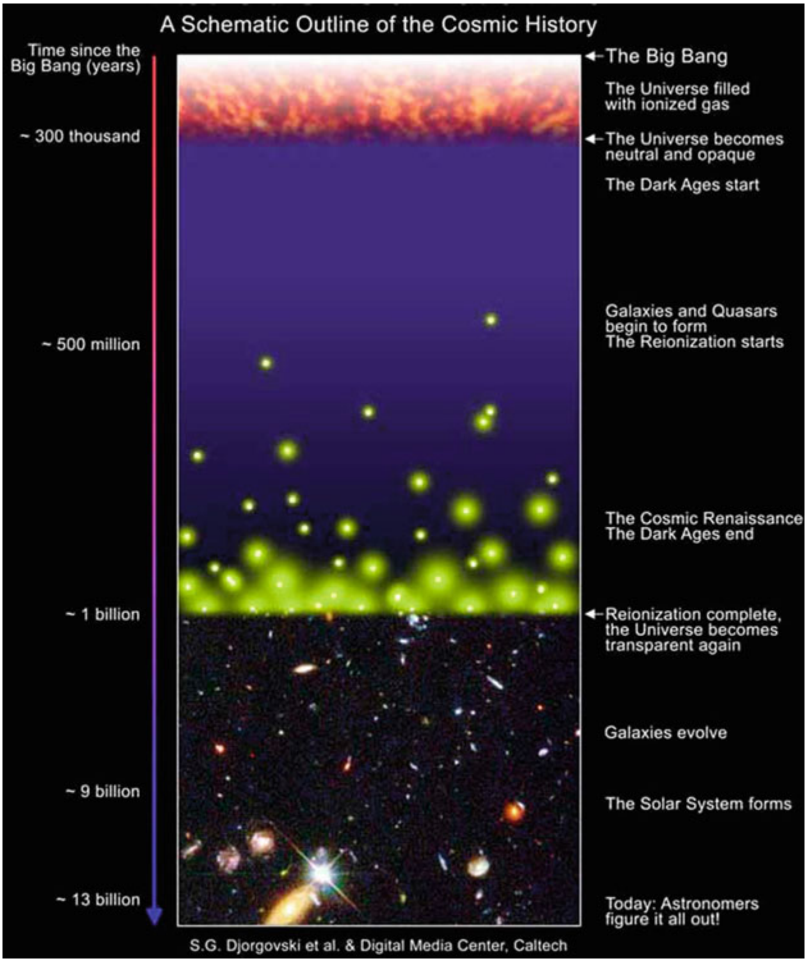

**Fig. 5.7** Cosmic History and the Dark Ages. Credit: S. Djorgovski et al., produced with the help of the Caltech Digital Media Centre

absorption and the experimental difficulties are discussed in more detail in Sects. 5.5.20 and 5.10.2.

Hydrogen is the most abundant element in the Universe. With a sensitivity to the 21 cm hyperfine transition of H I, allowing detection out to z > 1, the SKA will follow the assembly of galaxies and can use their H I emission to measure large scale structure and early galaxy evolution. This provides a strong SKA science case and has been a key science driver since its inception. Details of narrow-deep and wider-shallow surveys were considered within the context of surveys proposed at other wavelengths. Highly redshifted CO was also considered a possibility.

The deep radio continuum surveys are an obvious application with the easy detectability and spectral resolution of regions of star forming activity added to the fainter Active Galactic Nuclei (AGN)s (e.g. Hopkins et al., 1998). Probing dark matter through weak gravitational lensing (Kaiser & Squires, 1993) of radio continuum sources was a new application taking advantage of the SKA's very well-defined point spread function (PSF) and very large field of view. Another obvious extension of current radio galaxy research was to make high angular resolution observations of the radio structure surrounding the central black holes in active galaxies. This led to a science case to use the SKA core as the centre of a Very Long Baseline (VLBI) array spread over thousands of kilometres with milli-arcsecond angular resolution. The use of SKA stations in a future VLBI arrays extending over global baselines was also raised.

Other extragalactic topics covered were: OH and $H_2O$ mega masers,[33] extragalactic supernovae remnants, scattering, and Faraday rotation. Taylor and Braun (1999) included a substantial discussion of the uses of high sensitivity radio observations to study many different stellar processes. This aspect of the SKA science did not receive much attention since then and has only recently re-emerged with the possible detection of stellar systems with exoplanets. The pulsar case included surveys to find rare binary systems which, they note, would become future gravitational laboratories. The case was well emphasised but not developed further in the SKA Science book (eds Taylor and Braun). Pulsar timing arrays and their potential to detect gravitational waves were noted. Solar system science, including radar, was another topic raised in this SKA Science book but not subsequently followed up (see Sect. 5.10.11).

SETI opportunities were quantified and the huge sensitivity advance over any existing surveys was tabulated. This may have partially triggered the inclusion of SKA advocates in discussions of future technologies which were taking place in the SETI community—e.g. (Ekers et al., 2002) "*SETI 2020: A roadmap for the Search for Extraterrestrial Intelligence*" which summarised a series of workshops held in Silicon Valley which included the SETI community, radio and optical astronomers and industry.

### *5.5.9 SKA Key Science Goals: 1999*

This is a simplified version of the summary from Taylor and Braun (1999) extracting the key science goals.

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[33] Interstellar masers are regions in space where the molecules have inverted populations of energy levels and produce amplified stimulated spectral line emission at radio frequencies. Mega masers are those strong enough to be detected at distances beyond our galaxy. Interstellar masers were an unexpected discovery made in 1965 despite incorrect theoretical predictions, see Kellermann and Bouton (2023).

- Probing the dark ages before the first stars
- Evolution of galaxies and large scale structure in the universe
- Origin and evolution of cosmic magnetism
- The cradle of life (terrestrial planets)
- Strong field tests of gravity via pulsars and black holes
- Exploration of the unknown

A key change is the inclusion of the potential detection of HI spectral line during the epoch of reionisation (EoR) which was triggered by the formation of the first stars and given the evocative name "the dark ages" . This replaces the old concept of searching for Zel'dovich pancakes (Zel'dovich, 1970) which would have very low-density contrast and would be difficult to observe compared to spectral changes caused by reionisation. This possibility opened up a new research area of astrophysical modelling and made a strong case for extending the frequency range down to below a few hundred MHz to look for the signature of the HI line at redshifts greater than 6.

By 1999 the other topics are still broadly similar except SETI has been turned into the "cradle of life" and now includes the search for extra-terrestrial planets. Whether or not SETI is explicitly included depends very much on the personal view of the presenter. Some astronomers have always questioned whether SETI is a legitimate area of scientific research.

Exploration of the unknown was often listed and from time to time was included specifically as a key science goal—see Wilkinson et al. (2004). In addition, recognising the long history of discovery at radio wavelengths (pulsars, cosmic microwave background, quasars, masers, the first extrasolar planets, etc.), the international science community also recommended that the design and development of the SKA include "exploration of the unknown" as a philosophy. Wherever possible, the design of the telescope should be developed in a manner to allow maximum flexibility and evolution of its capabilities in new directions and to probe new parameter space (e.g., time variable phenomena). This philosophy is essential given that many of the outstanding questions when the SKA will be in its most productive years,—are not even known today. This philosophy generated pressure for flexibility in the instrumental design as discussed in Chap. 6. However, some astronomers felt that it was difficult to easily include this in the science case because it does not generate clear-cut specifications and because there is also a perception that it indicates that astronomers do not know what they are looking for.

### 5.5.10 Australian Mid-Term Review: 2001

The Australian mid-term review "Beyond 2000"[34] included an assessment that the SKA would be an extremely versatile instrument that will be able to make major contributions to a broad range of astronomical topics. Box 5.4 lists the topics that were included in the science case.

**Box 5.4 2001 Science Case**

- **The first stars and galaxies—**The SKA will detect the very first objects formed after the Big Bang from the primordial hydrogen gas.
- **The structure of the universe**—The SKA will detect the 'cosmic web' of hydrogen and reveal the distribution of the matter in the early universe.
- **Dark matter**—The SKA will measure the amount of dark matter in the universe by observing the rotation of galaxies and the gravitational distortion of distant objects.
- **Gravitational Waves**—By timing many rapid pulsars, the SKA will be able to detect gravitational waves produced by the collisions of black holes anywhere in the universe.
- **Planets around other stars**—By accurate positional measurements of nearby stars, the SKA will be able to detect Jupiter-like planets and study their orbits.

Occasionally, and depending on the audience, applications beyond science were included. The mid-term review page 28 noted "The SKA also has applications in radio science communities outside astronomy, such as deep space communications and geodesy."

### 5.5.11 Bologna Meeting: 2002

In January 2002 at the Bologna SKA meeting the Science Advisory committee (see Sect. 5.9.2) arranged a workshop dedicated to refining the science case for the telescope. Subgroups had been formed for the eight scientific areas identified and there were reports from the science subgroup chairs at the previous meeting in Berkeley. All groups provided reports in the SKA Memo series #5 to #13 (there is no SKA Memo #11).

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[34] hba.skao.int/SKAHB-132. *Beyond 2000* Australian mid-term review, July 2001.

- Milky Way and Local Neighbourhood Galaxies (SKA Memo #5)[35]
- Radio Transients, Stellar End Products, and SETI (SKA Memo #6)[36]
- Early Universe and Large-Scale Structure (SKA Memo #7)[37]
- Galaxy Formation (SKA Memo #8)[38]
- Active Galactic Nuclei and Supermassive Black Holes (SKA Memo #9)[39]
- Life Cycle of Stars (SKA Memo #10)[40]
- Intergalactic Medium (SKA Memo #12)[41]
- Spacecraft Communication (SKA Memo #13)[42]

The Radio transient Working Group provided a detailed analysis of the forefront science to be pursued with the SKA and looked carefully at the implications for the SKA specifications. Pulsars, transients, and some SETI observations require observing modes that differ markedly from those designed for imaging modes of sources that do not vary with time. Therefore, care must be taken to incorporate these cases in the conceptual and design phases of the SKA. They also emphasised that the science predictions are based on the known populations of transient sources. The greatest return from such a survey will (should!) be the detection of currently unknown populations of sources.

The Early Universe and Large-Scale Structure Working Group focussed entirely on the newly emerging field of EoR observations (see Sects. 5.5.20 and 5.10.2). The case for observing at lower frequencies was greatly strengthened and the case for a high brightness sensitivity centrally concentrated array was promoted.

The Galaxy Formation Working Group discussed making sensitive, wide field 21 cm HI line and radio continuum surveys. They drew attention to the conflicting baseline configuration requirements between HI and continuum surveys and they also suggested, as a compromise, the centrally concentrated configurations that have now become the norm. They also remarked on the need to restructure the science case based on the important questions. An issue that is discussed further in Sect. 5.10.

The largest group included much of the traditional continuum radio astronomy community who study radio galaxies, active galactic nuclei (AGN) and the supermassive black holes in the centres of the galaxies that create the jets and

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[35] hba.skao.int/SKAMEM-5. *Milky Way and Local Neighborhood Galaxies,* P. Sackett et al., January 2002.

[36] hba.skao.int/SKAMEM-6. *Radio Transients, Stellar End Products and SETI*, J. Lazio et al., March 2002.

[37] hba.skao.int/SKAMEM-7. *Early Universe and Large-Scale Structure,* F. Briggs et al., January 2002.

[38] hba.skao.int/SKAMEM-8. *Galaxy Formation,* C. Carilli, January 2002.

[39] hba.skao.int/SKAMEM-9. *Active Galactic Nuclei and the supermassive black holes,* D. Jones et al., January 2002.

[40] hba.skao.int/SKAMEM-10. *Life Cycle of Stars,* S. Dougherty et al., February 2002.

[41] hba.skao.int/SKAMEM-12. *Intergalactic Medium,* L. Ferreti et al., January 2002.

[42] hba.skao.int/SKAMEM-13. *Spacecraft Tracking,* D. Jones, January 2002.

**Table 5.2** The ISAC working groups[a]

| Area | Chair |
|---|---|
| The Milky Way and local galaxies | John Dickey (Minnesota) |
| SETI, Stellar end products, transient sources | Joseph Lazio (NRL) |
| Cosmology and large scale structure | Frank Briggs (ANU) |
| Galaxy evolution | Thijs van der Hulst (Kapteyn) |
| Active galactic nuclei and super massive black holes | Heino Falcke (ASTRON) |
| The life cycle of stars | Sean Dougherty (DRAO) |
| The solar system and planetary science | Bryan Butler (NRAO) |
| The intergalactic medium | Luigina Feretti (IRA) |
| Spacecraft tracking | Dayton Jones (JPL). |

[a] Carilli and Rawlings Introduction Table 1 (Carilli & Rawlings, 2004)

extended lobes of radio continuum emission. Radio galaxies and AGN are bright and had been well studied for the previous 50 years so it was hard to identify high level science goals where the SKA would have a dramatic impact. Much of the science case involved incremental improvements. The large number of elements in any of the "large N—small D" SKA designs meant excellent quality images would be possible (see Sects. 5.7.4 and 2.2.2.4) so this was as important as high sensitivity. Understanding the energetics, stability, and internal flows of radio jets and radio galaxy lobes[43] requires high dynamic imaging over a wide range of angular scales and frequencies so array configurations with the widest possible range of baseline lengths were desired. One SKA specific requirement identified was the ability to distinguish thermal from nonthermal compact radio sources at high redshift which requires both high angular resolution and sensitivity.

### *5.5.12 Lorentz Centre Meeting: Leiden 2003*

A new book on the science case was commissioned by the Science Advisory Committee at the Bologna meeting in 2002 and Schilizzi followed up by organising a meeting of all the International Science Advisory Committee Working Groups at the Lorentz Centre in Leiden from 10 to 14 November 2003. The Working Group chairs are listed in Table 5.2 and 45 astronomers from all around the world participated in this meeting. The goals were two-fold: to select key science projects, and to write the science case chapters for the new book. This was an extremely

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[43] Radio galaxies are galaxies with extremely powerful radio emission associated with an accreting black holes in their nuclei. Discovered serendipitously in 1949, they required a paradigm shift in radio astronomy from the prevailing concept where discrete radio sources were stars in our galaxy, see Goss et al. (2023) and Kellermann and Bouton (2023).

**Fig. 5.8** Chris Carilli, SWG chair 2002–2004 Credit: C. Carilli and NRAO

**Fig. 5.9** Steve Rawlings looking over the GMRT, credit Katherine Blundell

productive meeting[44] which significantly advanced the science case for the SKA as discussed in the next section.

### 5.5.13 SKA Science Book (Eds Carilli and Rawlings): 2003

Carilli and Rawlings[45] (Figs. 5.8 and 5.9) edited the publication of a complete revision of the SKA science case based on the Lorentz Centre meeting discussed in the previous section . *Science with the SKA* was published by Carilli & Rawlings in November 2004 and incorporated the latest results in astronomy, with emphasis on the most important outstanding problems.

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[44] hba.skao.int/SKAHB-452. *Astronomy with the Square Kilometre Array*, S, Rawlings, R. Schilizzi and C. Carilli, November 2003.

[45] Professor Steve Rawlings died in Jan 2012 leaving a massive legacy through his scientific contributions and promotion of the SKA.

Carilli and Rawlings emphasised the big picture by separating out the 5 key science projects (KSPs) that had been identified by a sub-committee chaired by Bryan Gaensler[46] (Harvard, USA): The Cradle of Life, Strong field tests of gravity, Cosmic magnetism, Galaxy evolution and cosmology and Probing the dark ages (EoR). The book then continues with another 43 chapters on different science projects with 106 contributing authors from 10 different countries.

It was this SKA science book, together with the 1999 Amsterdam meeting (Sect. 5.5.8), that brought the SKA to the attention of the entire astronomical community, extending it outside the community of radio astronomers.

These reports were authored by experts in a wide range of fields, some not traditional fields for radio astronomy. The incentive to contribute was driven by the thought that if an SKA was built, they wanted to ensure that their science area was covered by the design specifications. Outside the established radio astronomy community, there are contributions from the high energy particle physics community (Falcke et al., 2004) for the radio detection of high energy cosmic rays and neutrinos hitting the moon. There were also contributions on spacecraft tracking (Jones, 2004), precision astrometry (Fomalont & Reid, 2004) and planetary science (Butler et al., 2004).

Particularly noteworthy was the emergence of a range of transient science opportunities that had significant instrumental implications (see Chap. 6). The dynamic radio sky was summarised by Cordes et al. (2004) in a prescient paper which noted that extragalactic transients, which may be detectable with the high sensitivity of the SKA, are necessarily compact and would have measurable scattering and dispersion, all factors that would offer unique opportunities to probe properties of the intervening medium. The serendipitous discovery a few years later of Fast Radio Bursts (Lorimer et al., 2007), using the multibeam receiver on the Parkes radio telescope, made this prediction a reality before the SKA was built.

In their Introduction Carilli and Rawlings note "The time since the publication of the Taylor–Braun document has seen a revolution in our knowledge of the local and distant Universe. We have entered an era of 'precision cosmology', where the fundamental parameters ($H_0$, $\Omega_M$, etc.) describing the emerging 'standard model' in cosmology are known to ~ ±10%. This standard model includes 'dark energy' and 'dark matter' as the two dominant energy densities in the present-day Universe. We have probed into the time of the first light in the universe, the 'epoch of reionization', when the UV emission from the first stars and (accreting) supermassive black holes reionizes the neutral intergalactic medium. $\gamma$-ray bursts have been shown to be the largest explosions in the universe, tracing the death of very massive stars to the earliest epochs. Supermassive black holes have gone from being a hypothetical

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[46] hba.skao.int/SKAMEM-44. *Recommendations on Key Science Projects,* B. Gaensler for ISAC, November 2003.

by-product of general relativity (GR), to being a fundamental aspect of all spheroidal galaxies and how these objects formed."[47]

#### 5.5.13.1 Connecting Quarks with the Cosmos

In 2003 there was a major review by the US National Academy of Science "Connecting Quarks with the Cosmos: 11 Science Questions for the New Century"[48]. SKA had picked up four of these big questions in its science case so the SKA KSPs had meshed very well with these big questions in physics. Dark energy and dark matter had now made their appearance with increasing emphasis in the SKA science case. One example of what SKA could do well was the detection of baryon acoustic oscillations (BAO) , which are remnants of early density fluctuations in the Universe and serve as a tracer of early Universe expansion. For this, the large area neutral hydrogen surveys were now crucial and survey speed, achieved by high sensitivity and a large FoV, became an important driver of the telescope design. A sample selected by HI removes many of the biases introduced by selecting galaxies based on the integrated light from the stars formed in the galaxies; biases which are poorly understood because of the complexity of the star formation process. SKA will assemble a sufficiently large sample of galaxies to measure the BAO signal as a function of redshift and this can be used to determine the rate of evolution of the equation of state of dark energy.

#### 5.5.13.2 Using Pulsars for Tests of General Relativity

Pulsars have always been a significant component of the SKA science case because they provide unique opportunities to study neutron stars and detect gravitational waves. They also provide exquisite tests for gravitational theories.

The sheer number of pulsars that could be discovered by the SKA, in combination with the exceptional timing precision possible with SKA sensitivity, would be able to revolutionise the field of pulsar astrophysics. In 2004, just as the SKA Science Book was being written, this opportunity was greatly enhanced with the discovery of the double pulsar system, Lyne et al. (2004) and Burgay et al. (2005), a special binary neutron star system in which both neutron stars are pulsars. It was discovered using the Parkes radio telescope and its multibeam receiver. This amazing and so-far unique system gave astronomers a new probe of relativistic gravity theory. It was voted one of the top ten discoveries of 2004 by *Science* magazine. The system has one rapidly spinning pulsar (pulse period 22 ms) in an extremely tight binary orbit

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[47] This quote misses the 1963 discovery of the first quasars, the radio source 3C273. It was this discovery that first made the super massive black hole concept credible.

[48] https://doi.org/10.17226/10079

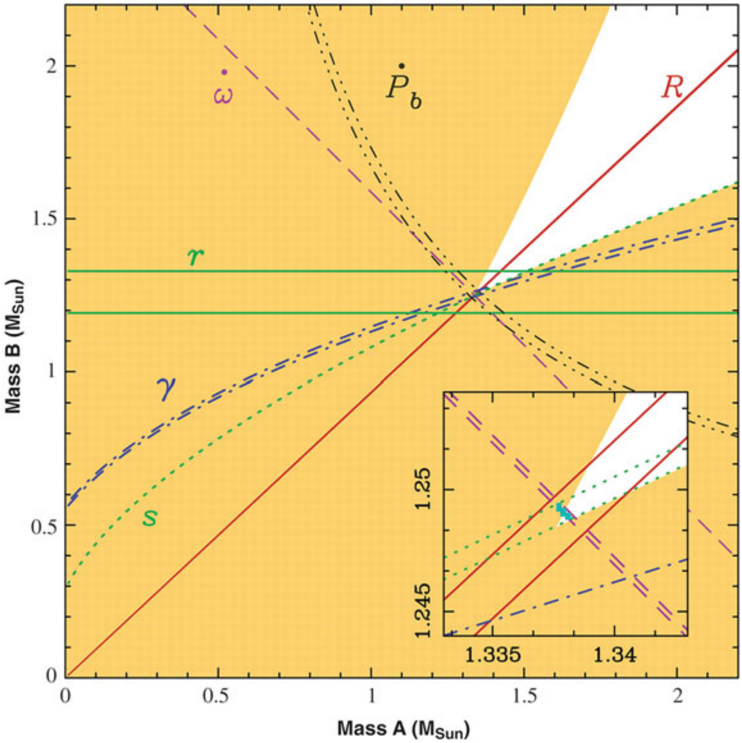

Fig. 5.10 Mass-mass plot for the Double Pulsar system. Constraints on the system from precision timing of the two pulsars are shown. Credit: Kramer, M., et al. (2006). “Tests of General Relativity from Timing the Double Pulsar”. *Science, 314*(5796), 97–102

with a second slower 2.8 s pulsar. The orbital period of the binary system is just 2.4 h.

The most important application of the double pulsar system is the test of gravitational theory made possible by the detection of relativistic perturbations to the pulse arrival times. The dependence of all these effects on the masses of the stars can be predicted by Einstein’s general theory of relativity. All the curves are consistent with the predictions to better than 0.05% and this became the most precise strong-field test of general relativity at that time (Fig. 5.10) With the SKA sensitivity, large numbers of the millisecond period pulsars would be discovered: including more binaries, and possibly even including a rare pulsar orbiting a black hole which would greatly extend the strong field tests of gravity.

Carilli revisited this 2004 science case in 2019[49] and discusses how well the KSPs have stood the test of time in the light of our current view of the most exciting science.

### 5.5.14 OECD Global Science Forum Astronomy Workshops (2003–2004)

As described in Sect. 4.3.1, two astronomy workshops convened by the OECD Global Science Forum (GSF, the successor to the Mega-Science Forum, (see Sect. 3.2.5.2) were held, in Munich in December 2003 and Washington in April 2004.[50] The intention was to review scientific priorities and challenges in astronomy and astrophysics. The US funding agencies argued that their decadal survey process was far more effective, and that the USA had little to gain from any proposed global coordination activities. However this activity did raise the profile of the SKA as an exciting new large international project in the minds of other physicists and astronomers around the world.

### 5.5.15 The SKA Newsletters 2004–2012

This period is well documented in the series of SKA Newsletters which include summaries of the activities of the International Science Advisory Committee (ISAC) and Science Working Group (SWG) committees which had been set up to manage the science case (see Sects. 5.9.1 and 3.3.1.2). The activities in the period from 2004 to 2006 were dominated by the production of the Carilli and Rawlings SKA science book and by the more active promotion of the science case. Considerable effort went into giving the SKA science case more visibility in the broader astronomy and physics community. At this time the SKA was transitioning from the development of a new telescope by a group of radio astronomers to a major global scientific endeavour. This was also enhancing the visibility of all radio astronomy and was the beginning of a path to other developments, such as the SKA precursors discussed in Chaps. 4 and 6.

The other major development in this period was the finalisation of the key science goals and a key science project list (see Sect. 5.9.4). and the descriptions of the science behind these key science projects, which is summarised in the following section.

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[49] hba.skao.int/SKAHB-138. *Key Science Projects for the SKA,* Chris Carilli, Presentation at the SKAHistory2019 conference, April 2019.

[50] hba.skao.int/SKAHB-126. Final report on the OECD Global Science Forum Workshops on Future Large-Scale Projects and Programmes in Astronomy and Astrophysics, December 2003 and April 2004.

### 5.5.16 A Summary of the Key Science Projects (KSPs): 2006

**Probing the Dark Ages**

At the end of June 2005, over 120 people attended the meeting "Reionising the Universe" in Groningen, at which theorists and observers came together to discuss the many exciting developments now taking place in this new field. A subset of the contributions to the Groningen meeting have been compiled by Bryan Gaensler, who was SKA project scientist at that time.[51]

**Strong Field Tests of Gravity**

About 20 pulsar experts attended a workshop in Sydney in August 2005, including many young scientists who were becoming involved in the SKA project for the first time. In another meeting, "Gravitational Waves, Radio Pulsars and Astrometry" held in Birmingham on 30–31 March 2006, a new level of interaction developed between the radio and the gravitational wave community. At that time, both the Laser Interferometer Gravitational Wave Observatory (LIGO) and the Laser Interferometer Space Antenna (LISA) were being designed to detect gravitational waves directly while the SKA had the goal of probing gravity using techniques based on pulsar timing. Pulsar timing can probe both near field gravitational effects as well as the far field gravitational wave effects. Near field effects can be tested by observing a pulsar in a close orbit around another star. The precise evolution of the orbit can be used to place strong limits on the validity of Einstein's general theory of relativity. The far field gravitational wave effects can be probed using observations of many pulsars seen in different directions. Correlation between pulsar timing residuals in different directions can be used to infer the presence of a gravitational wave background at the location of the earth.

**Cosmic Magnetism**

The magnetism team organised a conference in Bologna in August/September 2005.[52] A wide variety of topics were discussed, covering magnetic fields from the inflation era of the Universe through to magnetic fields in nearby galaxies. Many unanswered questions in cosmology and in fundamental astrophysics are closely tied to the questions of the origin and evolution of magnetic fields. The SKA is critical to making further progress in this area.

**The Cradle of Life**

A special session on the importance of radio astronomy for astrobiology was included in the Astrobiology Science Conference 2006, held in Washington, DC. This was a large interdisciplinary event and attracted roughly 1000 participants. The motivation behind the radio astronomy symposium was to increase the exposure of the SKA and inform the astrobiology community about the relevant questions that

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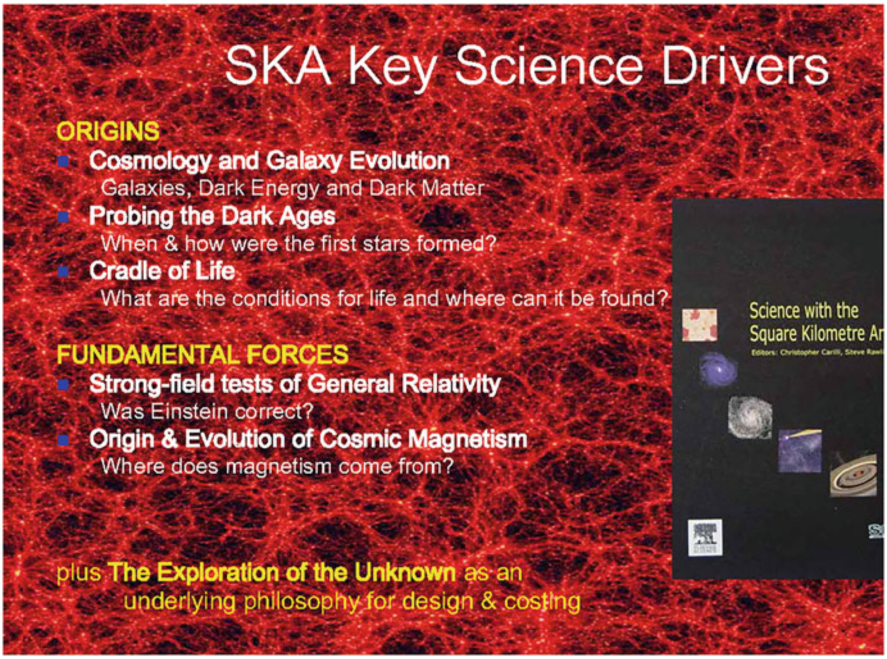
[51] hba.skao.int/SKAMEM-89. *Meeting on Key Science with the SKA,* B. Gaensler, November 2006.

[52] An excellent collection of papers from this meeting is published in a special issue of Astronomische Nachrichten, "*The Origin and Evolution of Cosmic Magnetism*" (Beck et al., 2006).



SKA Key Science Drivers

ORIGINS

- **Cosmology and Galaxy Evolution**
  Galaxies, Dark Energy and Dark Matter
- **Probing the Dark Ages**
  When & how were the first stars formed?
- **Cradle of Life**
  What are the conditions for life and where can it be found?

FUNDAMENTAL FORCES

- **Strong-field tests of General Relativity**
  Was Einstein correct?
- **Origin & Evolution of Cosmic Magnetism**
  Where does magnetism come from?

plus **The Exploration of the Unknown** as an underlying philosophy for design & costing

**Fig. 5.11** The five KSPs from various historical presentations in 2009. The insert is a truncated version of the cover of the Elsevier book version of Carilli and Rawlings (2004). Background is an N-body simulation of the ΛCDM universe constrained to reproduce the observed large scale structure of the local universe at $z = 0.84$. Credit for background: Springel, White, Lemson, Kauffman, Dekel and the GIF Consortium

can be pursued with the existing and planned tools of radio astronomy (particularly the SKA) in studying planet formation, organic biomolecules, pristine relics of our own solar system and techno-signatures (SETI) .

### Galaxy Evolution, Cosmology and Dark Energy

A large meeting was organised (April 2006) in Oxford, covering cosmology, galaxy evolution and astroparticle physics. There were sessions on science with the SKA, as well as with the 1% pathfinders and the 10% SKA (SKA Phase 1).

Figure 5.11 illustrates these five KSPs (re-ordered) at the time of the February 2009 Cape Town meeting. The exploration of the unknown was added; although not formally listed as a specific KSP it was recognised as part of the design philosophy.

In 2007 during a US review by a national "Dark Energy Task Force"[53] it was concluded that the SKA, as well as the Large-Sized Telescope (LST) and the Joint Dark Energy Mission (JDEM) are the future major projects needed to advance our

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[53] https://www.nsf.gov/mps/ast/aaac/dark_energy_task_force/report/detf_final_report.pdf

knowledge of dark energy. A corresponding UK review, carried out by the Particle Physics and Astronomy Research Council's (PPARC) Science Committee, emphasised that the two techniques the SKA will use to study dark energy, namely weak lensing and acoustic oscillations, together hold the most promise for future studies of dark energy.

### 5.5.17 SKA Key Science Requirements Matrix 2006: Prime Science Drivers

The initial compilations of science cases made no prioritisation of the different goals and made no analysis of how they were driving the specifications. The concept of a matrix emerged in 2002[54,55] with science goals on one axis and how these goals were met by different designs on the other axis. In 2004 the specification document was updated[56] and basic design specifications were linked back to the science goals. The matrix was successful in generating a dialogue between scientists and engineers but problems with the lack of uniformity across the complex space spanned by the matrix were emerging.[57] This was exacerbated by the ongoing debate between advocates of the different SKA design concepts (see Chap. 6). However, the key science requirements matrix did provide a consolidated, although complex, description of the SKA key science goals and the SKA requirements. It was updated and significantly expanded by the SWG between 2005 and 2006, as a result of discussions at Key Science workshops and at science meetings in Pune and Paris.[58]

### 5.5.18 SKA Reference Science Mission: 2009

By January 2009 the key science projects had evolved into the following (alphabetical) list. The structure of the science case has been changed with more emphasis on instrumental requirements rather than the broad science goals.

- **Astrobiology**: Search for organic molecules in molecular clouds and link them to proto-planetary discs; likely to require higher frequencies.
- **Cosmic Magnetism**: Understand the origin and evolution of cosmic magnetism; likely to require high polarisation purity

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[54] hba.skao.int/SKAMEM-28. *SKA Concept Designs* ISAC, 1 November 2002.

[55] hba.skao.int/SKAMEM-29. *SKA Science: a Parameter Space Analysis*, C. Jackson, April 2002.

[56] hba.skao.int/SKAMEM-45. *SKA Science Requirements*, D. Jones, 26 February 2004.

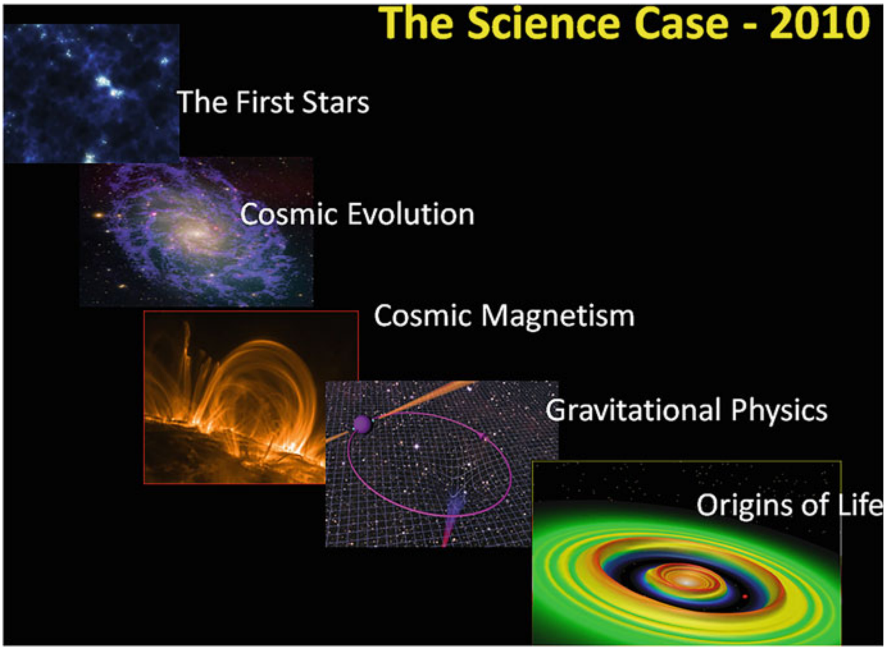
[57] hba.skao.int/SKAMEM-62. *Report on the final version of the Compliance Matrix*, S. Rawlings, July 2005.

[58] hba.skao.int/SKAMEM-83. *SKA Key Science Requirements Matrix 2006*, C. Jackson, August 2006.

**Fig. 5.12** Joseph ("Joe") Lazio, Project Scientist (2008–2011), Director of Science [acting] (2012). Credit: J. Lazio

- **Deep Continuum Field**: Probe the first galaxies and protoclusters; likely to require high sensitivity, high imaging dynamic range, and long baselines.
- **Deep H I Field**: Track the evolution of galaxies over a significant cosmic epoch; likely to require high sensitivity and high spectral dynamic range.
- **Galactic Centre survey**: Probe the spacetime environment around Sgr A*, the closest super-massive black hole in the centre of the Milky Way Galaxy; likely to require high time resolution and higher frequencies to avoid scattering. This also requires a Southern Hemisphere location (see Sect. 5.8.1).
- **Galactic Plane survey**: Use neutron stars as probes of gravitational and nuclear physics. Test theories of gravity using ultra-relativistic binaries in the Milky Way Galaxy's spiral disc; likely to require high time resolution.
- **HI Absorption survey**: Track the evolution of gas in galaxies to the earliest epochs; likely to require lower frequencies.
- **Wide Area survey (a.k.a. "all-sky survey"):** Various tests of theories of gravity, including studying gravitational waves using an array of millisecond pulsars and using baryon acoustic oscillations (BAO) in the galaxy distribution as a means of exploring dark energy; likely to require high survey speed and high time resolution.

Note the specification creep that is now becoming more significant with additional requirements including higher and lower frequencies, high time resolution, high survey speed, high polarisation purity and long baselines. The increase in cost, or reduction in sensitivity for a given cost, (see Sect. 4.4.3.3.1) is partly a consequence of the acceptance of these changing requirements. The scientific trade-off between the desire for increased capability even with a decrease in sensitivity may well have been justified but these very significant implications were not discussed by the science working group (see Sect. 5.9.2).



The Science Case - 2010

The First Stars

Cosmic Evolution

Cosmic Magnetism

Gravitational Physics

Origins of Life

**Fig. 5.13** The Science Case 2010. Credit: CSIRO Radio Astronomy Image Archive CRAIA-SKA010

With Joe Lazio (Fig. 5.12) as SWG chair we see an increased emphasis on the “Exploration of the Unknown.” Lazio noted that for all components of the Reference Science Mission, it was anticipated that the observations would also be exploring the largely unknown dynamic radio sky, consistent with the SKA design philosophy which included “Exploration of the Unknown”.

### *5.5.19 The Science Case: 2010*

Figure 5.13 still shows much the same information as in the 2006 KSPs but the presentation was now more refined and restructured with the evolution of structure in the universe as a unifying theme. The strong field tests of general relativity were further emphasised. The presentation styles and restructuring of the science management formulation had changed more dramatically than the actual science case. Visually impressive models showing how the universe evolved from its original big bang were now central to the presentation of the science case.

**Fig. 5.14** Bryan Gaensler. Project Scientist and Chair of the SWG 2006–2008. Credit: B. Gaensler

Joe Lazio wrote a feature article for SKA Newsletter #18 in July 2010 “Science with the SKA” highlighting SKA development and future science.[59] Lazio provided an excellent review of the original motivation for the SKA and the key areas of physics and astronomy that have been chosen as priorities for the SKA. His review includes

- Probing the Dark Ages,
- Galaxy evolution, cosmology and dark energy,
- The origin and evolution of cosmic magnetism,
- Strong field tests of gravity, using pulsars and black holes
- Cradle of life,
- Exploration of the unknown

#### 5.5.19.1 Identify Unique Radio Niches

By 2010 it had been recognised that to compete with the big telescope projects at other wavelengths, it was important to identify niche areas in astronomy which could **only** be tackled by radio astronomy.[60] One such area was the study of cosmic magnetism. Cosmic magnetism had always been included as part of the science case and was vigorously promoted by Bryan Gaensler, then at the University of Sydney (Fig. 5.14). When Gaensler became chair of the Science Working Group (2006 to 2008) he led a move to elevate the study of cosmic magnetism as a special unique component of the science case. Radio astronomy has a colossal advantage

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[59] hba.skao.int/NEWS-18. *Science with the Square Kilometre Array,* T. Joseph, W. Lazio, SKA #18, July 2010.

[60] hba.skao.int/SKAMEM-88. “Science with the Square Kilometre Array: Uniqueness and Complementarity”, B. Gaensler and J. Lazio, October 2006.

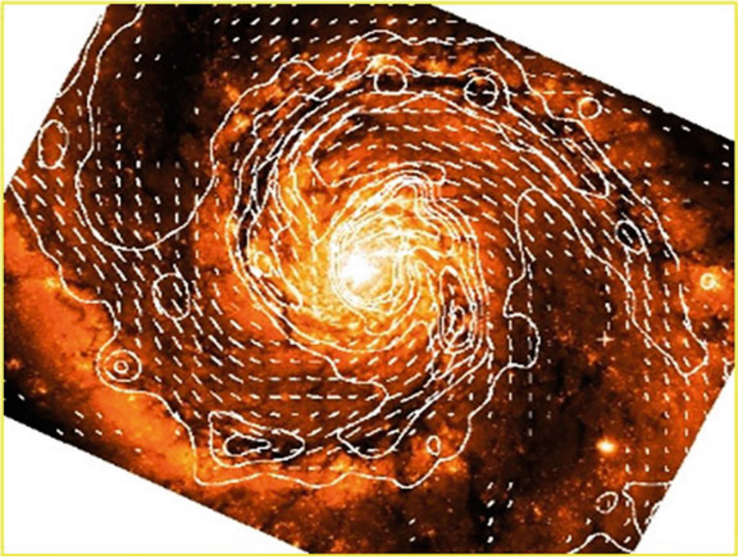

**Fig. 5.15** Magnetic field in the grand design spiral galaxy M51. Credit: Gaensler, B., Beck, R., & Feretti, L. (2004) "The origin and evolution of cosmic magnetism" in C. Carilli, & S. Rawlings (Eds.), *Science with the Square Kilometre Array,* 48, 1003. Elsevier

over other wavebands when it comes to studying astrophysical magnetism. Radio astronomers could measure the Zeeman effect, they could measure the magnetic field directions through the polarised synchrotron emission (Fig. 5.15), and they could study the Faraday rotation of the linear polarisation as radio waves propagated through the intervening medium. Instead of being a part of other science, cosmic magnetism now became a main science driver and was indeed an excellent example of a unique niche for radio astronomy.

#### 5.5.19.2 More Focussed Science Case

The external system engineering concept design review in 2010 (see Sect. 5.9.10) included a recommendation for greater focus which resulted in an extreme reduction in the number of science goals. The factors which led up to this review have been discussed in Chap. 4, Sect. 4.5.2. This recommendation meant that many in the astronomy community felt disenfranchised. Radio continuum imaging and VLBI were no longer listed as they covered such a large range of astronomical objectives that they appear to lack focus. Although this change in focus had a positive effect on the funding agencies it resulted in an increasing disparity between the well-focussed goals needed by funding agencies and design engineers and the need for a flexible facility that could support a wide range of different observing programs and adapt to new discoveries.

### 5.5.20 The Epoch of Reionisation (EoR) Science Case

The style of the SKA Newsletters from # 20 (2011) changed to provide reviews of single topics by outside experts. The January 2011 Newsletter included a review of experiments exploring the *Epoch of Reionization and the Dark Ages by C. Carilli, L. Greenhill, and L. Koopmans.*[61] This topic, now referred to as the Universe's Dark Ages, became one of the key scientific frontiers for the SKA. It is the time soon after the Big Bang before there were any stars. The Universe was in a hot and dense state, so hot that it was completely ionised. As the Universe expanded, it also cooled, until about 400,000 years after the Big Bang when it was sufficiently cold that neutral hydrogen atoms could form. This neutral hydrogen gas filling the Universe would be the raw material from which the first stars could form. The 21 cm neutral hydrogen signal from this very distant gas is redshifted to lower frequencies. Simulations of the spatial structure were computed to illustrate how the reionisation proceeds.

The EoR is certainly a unique niche for the SKA. The Hubble Space Telescope (HST), the Atacama Large Millimeter Array (ALMA) and the James Webb Space Telescope (JWST) can study the first galaxies (assemblies of stars) but the only means by which to quantify the rapidly evolving physical conditions during the first billion years of the Universe's history is to study the neutral hydrogen from which the first stars and galaxies formed.

## 5.6 International SKA Forums 2007–2012

The Funding Agencies Working Group (FAWG) established an International SKA Forum to facilitate engagement between scientists and representatives from government departments and funding agencies (see Sect. 4.2.1). The first International SKA Forum meeting took place in Manchester in October 2007. These meetings, which were held annually and rotated around the member countries, included science and engineering presentations in association with the national status reports, presentations on specific scientific topics by invited speakers, and meetings of the funding agencies.

### 5.6.1 The Science Case in 2011 and the Data Processing Requirements

The final International SKA Forum meeting was held in Banff, Canada, in 2011, with the case summarised neatly by Lazio:

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[61] hba.skao.int/SKANEWS-20. *Zooming in on the Epoch of Reionisation and the Dark Ages of the Universe,* C. Carilli, Newsletter #20, January 2011.

20th Century: We discovered our place in the Universe.
21st Century: We understand the Universe we inhabit.

Box 5.5 based on Lazio's presentation[62] summarises how a radio wavelength observatory, the SKA, will contribute to this goal. The basic science cases for cosmology, fundamental physics and galaxy evolution remain similar, but reorganised. Topics like the Epoch of Reionisation are reworded as "how did the Universe emerge from the Dark Ages". The life cycle of the interstellar medium and stars, the evolution of planetary systems and evidence for life on exoplanets have been added. Detection of ultra-high energy cosmic rays gets a mention as does a wider range of transient phenomena. In this presentation Lazio added details on the scientific requirements and translated these into technical requirements. The difficulty of measuring the epoch of reionisation was recognised. Lazio included a summary of the imaging requirements and the massive data processing implications for an array of this size. See Cornwell's memo on the enormous software challenges facing the SKA.[63] From this time it was understood that the SKA science would be computationally limited. This was even predicted to become an issue for the SKA pathfinders and the scalability of processing solutions was a serious concern.

**Box 5.5 Science Case 2011**

- **Cosmology**
  - Era of precision cosmology, dark matter and dark energy
  - Large scale surveys in continuum and line, 1 billion galaxies
  - Detection of weak lensing
- **Gravity**
  - Can strong gravity be observed in action?
  - What is dark matter and dark energy? (dark energy and BAOs with H I galaxies)
- **Magnetism**
- **Strong force**
  - Nuclear equation of state

(continued)

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[62] hba.skao.int/SKAHB-127. *The Square Kilometre Array Massive Data Challenges at the Frontiers of Astronomy,* Physics, & Astrobiology, Joseph Lazio, presentation at the International SKA Forum, Banff, Canada, July 2011.

[63] hba.skao.int/SKAMEM-128. *SKA Exascale Software Challenges*, T. Cornwell and B. Humphreys, October 2010.

**Box 5.5** (continued)

- **Evolution of Galaxies and the Universe**
  - How did the Universe emerge from its Dark Ages? [Epoch of reionisation renamed]
  - How did the structure of the cosmic web evolve?
  - Where are most of the metals throughout cosmic time?
  - How were galaxies assembled?
- **Stars, Planets, and Life**
  - How do planetary systems form and evolve?
  - What is the life-cycle of the interstellar medium and stars? (biomolecules)
  - Is there evidence for life on exoplanets? (SETI)

### *5.6.2 Long Baseline Science with the SKA (VLBI)*

At the Banff meeting in 2011 Lisa Harvey-Smith (CSIRO, Australia) summarised the many areas of SKA research that required long baselines (>1000 km).[64] These touched on almost all aspects of the science case, including strong-field tests of gravity, gravitational-wave experiments, evolution of galaxies, galactic magnetic fields, protoplanetary discs, first-generation active galactic nuclei (AGN) and radio transients. Examples explored included high precision astrometry to measure pulsar parallax and hence distances and proper motions to constrain tests of general relativity.

### *5.6.3 HI Stacking*

Andrew Hopkins[65] (University of Sydney) outlined the current developments in the stacking of HI emission from galaxies. If you have a sample of galaxies with known redshift the radio spectra can be aligned at the anticipated HI line frequency and averaged (stacked) to improve the sensitivity for sample average. The value of this technique is dependent on the future optical redshift surveys and Hopkin's paper discussed opportunities in the $0.5 < z < 2$ range. Demonstrations of HI stacking feasibility in the $0.2 < z < 0.7$ range will be possible with the SKA pathfinders.

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[64] hba.skao.int/SKAHB-128. *The science case for SKA long baselines*, Lisa Harvey-Smith, presentation at the International SKA Forum, Banff, Canada, July 2011.

[65] hba.skao.int/SKAMEM-138. *HI stacking*, A. Hopkins, December 2011.

Introductions to the process and existing results can be found in papers by Philip Lah and summarised in his ANU PhD thesis (Lah, 2009). Note that any stacking type analysis provides essentially the same cosmological information as the cross-power spectrum.[66]

### 5.6.4 SKA Surveys and Cosmology

SKA Newsletter #23 (November 2011) includes a review: "*Paths to cosmology with the SKA*" by David Bacon and Chris Blake.[67] This newsletter articles provides a good summary of the impact of deep continuum and HI surveys including subtle effects due to clustering, CMB distortion and lensing. It also discusses the Baryon Acoustic Oscillations (BAO) method which provides a cosmic yardstick and concludes that the SKA is well placed to make a major contribution.

## 5.7 Impact of Science Requirements on Design

Throughout the life of the project, it was well understood that the technical consequences of the developing science case had to be considered. Early in the project, this was a natural consequence of having scientists with broad knowledge of both the astronomy and the engineering designing the telescope. As time went on and both the scientists and engineers involved in the SKA were attracted from larger but more specialised communities, the integration of the astronomy and the engineering had to be more actively managed. The practical constraints required prioritisation and complex trade-offs between different options. Separate, more specialised, advisory committees were being appointed. Managing the interactions between the astronomy and the engineering groups was a complex process and a matrix of science requirements versus technical options (the compliance matrix), had been developed between 2002 and 2006 (Sect. 5.5.17). A large number of science drivers had emerged with a mixture of different specifications on the telescope design, and all these were all being considered to generate an integrated SKA specification. The matrix included the required values for different design parameters, including frequency range, sensitivity, spatial resolution, surface brightness sensitivity, field of view, multi-beaming, dynamic range, number of spectral line channels, frequency agility, total power, polarisation, and time resolution. The full details of the matrix

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[66] From Kiyoshi Masul discussion, IAU symposium FRB 2022.

[67] hba.skao.int/SKAHB-134. *Paths to cosmology with the SKA*, David Bacon and Chris Blake, November 2011.

are included in SKA Memo 83.[68] Here we summarise some of the science requirements that had a major impact on the design in ways that are discussed in Chap. 6. Comments on these design implications had already been summarised in separate memos from the Engineering Management Team (EMT)[69] and the Science Advisory Committee (ISAC).[70]

### *5.7.1 Sensitivity*

Sensitivity a factor of 10–100 times greater than any existing telescopes was always the goal and this was driven by essentially all the science cases being discussed. The issue here was the most cost-effective way to realise the required sensitivity, and this is discussed in Chap. 6.

### *5.7.2 SKA Survey Speed*

A large field-of-view (FoV) which is achievable at these long radio wavelengths, had already been recognised as a very desirable feature. The development of the science case for cosmology and dark energy experiments (Sects. 5.5.11 and 5.6.4) made surveys and hence survey speed a critical design criterion for the SKA, with Bunton (CSIRO, Australia) and Cordes (Cornell University, USA) independently developing a figure of merit to explore trade-offs between sensitivity (Area/Tsys) and FoV.[71,72] An instrument with half the sensitivity will need four times as much integration time per field to achieve the same sensitivity, reducing its survey speed by a factor of four. Survey speed also depends directly on the imaging field of view (FoV) and on the correlator bandwidth (BW). Thus a simple measure of survey speed is the product of the FoV and the BW, weighted by the sensitivity squared.

$$\text{Survey speed} = \text{FoV} \times \text{BW} \times (\text{Area}/\text{Tsys})^2$$

The implications of this requirement are discussed in Chap. 6. However, Cordes added an important caveat noting that this treatment does not apply to intermittent

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[68] hba.skao.int/SKAMEM-83. *SKA Key Science Requirements Matrix 2006*: *Prime Science Drivers,* C. Jackson, August 2006.

[69] hba.skao.int/SKAMEM-27. *SKA Concept Designs—EMT Comments,* P. J. Hall, October 2002.

[70] hba.skao.int/SKAMEM-28. *SKA Concept Designs—ISAC Comments,* C. Carilli, November 2002.

[71] hba.skao.int/SKAMEM-40. *Figure of Merit for SKA survey speed,* John D. Bunton, 9 September 2003.

[72] hba.skao.int/SKAMEM-109. *Survey Metrics,* J. M. Cordes October 2007 (revised January 2009).

transient sources for which FoV becomes more strongly weighted.[73] But in 2007 the Fast Radio Burst population had not yet been discovered so the implications of the need to modify the survey speed metric did not influence design choices and the final design was not optimised for this class of object.

### 5.7.3 Frequency Range

The required frequency range was a critical SKA design issue, and the impact is discussed in Sects. 6.2.2.8 (exploration of the unknown) and 6.5.1 (low frequency range). The initial emphasis on high sensitivity observations of the 21 cm neutral hydrogen line, both in the local universe and at high redshift required frequencies from a few hundred MHz to 1.4 GHz and this was a wavelength range where it was thought that a large collecting area would be possible within a modest cost envelope. The other early science cases including pulsars, radio galaxies, non-thermal stellar radio emission and SETI, as well as propagation effects such as Faraday rotation, could be included with a modest extension of the upper frequency range to a few GHz.

Two factors were to dramatically change this view and have a huge impact on the development of the SKA. By the late-1990s the recognition that radio astronomy could explore the dark ages and the epoch of reionisation pushed the lower frequency down from a few hundred MHz to 30–50 MHz and this change required a split between SKA-low and SKA-mid with different antenna designs. The second factor resulted from the interest in this next-generation radio telescope in the broader astronomy community. This broadened the science case, and the initial upper frequency of a few GHz ($\lambda = 10$ cm) was soon extended to 10 GHz ($\lambda = 3$ cm). But a cut-off at 10 GHz still precludes most thermal science such as mm molecular line emission redshifted down to cm wavelengths and terrestrial planet formation so the upper frequency was further extended to 20 GHz ($\lambda = 1.5$ cm).[74]

### 5.7.4 Image Properties

The quality of the images that the SKA will produce, and ultimately its scientific performance, will be determined in no small part by the distribution of antennas that comprise it, also known as the “array configuration". The array configuration

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[73] hba.skao.int/SKAMEM-97. *The SKA as a Synoptic Survey Telescope: Widefield Surveys for Transients, Pulsars and ETI,* Jim Cordes, September 2007.

[74] hba.skao.int/SKAMEM-70. *The case for frequencies > 10 GHz for the SKA phase I: Thermal science at cm wavelengths,* Chris Carilli, late 2005 or early 2006.

requirements affect both hardware design (Chap. 6) and geographical constraints (Sect. 5.8.5).

In 2003 Andrei Lobanov[75] argued that, in addition to a significant improvement in sensitivity, high angular resolution images with high spatial dynamic range would be needed to take full advantage of the image quality being achieved in observations made at other wavelengths. Lobanov made an analysis of the Spatial Dynamic Range (SDR) for the different designs being considered at that time. As expected, the strongest requirement would be the filling factor achieved from the distribution of antennas across the array. This requirement strongly favours the large N—small D design approach (see Sect. 5.3.6) and a central concentration of antennas with optimised antenna locations. This analysis was ongoing, and a further report including simulations was provided by Lal, Lobanov and Jimenez-Monferrer in December 2008.[76]

### 5.7.5 Simulations

A team at the University of Oxford (Wilman et al., 2008), developed a semi-empirical simulation of the extragalactic radio continuum sky to aid the design of the SKA. Their emphasis was on modelling the large-scale cosmological distribution of radio sources rather than the internal structure of individual sources. These simulations were developed under the European Comission funded SKA Design Study (SKADS) project and referred to collectively as SKADS Simulated Skies ($S^3$). Access to these simulations was made available to the community through a set of Python-based software routines and interfaces.

The primary telescope specifications such as sensitivity, angular resolution and FoV could be specified, and the simulations could be used to quantify the achievability of various scientific goals. The simulations also provided datasets that could be used to develop data processing systems. There were limitations, such as the need to extrapolate properties of known populations, and of course any new classes of radio source could not be included. It was too difficult to realistically include the more complex instrumental behaviour so the simulations did not have impact on any design details.

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[75] hba.skao.int/SKAMEM-38. *Imaging with the SKA: Comparison to other future major instruments,* A. P. Lobanov, 2003.

[76] hba.skao.int/SKAMEM-107. *Array configuration studies for the Square Kilometre Array, - Implementation of figures of merit based on spatial dynamic range*, Dharam Vir Lal, Andrei P. Lobanov, Sergio Jiménez-Monferrer, December 2008.

## 5.8 Impact of Science Requirements on Siting

### *5.8.1 Access to the Southern Sky*

The Southern Sky has special significance for astronomers because the centre of our galaxy passes overhead and while it is still visible from sites in the northern hemisphere it would be near the horizon so image quality would be degraded. The two nearest galaxies, the Large and Small Magellanic Clouds are only visible from the southern hemisphere and this provides an exceptional opportunity for a more sensitive radio telescope to detect objects in other galaxies that were previously only visible in our galaxy. At long radio wavelengths there is an additional instrumental problem in the northern hemisphere caused by the two strongest sources in the sky, Cygnus A and Cassiopeia A which are both so strong that they will be seen through the far sidelobes of the telescope degrading the dynamic range. The largest optical telescopes which are often needed to complement SKA observations are also located in the southern hemisphere. For these reasons the strong advantage of a site in southern hemisphere has always been accepted.

### *5.8.2 Radio Frequency Interference (RFI)*

The need to avoid RFI[77] may be the highest impact scientific requirement for the SKA site selection. Beyond our solar system the universe can only be explored by analysing the radiation we receive from distant stars and galaxies. These signals which may have travelled across the universe are incredibly weak. For example, the signal from the brightest natural radio source in the sky is more than 1000 times fainter than the signal from a radio navigation satellite and the faintest signals detectable with the SKA can be a hundred million times fainter than signals from typical Low Earth Orbit (LEO) satellites! The expansion of the universe causes a Doppler shift of the frequency of signals such as the 21 cm hydrogen line at great distances. This requires changes in observing frequency and means that the narrow bands allocated by the International Telecommunications Union (ITU) for radio astronomy are completely inadequate.

As outlined by the spectrum management task force[78] the SKA can deal with RFI by the combination of:

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[77] The radio spectrum is shared by many different interest groups, including both passive (receive) and active (transmit) use of the bandwidth allocated to them. The allocations are agreed at meetings of the International Telecommunications Union (ITU). Radio Frequency Interference (RFI) occurs when signals emitted by an active user result in a loss of information by another user.

[78] hba.skao.int/SKAMEM-73. *Spectrum Protection Criteria for the Square Kilometre Array,* SKA Task Force on Regulatory Issues, November 2005.

1. seeking a remote location with low population density;
2. establishing protection and coordination of radio quiet zones around the SKA (RQZ) and,
3. building RFI mitigation technology into the SKA system.

The need to build the observatory in remote low-RFI locations has had a huge impact on site selection[79] and on the additional operating costs incurred at such remote locations. This will be discussed in detail in Chaps. 7 and 8. The need to establish a Radio Quiet Zone (RQZ) at the selected sites is discussed in Sect. 6.2.2.11.

A further option is to develop RFI mitigation technology and for this there is great potential for advances including adaptive nulling techniques.[80] This will also be discussed in more detail in Sect. 6.2.2.11.

The problem of RFI in radio astronomy was considered of such global importance that in January 1997 the Organization for Economic Co-operation and Development (OECD) Mega-Science forum established a working group on radio astronomy, to report on the impact of radio frequency interference on radio astronomy. As already discussed in Chap. 3, Sect. 3.2.5.2 the OECD working group's report was prepared specifically for use by science policy makers.[81] The report noted that: "The Universe beyond our Solar System can only be studied using "remote sensing" techniques, whereby electromagnetic signals emitted by distant objects, such as stars and galaxies, are captured by telescopes and subsequently analysed. Astronomical signals from even the closest stars and galaxies are very faint by the time they reach the Earth, overwhelmingly so in comparison with any man-made signal. Since the signals received at their telescopes are the only source of information for astronomers, terrestrial contamination of these signals is a very serious concern." The OECD working group made several endorsements and recommendations to minimise the impact of RFI on future radio astronomy facilities.

### *5.8.3 Ionospheric Conditions*

The Ionosphere causes frequency-dependent phase distortions of the incoming cosmic radiation and this can be a large effect at the low frequencies envisaged for the Epoch of Reionisation observations. If these phase gradients are linear across the array, they can be easily corrected using calibrators within the field of view, but at higher resolution (large baseline lengths) the region of the ionosphere seen by the array will vary across the field of view and the required corrections become position

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[79] hba.skao.int/SKAMEM-37. *RFI Measurement Protocol for Candidate SKA Sites*, R. Ambrosini, R. Beresford, A.-J. Boonstra, S. Ellingson, K. Tapping, 23 May 2003.

[80] hba.skao.int/SKAMEM-34. *Spatial Nulling for Attenuation of Interfering Signals,* A. R. Thompson, July 2003.

[81] OECD MEGASCIENCE FORUM, Final Report of the working group on radio astronomy, November 1998.

dependant and very much more difficult.[82] In even more extreme situations when the phase changes are sufficiently large that the waves interfere before reaching the telescope the resulting amplitude modulation cannot be corrected. This is known as ionospheric scintillation and is strongest near the geomagnetic equator of the Earth. One region known as the "southern equatorial anomaly" is known to cause particularly severe ionospheric scintillation. Avoiding the worst ionospheric effects has serious consequences for site selection as is discussed in Sect. 7.3.8.1.

### *5.8.4 Tropospheric Requirements*

It is well-known that ground-based astronomical observations are affected by the wavefront distortion caused by a turbulent troposphere.[83] Such distortion translates into a deformation of the observed source structure and higher sidelobe imperfections in the image. In most cases the effects of the troposphere can be calibrated using antenna-based self calibration algorithms,[84] which are relatively simple and computationally inexpensive at radio wavelengths. An ad hoc troposphere advisory group was established and their report[85] concluded that while tropospheric phase stability was an issue, especially at the higher frequencies; this will be mitigated by the power of the SKA to self-calibrate and the sensitivity of the telescope, and its large number of elements will make self-calibration effective even at 22 GHz. Furthermore, a spot measurement, or even an average over a year, is not a reliable long-term predictor of total water vapour content so detailed local studies will have limited value for site selection.

### *5.8.5 Geographic Requirements for the Antenna Configuration*

The different science cases make very different demands on the array configuration which involve a trade-off between brightness sensitivity (HI and EoR detections, and transient surveys) and angular resolution (most continuum observations). Centrally condensed configurations optimise brightness sensitivity for HI and EoR surveys and minimise the number of coherent beams needed for transient searches. However,

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[82] The region over which the correction can be made is called the isoplanatic patch.

[83] hba.skao.int/SKAMEM-112. *On the SKA Sensitivity and Astrometric Precision under a Turbulent Atmosphere*, I. Marti-Vidal, J. C. Guirado, S. Jiménez-Monferrer, J. M. Marcaide, May 2009.

[84] Also known as adaptive optics.

[85] hba.skao.int/SKAHB-129. Report by the ISSC Working Group on tropospheric site testing, Burke, B. F., Ekers, R. D., Kellermann, K. I., and Hall, P. J., Minutes of the 12th ISSC Meeting, July 2004.

high angular resolution observations which provide finer detail in images of high brightness sources and avoid source confusion require a more uniform distribution of the array spacings out to the maximum baseline. This has resulted in a compromise with a significant fraction of the array centrally concentrated. To satisfy these requirements a central relatively flat area several kilometres in size is required as well as suitable locations for elements which provide a range of baselines up to many thousands of kilometres from the core.

Leith Godfrey, Hayley Bignall and Steven Tingay (Curtin University, Australia) made a detailed analysis of the high angular resolution science case discussed in Sect. 5.6.2[86] and noted that "The science goals and corresponding technical requirements for the high angular resolution component of the SKA are significantly different to those of the SKA core. Consequently, the requirements for remote stations must be considered separately." They went on to define the technical requirements for the remote stations. In order to maintain an angular resolution of 0.1" at all SKA wavelengths, baselines of at least 1000 km are needed. However as discussed in Sect. 5.10.11 the long SKA baselines were not included after descoping in 2014.

## 5.9 Managing the Science Case

### *5.9.1 Science Working Group (SWG), 1994*

As discussed in Chap. 3, Sect. 3.3.1.2, three advisory committees reporting to the ISSC were established by the ISSC at its meeing in Manchester in August 2000. These included a Science Working Group (SWG) , to coordinate the development of the SKA science case. The SWG initially chaired by Russ Taylor (University of Calgary, Canada), held its first meeting in Berkeley, California in July 2001. An initial membership of 24 with representation from all signatories to the MoU was established (see hba.skao.int/SKASUP4-5) with the task of defining the main SKA science drivers and developing a revised set of science requirements.

### *5.9.2 Science Advisory Committee, 2002*

In 2002, the SWG was renamed the Science Advisory Committee (SAC) and a tentative set of sub-groups was formed ahead of a Science workshop in Bologna. At the workshop, the subgroups were charged with identifying Level I (high priority, unique to SKA) and Level II (high priority, complementary to other instruments) science requirements within their area and to determine the technical requirements

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[86] hba.skao.int/SKAMEM-135. *Very High Angular Resolution Science with the SKA, L. Godfrey,* H. Bignall, S. Tingay, May 2011.

such science would place on SKA, compared to the Strawman Technical Specifications[87] (see discussion in Sect. 6.2.1.3). In the two subsequent meetings in Groningen, August 2002, and in Leiden, November 2003, the SAC carried out a complete revision of the science case and this formed the input for the (Carilli & Rawlings, 2004) book "*Science with the SKA*" (see Sect. 5.5.13).

The autumn of 2004 saw the formation of a new SKA Science Working Group (SWG) reverting to its original name but now reporting to the newly appointed International SKA Project (ISPO) Director (see Sect. 3.3.1.3). The SWG was now part of the new management structure which also included the Engineering Working Group (EWG) and the Site Evaluation Working Group (SEWG). The remit of the SWG was wide ranging with activities planned for 2005 including the further development of the science case as discussed in the previous section, organising worldwide advocacy for the SKA, and providing information on the trade-offs between the science achievable with the SKA and site and design choice. Following publication of the SKA science book in 2004, the SWG started getting down to the detailed work on the trade-offs. The SWG started adding details and continued the development of the key science requirements 'matrix' introduced in Sect. 5.5.17. This matrix continued to play a key role identifying the trade-offs needed between the scientific desires of the KSPs and the harsh realities of real SKA designs.[88]

| Year | Science Advisory Committee/Science Working Group chairs |
|---|---|
| 2000–2002 | Russ Taylor (University of Calgary) served as the first chair of the newly created SWG |
| 2002–2004 | Chris Carilli (NRAO) appointed as SWG (renamed ISAC for this period) chair |
| 2004–2006 | Steve Rawlings (Oxford University) appointed SWG chair |
| 2006–2008 | Bryan Gaensler (University of Sydney) appointed chair with Joseph Lazio as vice-chair |
| 2008–2011 | Joseph Lazio (NASA Jet Propulsion Laboratory) appointed SKA Project Scientist and SWG Chair |

### 5.9.3 Managing the Compliance Matrix

Carilli[89] chairing the International Science Advisory Committee (ISAC) [90] was aware that the scientific working groups were in the process of refining the compliance Matrix, and he reconnected the engineering and astronomy communities by

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[87] hba.skao.int/SKAMEM-18. *The Square Kilometer Array Preliminary Strawman Design Large N - Small D,* USSKA Consortium, 2002.

[88] hba.skao.int/SKANEWS-8. Steve Rawlings, SKA Newsletter #8, July 2005.

[89] hba.skao.int/SKAMEM-28. *SKA Concept Designs—ISAC Comments,* Chris Carilli, November 2002.

[90] The Science Advisory Committee (SAC) was renamed the International Science Advisory Committee (ISAC) during the period 2002–2004. The ISAC membership can be found in hba.skao.int/SKASUP4-5.

inviting the proposers of the different SKA telescope designs (see Chap. 6) to participate in the process. The ISAC identified four issues that appeared paramount at that time: high and low frequency limits, multi-beaming, response times, configuration, and field of view. Many of these Matrix entries were vigorously debated in the SKA community due to a lack of consistency in grading of the scientific requirements and, in some respects, a lack of understanding of the technology. The Matrix was revisited in the Geraldton SKA meeting in Aug 2003 to address these issues. The changing science priorities were also compromising the Matrix. For example, the elevation of the EoR case and the large volume redshift surveys to high priority made significant changes. A new "Final version of the compliance Matrix"[91] was discussed extensively at the *Transformational Science* meetings in Pune, India in October 2005. The Matrix was used to evaluate the different design concepts and eventually the down select process in late 2005 leading to the Reference Design (see Sect. 3.4.1 and Chap. 6).

As already noted in Chap. 1, Rawlings[92] commented on the importance of the interaction between science and engineering which was required in the development of the Matrix. These interactions between scientists and engineers were a critical element for the development of the SKA. This had always been part of the radio astronomy culture which was born from the engineering innovations of the early pioneers, however, as the SKA project grew maintaining this interaction was increasingly difficult.

### *5.9.4 Key Science Projects (KSPs)*

In May 2003 the ISAC formed a subcommittee to identify a handful of "level 0" science goals, which could be used to attract funding and publicity, focus efforts to ensure that SKA can provides complimentary research to that proposed for other telescopes, and which can be used to optimise the SKA design.[93] Carilli, Chair ISAC, summarised the process of developing the KSPs as follows.[94] "A subcommittee chaired by Bryan Gaensler determined the highest priority science for the SKA. After an extensive review process by the subcommittee and the full ISAC, a final list of five topics was selected. Establishing the key science goals was a difficult process, with significant design (and possibly political) ramifications, and the Gaensler sub-committee carried through the process thoroughly, and most importantly, in a transparent and clearly unbiased manner." The final report[95] includes a

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[91] hba.skao.int/SKAMEM-62. *Final version of the Compliance Matrix,* S. Rawlings, July 2005.

[92] hba.skao.int/SKAMEM-62. *Final version of the Compliance Matrix,* S. Rawlings, July 2005.

[93] hba.skao.int/SKAMEM-35. *The Square Kilometer Array: The Path to Level 0 Science*, Level-0 Subcommittee, August 2003.

[94] hba.skao.int/SKANEWS-6. *ISAC News,* Chris Carilli, SKA Newsletter #6 June 2004.

[95] hba.skao.int/SKAMEM-44. *Recommendations on Key Science Projects*, B. Gaensler for ISAC, November 2003

flow-down of the telescope requirements set by the key science goals. The key projects chosen were:

- Strong field tests of gravity using pulsars
- Probing the dark ages (cosmic reionisation and the first luminous objects)
- The origin and evolution of cosmic magnetism
- The cradle of life (terrestrial planet formation and astrobiology)
- The evolution of galaxies and large-scale structure

A Position Paper[96] was prepared as input to the June 2005 Heathrow meeting of the funding agencies (Sect. 3.4.1) in which the concept of Key Science Projects was further emphasised, This paper set out a small subset of prioritised science requirements that could be used for engineering design and to provide the funding agencies and the wider community with a brief statement of key science goals. As discussed in Chap. 4, Sect. 4.3.2, one of the primary roles for the funding agencies was to monitor progress in the international SKA project and balance that against their own national efforts and funding opportunities. To do this the funding agencies needed a simple focused set of science goals. This discussion was strongly influenced by the US decadal review (McKee & Taylor, 2001) and the US National Research Council's big questions in physics (US National Research Council, 2003). For the first time these discussions now included concepts like: ensure that level-0 projects align with the broad themes and priority areas laid out by various funding agencies.

### 5.9.5 The Science Case for a 10% SKA: 2006

The need to develop the cases for a 10% SKA was recognised in late 2005 see Chap. 4, Sect. 4.4.1. It would need to be compelling in its own right but must also act as a strong argument for building the full SKA. In 2006 the SWG developed a science case for a SKA Phase I, with 10% of the full SKA collecting area and maximum baselines of approximately 50 km, but keeping the other specifications as laid out in the Reference Design. The SWG converged on three key topics for the SKA Phase I:

- First Light: The Epoch of Reionisation
- Building Galaxies: Hydrogen and Magnetism`
- Pulsars and the Transient Sky

These represented a sampling of the five KSPs for the full SKA, but also include some discovery science for which the SKA Phase I could carve out its own exciting niche. The SWG also identified other secondary experiments for the SKA Phase I,

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[96] hba.skao.int/SKAHB-35. Position paper on the SKA, ISSC, submitted to the Funding Agencies May 2005, Supporting Paper for the ISSC Teleconference, June 2005.

including weak lensing, the inter-cluster medium, spacecraft tracking, X-ray binaries, the cosmic web and interstellar scintillation.

SKA Phase 1 was to demonstrate many of the scientific and technical underpinnings for the mid- and low frequency SKA that would enable "killer science" with the full SKA. Several aspects of the SKA Phase 1 science case that had previously been developed by the SWG (circa March 2007) had been overtaken by both scientific and technical developments. Headline science themes for SKA Phase 1 were defined as neutral hydrogen from the epoch of reionisation to the present, testing general relativity theory and detecting gravitational waves using pulsar timing, and discovering transients and other new phenomena.

### *5.9.6 The Magnificent Memo Series*

One of the challenges for SKA design and planning was to make the appropriate trade-offs between scientific requirements and engineering reality. The ISSC posed eight questions related to the impact of these trade-offs on the five KSPs and presented these questions at the Pune *Transformational Science* meeting in October 2005. The answers to these questions were the "Magnificent Memos Series" which were incorporated into SKA Memo 82 submitted by Bryan Gaensler, SKA Project Scientist, and Joseph Lazio, Deputy Project Scientist, on behalf of the SWG.[97] The questions addressed were:

- What key science can be delivered by SKA Phase 1 (10% collecting area)?
- What is the science case for multiple independently steerable fields of view?
- What is the impact of limiting the field of view at high angular resolution?
- What is the case for high angular resolution below a few GHz?
- What is the case for frequencies between 200 and 500 MHz?
- What is the case for high filling factor at high frequency?
- What are the options for transient detection?
- What is the impact on key science of having just a high- or just a low-frequency array?

The first and last question were deferred for separate discussions (see Sects. 5.9.5 and 5.9.9). The Magnificent Memos identified the specific science that would be affected in each case and identified many caveats, some of which were followed up in subsequent memos. This document certainly clarified the relationship between the science and the telescope design and was the basis for more realistic discussions, but it did not attempt to make any specific design recommendation, an issue that was taken up by the "Tiger Team" discussed in the next section.

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[97] hba.skao.int/SKAMEM-82. *The "Magnificent Memo" Series: Trade-offs between Science and Engineering for the Square Kilometre Array*, B. Gaensler and J. Lazio, August 2006.

### 5.9.7 Preliminary Specifications for the Square Kilometre Array

A Tiger Team was established by the ISSC to revise the SKA specifications and propose a realisable baseline implementation.[98] This included the identification of cost-driving specifications and the use of cost-performance estimation tools[99,100] to guide a detailed trade-off analysis as discussed in detail in Sects. 6.2.2.7 and 6.4.6.

### 5.9.8 The SKA Design Reference Mission (DRM): 2009

In January 2008 the SKA Specifications Review Committee[101] (see Sect. 6.2.1.4) recommended that the Project Scientist and the SWG develop a Reference Science Mission. The term "Reference Science Mission" was chosen to align the SKA with other major projects (PanSTARRs, LSST,[102] James Webb Space Telescope, etc.), which typically have "Design Reference Missions. " The SKA Reference Science Mission was intended to lay out clearly the observational science requirements needed to achieve the SKA Science Case. The components of the science case included in the Reference Science Mission have been discussed in Sect. 5.5.18. In July 2009 the Reference Science Mission was renamed the Design Reference Mission (DRM). In 2010 the DRM underwent a technical review by the SPDO domain specialists. It was now expected to become a "living document", responding both to scientific and technical developments. It became one of the key documents provided during the System Concept Design Review (CoDR) and together the SKA Science Case and DRM provided the overarching set of scientific requirements that the telescope was required to meet.

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[98] hba.skao.int/SKAMEM-100. *Preliminary Specifications for the Square Kilometre Array.* R. T. Schilizzi et al., December 2007.

[99] hba.skao.int/SKAMEM-92. *SKAcost: a Tool for SKA Cost and Performance Estimation,* A. P. Chippendale, T. M. Colgate and J. D. O'Sullivan, June 2007.

[100] hba.skao.int/SKAMEM-93. *SKADS Benchmark Scenario Design and Costing,* Paul Alexander et al., June 2007.

[101] hba.skao.int/SKAHB-245. *Report of the SKA Specifications Review Committee,* Booth, R., et al., report commissioned by the ISSC, 2008-01-30.

[102] LSST is now called the Vera Rubin Observatory.

### *5.9.9 The Science Implications of an SKA "Win-Win" Siting Scenario: 2009*

In October 2009 the SWG was asked by the SSEC to consider the science implications of a so-called "win-win" scenario in which SKA infrastructure is located on both candidate sites (Australia and South Africa). The SWG found that there would be little scientific advantage to a "win-win" scenario.[103] They considered three specific cases:

- A frequency split with the full SKA-mid on one site and the full SKA-lo on the other site.[104] The most relevant factor would be the radio frequency interference (RFI) situation and there would be little other scientific advantage to a frequency split. Some disadvantages that were noted related to the reduced capability for calibration of the ionosphere above SKA-lo and the need for transient observations at multiple frequencies at or near the same time.
- A separate large remote SKA-mid station constructed of dishes. The separation between the two candidate sites produced a significant gap in spatial frequencies (*u*-*v* plane). If the array was divided equally between the two sites, the u-v plane coverage would be unacceptable, so the SWG only considered a smaller remote station with 10% of the total collecting area. This would still be of limited utility, except for astrometric programs.
- A separate large remote SKA-mid station constructed of dense aperture arrays. Many of the same considerations applied as for a large remote SKA-mid station constructed of dishes.

### *5.9.10 SSEC Forms an Internal SKA Phase 1 Definition Sub-Committee: 2010*

The report from an external panel carrying out the System CoDR in February 2010 (see Chap. 4, Sect. 4.4.2) included criticism that the science case was too broad. Following this report the SSEC formed an internal subcommittee with a mandate to produce an SKA Phase 1 (SKA1) Concept Design with high-level targeted science goals. The subcommittee was chaired by Mike Garrett[105] (ASTRON, Netherlands) and quickly came up with the following short list of key scientific drivers:

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[103] hba.skao.int/SKAHB-131. *The Science Implications of an SKA "Win-Win" Siting*, Science Working Group, October 2009.

[104] Chapter 8 summarises the site decision discussions which led to the decision to adopt this frequency split in a dual site option.

[105] hba.skao.int/SKAMEM-125. *A Concept Design for SKA Phase 1*, M. Garrett et al., August 2010.

- History of neutral hydrogen: Epoch of Re-ionisation (EoR) to the current epoch;
- Pulsars for Gravity (General Relativity and the detection of gravitational waves), and
- Transient Universe (new phenomena).

### *5.9.11 Transition to the Pre-Construction Phase: 2011*

When the Founding Board was established in April 2011 (see Sect. 4.6) it moved to complete the Joint Implementation Plan which included the plan for the pre-construction phase of the SKA. The scope of the associated Business Plan, discussed in Chap. 4, Sect. 4.7.3, included building relationships with relevant national and international astronomy organisations to leverage skills and ensure SKA Phase 1 science and opportunities were fully integrated into a global astronomy perspective. From this time, the SKA management team had a relatively light involvement in the Science case as the SKA moved into the pre-construction phase and then finally the construction phase. The SAC and its sub-committees continue to exist and to monitor changes in science opportunities and keep the astronomy community informed of progress. However as with any large-scale project it becomes increasingly difficult to respond to any changes in science requirements during the final planning and nearly impossible once the construction phase has begun.

## 5.10 Evolution of the Science Case and Comparison with the Current Vision

We can compare the evolving science case with the science case at the start of construction in June 2021. This is based on an old SKA web page from 2021 see (Box 5.6).

**Box 5.6 Science Case 2021 (Taken from a 2021 SKA www Page)**

- Galaxy evolution, cosmology, and dark energy
  - How do galaxies evolve
  - What is dark energy
- Challenging Einstein
  - Strong-field tests of gravity using pulsars and black holes
  - Gravitational wave detection by pulsar timing
- Understanding cosmic magnetism

(continued)

**Box 5.6** (continued)

  - Polarised synchrotron emission
  - Rotation measure

- Probing the Cosmic Dawn
  - Epoch of reionisation (EoR)
  - quasars
- The cradle of life—searching for life and planets
  - Technosignatures
  - Amino acids
  - Thermal emission from dust
- Continuum surveys
- Radio transients
  - Gamma Ray Bursts
  - Supernovae
- Solar & Heliospheric Physics
  - Solar flares
  - Coronal mass ejections (space weather)

The list has also now been expanded due to the transition from a project seeking funding, which requires a focussed science case, to a construction project at which point all possible science options may need to be considered. Many of these science drivers have been present for three decades as illustrated in Fig. 5.4 and although the science case has involved similar topics over the last 30 years, there have been big changes in detail. Detecting hydrogen at high redshift has not changed from the beginning of the SKA concept, but the way the hydrogen line observations are used has changed a lot. The earlier ideas of simply looking for clouds of collapsing gas was replaced in 2003 by a new concept to look for the change in the state of the HI (EoR) as the first stars form and this has all been named the more generic "Cosmic Dawn". The use of the HI to trace large scale structure (e.g. BAO) emerged in 2004 and strengthens the case for survey science but since this was also part of the science case for other proposed new instruments, it is no longer emphasised as unique SKA science. Some areas that were given lower priority in the funding stage now re-emerge. These include the HI and continuum surveys and the solar observations.

As new discoveries are made at radio or other wavelengths new sciences opportunities have opened up and the emphasis has changed. Examples are: gravitational wave detection, exoplanets, and new classes of transient radio sources. The SKA precursors and SKA pathfinders are also influencing the science case as they make new discoveries (see Sect. 5.11.1).

Following the Bologna meeting of the SAC in January 2002 (Sect. 5.5.11), Chris Carilli recognised the need for changing emphasis and added the following general note[106] "*The current document (2002) presents the SKA capabilities, and then shows all the gee-whiz stuff that can be done. In order to better impress the general astronomical community, we should start by considering the important questions facing astrophysics today, and then show how the SKA will help to solve these questions.*" This change in the perceived requirements for the science case had a profound impact on the development of the science case from this time onwards, with much greater emphasis on what were considered to be the most important questions. We pick up on this issue again in Chap. 11.

We now depart from our chronological discussion and look at the way the different science cases listed in Fig. 5.4 have changed over this thirty year period of time.

### 5.10.1 HI at High Redshift: Evolution of Structure, Cosmology, and Dark Energy

The sensitivity needed to detect HI at high redshift was the initial driver for the SKA concept. It was also emphasised that while telescopes working at other wavelengths can detect the galaxies made of stars at high redshift, only HI observations can detect the gas from which they form. Existing all-sky neutral hydrogen line surveys only have sufficient sensitivity to reach a redshift of about z = 0.04, so estimates of the distribution of gas at higher redshift are entirely dependent on models. If the SKA could detect a large number of HI galaxies out to a redshift of z = 1.5, these models of the evolution of the universe could be tested and various cosmological tests were considered. Measurement of the HI mass function at high redshift could be used to determine the evolution of dark matter in the Universe. Such a survey could also measure the "wiggles in the power spectrum" now known as the "Baryon Acoustic Oscillations" (BAO) and this could constrain the properties of dark energy. These exciting possibilities, which would be realised through Rawlings' dream of a "billion galaxy survey", elevated the high redshift HI survey science case over time so cosmology and dark energy become a key theme in the SKA science case. But it should be remembered that these are very demanding requirements needing the survey speed and sensitivity of the full SKA.

Another approach is to search for HI in absorption against bright background radio sources. For such an absorption survey the sensitivity needed is independent of distance and there are no reasons why there should not be radio galaxies out to redshifts $z > 7$. With a lowest frequency of 130 MHz it would be possible to trace HI

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[106] hba.skao.int/SKAMEM-8. *Summary of the discussion from SKA Science Working Group 4, Galaxy Formation,* Chris Carilli, November 2002.

absorption up to redshift $z = 10$.[107] This is a less demanding experiment and does not require a centrally concentrated array.

### 5.10.2 Epoch of Reionisation (EoR): Probing the Cosmic Dawn

The initial thoughts on the study of the high redshift universe in 1980s and 1990s were focussed on providing enough sensitivity to detect HI emission from galaxies at high redshift. The idea was that before stars formed it might be possible to detect the collapsing gas clouds of neutral hydrogen, the Zel'dovich pancakes, but these would have very low contrast and be difficult to observe. An early VLA detection was never confirmed (see Sect. 5.5.1). Scott and Rees (1990) took a different approach by looking at the evolution of the spin temperature of the neutral hydrogen as the gas collapsed and even conjectured that the proposed GMRT in India might be able to observe hydrogen gas in this phase. A more detailed analysis of the state of the gas as galaxies formed was published by Gnedin and Ostriker (1997). Piero Madau was probably the first to introduce these ideas to the SKA community at the Oort Workshop (1997) and specifically included the possibility of using the spectral signature of the 21 cm line to probe the epoch of reionisation and heating in the early universe as discussed in Sect. 5.5.5. Theoretical studies have continued, e.g. see Pritchard and Loeb (2012) for a detailed theoretical review, and detection of the EoR has become the most important science case for SKA-low.

Very soon after the realisation by the radio astronomer, Peter Shaver (ESO), that the global redshifted spectral signal would be detectable as a sharp step in the radio spectrum at the epoch of reionisation (Shaver et al., 1999), radio astronomers started paying attention to this possibility. However, detecting the relatively strong global EoR signal has remained elusive due to contamination by foreground emission and the extreme spectral line dynamic range requirements, e.g. (Singh et al., 2022). Attention has turned back to the large imaging radio telescopes such as the SKA and its precursors and pathfinders, the Low Frequency Array (LOFAR) and the Murchison Wide-field Array (MWA). The spectral line baseline requirements become easier but only the full SKA (SKA Phase 2) will have enough sensitivity to search for the much weaker spatial structures in the EoR signal using direct imaging. However, a statistical detection of the angular and frequency power spectrum is possible with the lower sensitivity precursors. The requirements on the spectral dynamic range now sets the most stringent specifications on the SKA-low spectral bandpass and chasing the changing frequency requirements[108] has added design complexity

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[107] hba.skao.int/SKAMEM-141. *Is There an Optimum Frequency Range for SKA1-lo?* M. Huynh, August 2012.

[108] hba.skao.int/SKAMEM-141. *Is There an Optimum Frequency Range for SKA1-lo?* M. Huynh, August 2012.

(see Sect. 6.5.3). While the need for extremely accurate spectral baselines was noted, there was no corresponding instrumental analysis on how to achieve this with an array.

The SKA precursor and pathfinder telescopes around the world are making rapid progress in laying the scientific and technical foundations for EoR observations with the SKA. Ongoing efforts include the Low Frequency Array (LOFAR) in the Netherlands, the Murchison Wide-field Array (MWA) in Western Australia, and the Precision Array to Probe the Epoch of Reionisation (PAPER) which has now become HERA, the Hydrogen Epoch of Reionisation Array now being built on the SKA site in the Karoo in South Africa. The technical difficulties encountered when making these observations had been hugely underestimated and obtaining a better understanding of how to build a telescope which can achieve the required dynamic range will be essential. We will follow up on the important role being played by the SKA precursors and pathfinders in Chap. 11.

### *5.10.3 Gravity: Challenging Einstein*

Aspects of this key theme have been consistently included in the science case from the beginning. Radio observations of pulsars provide unique opportunities to study the properties of neutron stars, they can also provide exquisite tests for gravitational theories and pulsar timing networks are being used to detect gravitational radiation (see Sect. 5.5.13.2).

The tests of Einstein's General Theory of Relativity can be extended to the very extreme environments where gravity is exceptionally strong, such as around supermassive black holes, and these rare systems are expected to be found with the increased sensitivity and survey speed of the SKA.

In the physics community the development of instruments to make a direct detection of gravitational waves had been ongoing since the 1960s and, in 1982, the Hulse and Taylor Nobel prize winning discovery of a pulsar in a binary system indirectly confirmed the reality of the gravitational wave predictions. This reinforced the link between the precision pulsar timing community and gravitational wave detection community. In 2015, the LIGO consortium made a direct detection of gravitational waves produced by in-spiralling black-holes (Abbott et al., 2016).[109] This was the beginning of a new era of observational gravitational wave astronomy.

Indirect detection of gravitational waves is also possible using a network of pulsars to detect changes in the arrival time on earth of the signals emitted by millisecond pulsars. These times are modified by the effect of gravitational waves as they pass the earth and the pulsars. These pulsar timing observations are sensitive to much longer wavelength gravitational waves than LIGO and would be sensitive to a stochastic gravitational wave background that could be produced during the brief inflationary period following the Big Bang. Current pulsar observations are

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[109] Nobel prize in physics, 2017. https://www.nobelprize.org/prizes/physics/2017/

tantalisingly close to detecting such a background so the advances which will be provided by the SKA are keenly anticipated.

The pulsar timing requirements on the SKA are twofold. They include first finding suitable pulsars with the very stable periods needed for precision timing observations and this requires a pulsar search capability over a large field of view. Then the precision timing observations require high sensitivity when pointing at the known pulsar. These two steps require quite different specifications[110] and these more complex and demanding requirements have been continually refined over time.

### *5.10.4 Cosmic Magnetism*

Since the mid-1990s, cosmic magnetism has been included as one aspect of many different science cases and, from 2000, the study of magnetism was recognised as a unique radio astronomy niche for the SKA. The general topic of magnetism was identified as a KSP in 2006 and it was noted that many unanswered questions in cosmology and in fundamental astrophysics are closely tied to the questions of the origin and evolution of magnetic fields. This move was enthusiastically promoted by Bryan Gaensler who was chair of the SWG from 2006 to 2008. It is certainly the case that the role of magnetism in the evolution of the universe had been largely ignored by astronomers in the past. This is partly because it is quite hard to measure magnetic field properties and partly because when magnetic fields are included, the physics becomes much more complicated and fewer astrophysicists have the expertise needed to include magnetic fields in their models.

### *5.10.5 Stars*

Observing radio emission from stars has been raised throughout the life of the project but has not been a consistent part of the SKA science case and has never been raised to the level of a key science project. It has always been clear that the SKA would enable new advances in the sensitivity-limited field of stellar radio astronomy as discussed in Taylor and Braun (1999). The LOFAR detections of a new population of stars with non-thermal emission (Callingham et al., 2021) has now strengthened this case. It is also possible that exoplanets may trigger radio emission processes in the parent star, perhaps heralding the dawn of a new era in exoplanet research.

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[110] hba.skao.int/SKAMEM-105. *Pulsar searches and timing with the SKA,* R. Smits et al., November 2008.

### 5.10.6 *Transient Universe: The Bursting Sky*

Pulsars are a great example of rapid variability of radio sources beyond the solar system, and observing pulsars has always been an important part of the SKA science case. It is an excellent example of a niche area for radio astronomy. The sheer number of pulsars that could be discovered, in combination with the exceptional timing precision made possible with the SKA sensitivity would clearly have a revolutionary impact as discussed in Sect. 5.5.13.2.

The idea of a broader search for transient events started in 2003 with a chapter by Cordes et al. (2004) considering the science case for observations of the dynamic radio sky. They made a prescient suggestion that SKA might find a new class of extragalactic transients which could be used to probe the intergalactic medium, as had been suggested by Ginzburg (1973). Cordes et al. (2004) also correctly recognised the need for different survey speed metrics for different classes of transients and drew attention to the difference between the survey speed metric for transients and for persistent sources. This research area jumped into prominence following the discovery of a new class of radio-transient, the Fast Radio Bursts (FRB), by Lorimer et al. (2007) and finally confirmed by Thornton et al. (2013).[111] Much of the current research on FRBs is being done by the SKA precursors: ASKAP, and MeerKAT, and also the Chinese Five-hundred metre Aperture Spherical radio Telescope FAST. The field is now dominated by the results from the Canadian Hydrogen Intensity Mapping Experiment (CHIME) which was built using a cylindrical reflector proposal developed as one of the SKA design options (see Chap. 6). In future the Deep Synoptic Array (DSA-110), and eventually DSA-2000 being developed at Caltech[112] will be optimum transient search and localisation instruments based on the large N—small D concept promoted throughout the SKA project development. By focussing on a specialised continuum transient survey mode in the 0.7–2.0 GHz frequency range, these instruments will be relatively inexpensive compared to the far more flexible SKA observatory.

### 5.10.7 *Solar and Heliospheric Physics*

Solar radio astronomy is a broad field of research all around the world. Radio observations of solar activity are being monitored with relatively modest scale solar radio observatories so the case for using the SKA is restricted to specialised areas. Imaging the complex and variable spatial and frequency structure of solar radio flares can take advantage of the large number of elements in the SKA which provide excellent instantaneous imaging capability over a wide range of frequencies.

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[111] Bailes, Lorimer & McLaughlin were awarded the 2023 Shaw prize for the discovery of fast radio bursts.

[112] https://www.deepsynoptic.org/overview

The practical value of observations of coronal mass ejections (space weather) is increasingly acknowledged due to their impacts on earth and on orbiting spacecraft. Observations of Interplanetary Scintillation can take advantage of the wide field of view at the lower frequencies to map the structure and motion of the coronal mass ejections against a dense background of scintillating radio sources (Morgan et al., 2003).

### 5.10.8 Cradle of Life: Technosignatures, and SETI

One of the first concepts for a cm wavelength radio telescope with more than 1 km$^2$ collecting area was the 1971 project Cyclops "A Design Study of a System for Detecting Extraterrestrial Intelligent Life" (Oliver & Billingham, 1972) and see Chap. 2. In September 1994 Bobbie Vaile (University of Western Sydney) presented the idea of the SKA aperture tile array to Barney Oliver and Frank Drake at the SETI institute in California. This was probably the trigger for Ekers to be invited to give the Pesek Lecture in October 1995 (see Sect. 5.5.4) on the potential of a "one square kilometre array" for SETI. The *cradle of life* has always been included in some form in the SKA science case, but sometimes with more emphasis on detecting planetary systems, rather than technosignatures, which requires the evolution of intelligence and technology as well as having a habitable environment. Jill Tarter[113] (SETI Institute) proposed that the search for extra-terrestrial intelligence (SETI) be renamed "the search for technosignatures" to broaden the approach and to remove the "not a science" stigma sometimes associated with SETI.

### 5.10.9 Exploration of the Unknown

Back in 1961 when Jan Oort (Leiden Observatory, Netherlands) was making a presentation to the OECD about a proposal for a future large radio telescope (the Benelux Cross which later became the Westerbork Synthesis Radio Telescope) he made the following remark which remains just as applicable today[114]: "*It is an unrewarding task to outline programmes for an instrument that does not yet exist, especially if the exact design and wavelength have not been definitely fixed. It is unrewarding in several respects. In the first place, those who will work with the instrument should themselves think out their programmes, at least to a considerable extent. In the second place, as has been so regularly the case in research with new types of instruments and new methods, it may well be that the instrument will lead into new, at present unpredictable, types of research; and these might become the*

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[113] https://www.space.com/39474-search-for-extraterrestrial-intelligence-needs-new-name.html

[114] From "*Oort's Dream (1961)*" in Raimond and Genee (1996).

*most important. But, in order to discuss and fix the requirements for so expensive an instrument as we are about to construct, some consideration of astronomical aims is unavoidable. As an introduction to the discussions of the instrumental design I shall therefore briefly consider some of the major programmes that would be envisaged.*"

In March 2002 the International Science Advisory Committee (ISAC) radio transients working group[115] made explicit comments on the need to explore the unknown transient population. They emphasised that science predictions are based on the known populations of transient sources. The greatest return from such a survey will (should!) be the detection of currently unknown populations of sources. As discussed in Sect. 5.10.6 one such new and unexpected population, the Fast Radio Bursts, has now been found.

In their book on discoveries in radio astronomy (Kellermann & Bouton, 2023) emphasise that astronomy is an observational science. Astronomers cannot do experiments; they can only observe. Kellermann & Bouton explore the circumstances leading to the plethora of previously unknown phenomena discovered since the beginning of radio astronomy in 1933. One extraordinary consequence, strongly emphasised throughout their book, is that the scientific discoveries for which facilities become famous are rarely those they were built for. Given the nature of many of the discoveries in radio astronomy, this outcome is not unexpected. But what is surprising is that this obvious fact has had so little influence on the discussions of future facilities and concepts like "exploring the unknown" get little emphasis, and in some cases have been actively discouraged (e.g. the US Astronomy and Astrophysics Decadal Survey—ASTRO2010, see Sect. 4.5.3.4). In Fig. 5.4 it can be seen that the science case for the exploration of the unknown has been present over the history of the SKA, but emphasis has been sporadic.

### 5.10.10 Impact of New Discoveries on the Science Case

Looking back over the detailed science case summaries, the influence, sometimes fleeting, of the more recent discoveries is evident. Examples already discussed include:

The optical discovery of exoplanets orbiting normal stars (Mayor & Queloz, 1995) which gave credibility to the pulsar timing searches for exoplanets orbiting neutron stars discussed in Sect. 5.5.3. The indirect detection of gravitational waves based on the timing of a binary pulsar triggered the development of pulsar timing searches for primordial gravitational waves. When Fast Radio Bursts (FRBs) were discovered in 2007 by Lorimer et al. (2007), this greatly increased the importance of the transient discovery space and since these sources were extragalactic, they added cosmological significance to transient radio astronomy science.

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[115] hba.skao.int/SKAMEM-6. *Radio Transients, Stellar End Products, and SETI,* J. Lazio, March 2002.

The summary of all the major discoveries in radio astronomy (Kellermann & Bouton, 2023) not only expands on the more recent discoveries which have affected the SKA science case, but it also provides a perspective on how the discoveries have been made.

### 5.10.11 Science Cases Which Have Disappeared or are no Longer Emphasised

The VLBI science enabled by long SKA baselines, as summarised in Sect. 5.6.2 was no longer feasible with the relatively short baselines in the 2014 descoped SKA Phase 1 (SKA1), although some less sensitive VLBI capability with limited baseline coverage remains possible by using the SKA core in combination with existing radio telescopes.

The emphasis on stars and planetary science slowly declined, possibly because of changing scientific interests of the astronomers writing the science case.

In the past there were many discussions about using the SKA as a receiver for planetary radar and for spacecraft communication, and these options were seriously considered by NASA. With radar, the return signals decrease with the fourth power of the distance, so even an SKA cannot make a big impact on the maximum distance that can be probed. For deep space communications a detailed analysis by Fridman, Gurvits & Pogrebenko[116] indicated a significant potential of the SKA as a “Direct to Earth” deep space communication facility.

However, NASA planned to go to higher frequencies moving outside the range considered for SKA-low and SKA-mid[117] and was more interested in pursuing the future of optical communications. The NASA funding structure also changed so when the cost of the deep space communications was charged to the missions, the scope for expensive deep space communications developments was limited. These projects are no longer included in the SKA science case.

Some science topics are still included in the SKA design but never get promoted, for example radio emission from Ultra High Energy (UHE) cosmic ray showers, perhaps because the community of astronomers affected is relatively small and because the advocates for this research are mostly outside the astronomy community.

Over the 30-year lifetime of the SKA project, other telescopes have been built so some of the original SKA science projects had already been done.

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[116] hba.skao.int/SKAMEM-104. *The SKA as a “Direct-to-Earth” Facility for Deep Space Communications,* P. A. Fridman, L. I. Gurvits, S. V. Pogrebenko, September 2008.

[117] hba.skao.int/SKAMEM-13. *Spacecraft Tracking,* D. Jones, January 2002.

## 5.11 Impact of the SKA Project on the Science

It is interesting to realise that while the science case was developed to motivate and develop the design specifications for an SKA telescope, the SKA project has itself had significant impact on the science case. In this section we discuss some of the ways in which this has happened.

### *5.11.1 Role of the Precursors and Pathfinders*

As discussed in Chap. 4, Sect. 4.3.3, by 2006 the SKA pathfinders had made their way onto national roadmaps (LOFAR in the Netherlands, and MeerKAT in South Africa) or were funded to do so (ASKAP in Australia). Originally, these three instruments were designated "pathfinders", but after a surge of interest in 2008 in the designation from many existing telescopes, the small number located on the two candidate SKA sites were called "precursors" to distinguish them from the others.[118] These facilities were initially conceived as technology demonstrators, but there were national drivers to make these significant observatories that could do useful astronomy using state-of-art technology. In 2011 John Womersley (STFC, UK) noted[119] "*The phased nature of the project also needs to be emphasised—science from pathfinders/precursors leads to science from phase I which leads to the full array in due course*."

In retrospect these SKA precursors and pathfinders greatly invigorated the radio astronomy research environment worldwide and they have made important new observations and a number of significant discoveries, some of which are illustrated in the following section. Here are some examples of the discovery of previously unknown phenomena made with the SKA precursors and the pathfinders, which already demonstrate the importance of the exploration of the unknown:

- FRBs were discovered with the existing Parkes radio telescope, but the SKA precursors (ASKAP in particular) played a major role in follow-up observations to localise these events. The most prolific FRB radio telescope now is CHIME, a facility based on the parabolic cylinder technology that was evaluated as part of the SKA project (see Sect. 6.4).
- Ionospheric ducts were discovered using the MWA (see Fig. 5.17).
- Our knowledge of the amazing population of Galactic Centre filaments was greatly enhanced following some of the first observations with the MeerKAT SKA precursor (Fig. 5.18).
- LOFAR detections of stars (Callingham et al., 2021)

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[118] SKASUP4-1 *A compilation of the designated SKA Pathfinders*.

[119] hba.skao.int/SKAHB-139. *Update from the Founding Board*, presentation by John Womersley at the International SKA Forum, July 2011.

- Long period radio transients found by MWA and MeerKAT (Hurley-Walker et al., 2023)
- Odd Radio Circles—ORC discovered by ASKAP and MeerKAT. Norris et al. (2021, 2022), see Fig. 5.21.

### 5.11.2 How the SKA Predicted the Discovery of the Fast Radio Bursts (FRBs)

This discovery of the first FRB in 2007 and the use of FRBs to make a census of the baryon content of the universe by Macquart et al. (2020) is an example of how a successful future prediction was made by the International Science Advisory Committee (ISAC) in March 2002. The ISAC report from the radio transients working group[120] (March 2002) noted: "*Based on the known populations of radio transient sources, an unbiased survey of the variable radio sky could reveal populations of radio pulsars in nearby galaxies (via the emission of giant pulses like those of the Crab pulsars), possibly as distant as the Virgo Cluster. A by-product of the detection of such pulsars would be direct detection of the ionized local intergalactic medium. In turn, this would allow study of the bulk of the baryons in the local Universe.*"

### 5.11.3 Impact of the Science Case on the SKA Project

As discussed throughout this chapter there is an underlying tension between the emphasis on a range of key science drivers, and the technology generated opportunities which have historically triggered most of the discoveries in radio astronomy; this is why (Sullivan, 2009, p. 449) classified radio astronomy as a "technoscience". The potential science is what drives the building of the telescope and is used to justify a particular funding investment. The science case is also used to guide the design of the telescope and for the SKA a complex process was set up to explore the design impact of a multitude of science cases. This had the crucial benefit of engaging with a much broader scientific support base. So, while the continuing effort to develop the science cases did not change the basic telescope design in any fundamental way, it was necessary to involve the broader community. This resulted in expanded specifications and made the SKA a general-purpose international observatory rather than just a big new telescope, as we discuss further in Chap. 11.

Different strategies are needed to convince different target communities. The most important role of the science case was to engage with the broader science community and identify niche opportunities. Some aspects of the science case drove

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[120] hba.skao.int/SKAHB-130. Report from the Science Advisory Committee in minutes of the 8th meeting of the ISSC, August 2002.

specifications which were essential for the engineering design and an exciting science case was motivational for both the public and all those involved in the project. Funding agencies want to see a clear process to evaluate scientific excellence and value for money. They also expect appropriate management structures and risk management. Governments consider other benefits for large scale research infrastructures projects which go beyond the science, such as discussed at the strategic workshop "Benefits of Research Infrastructures beyond Science: the example of the Square Kilometre Array (SKA)", organised by the European Cooperation in Science & Technology (COST) and held in Rome in March 2010.[121]

The COST report summary included: "When decisions on large scale research infrastructures are being made, aspects beyond the respective excellent scientific cases need to be considered. These aspects should include topics like the use of sustainable energy sources, the development and building of human capacities, new communication strategies and technologies and, finally, that the project would generate incentives to enhance global and transcultural collaboration in communicating the advancement of knowledge for the benefit of mankind."

## 5.12 Current Science

The authors have selected a small sample of impressive results already achieved by the SKA precursors and pathfinders that were developed as part of the SKA project. These are leading the way and provide a glimpse of the science still to come with the SKA Observatory.

### *5.12.1 The LOFAR Pathfinder and the Radio Galaxy Cygnus A*

Cygnus A observations with LOFAR (McKean et al., 2016) show extended lobe and counter-lobe emission, consistent with previous observations. But LOFAR provides the first direct evidence for a turnover in the spectra of both 'primary' hot spots (see Fig. 5.16). The very rapid turnover in the hotspot spectra cannot be explained by a low-energy cut-off in the electron energy distribution, as has been previously suggested. Thermal (free–free) absorption or synchrotron self-absorption models are able to describe the low-frequency spectral shape of the hotspots; however, the implied model parameters are unlikely, and interpreting the spectra of the hotspots remains enigmatic.

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[121] *hba.skao.int/SKAHB-140*. *Benefits of Research Infrastructure beyond Science: The Example of the Square Kilometre Array (SKA)*, Final Report, COST Workshop, 30–31 March 2010, Rome.

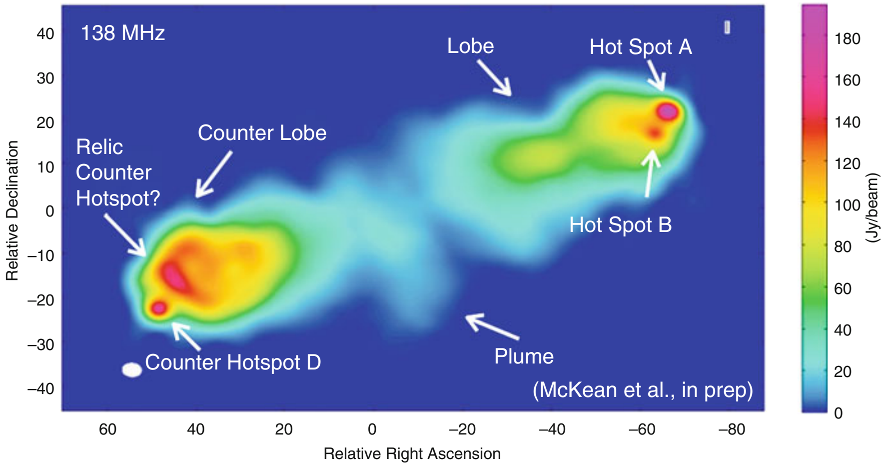

**Fig. 5.16** LOFAR Observation of Cygnus a at 138 MHz. Credit: J. McKean and ASTRON

### *5.12.2 The MWA Precursor and the Discovery of Ionospheric Ducts*

While analysing the ionospheric refraction effects in MWA data, Shyeh Tjing (Cleo) Loi and Tara Murphy (University of Sydney) discovered a very regular pattern of source position offsets which were aligned with the earth's magnetic field lines, see Fig. 5.17. This was the discovery of ionospheric ducts, and the image was used on the February 2016 cover of the Journal of Geophysical Research (Loi et al., 2015).

### *5.12.3 MeerKAT, the South African Precursor Observes the Galactic Centre*

The centre of our galaxy was one of the first images obtained with MeerKAT. The 64 antenna elements in the MeerKAT array provide a level of detail never seen before. This version of the galactic centre image (Fig. 5.18) is generated from MeerKAT observations described in Heywood et al. (2022). The image uses pseudo-colour to indicate the spectral slope of the radio emission. This image reveals nearly a thousand mysterious filaments as well as circular supernova remnants and regions of on-going active star-formation.

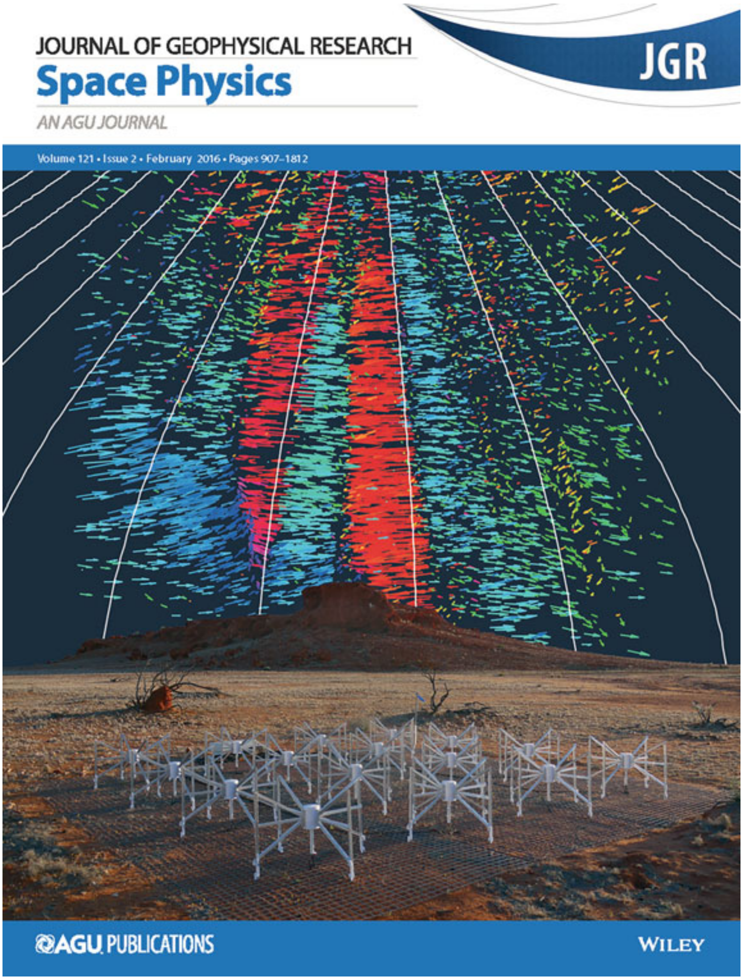

**Fig. 5.17** MWA discovery of ionospheric ducts, February 2016 cover, Journal of Geophysical Research, Space Physics. Credit: Shyeh Tjing Loi and Tara Murphy. Front cover reproduced with permission of John Wiley & Sons

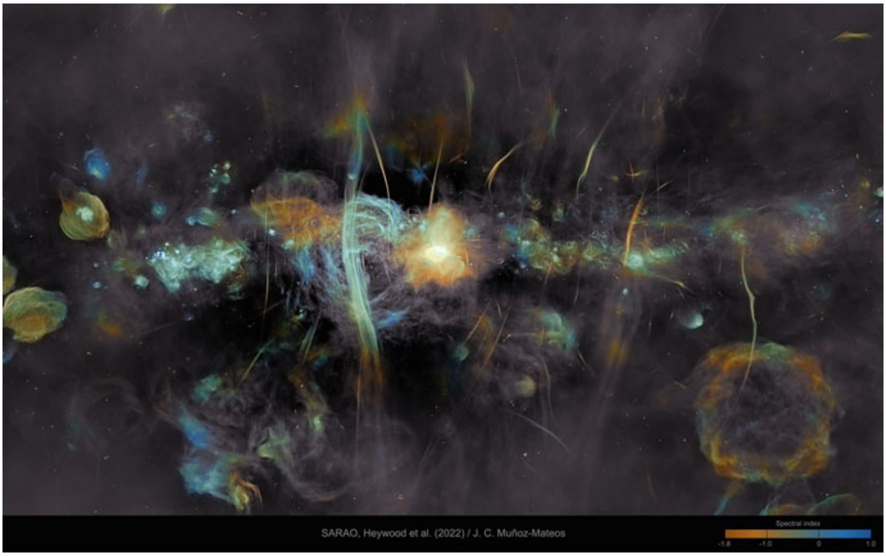

**Fig. 5.18** MeerKAT observation of the Galactic Centre at 1.28 GHz using pseudo-colours to show the large range in radio spectral index. Credit: J.C. Muñoz-Mateos, I. Heywood and SARAO. Copyright: CC-BY-NC-4.0

### *5.12.4 ASKAP, the Australian Precursor Finds a Rare Polar Ring Galaxy*

HI surveys taking advantage of the wide-field-of-view obtained with the ASKAP focal plane array can find rare objects such as the polar ring galaxy NGC4632 shown in Fig. 5.19 (Deg et al., 2023).

### *5.12.5 FAST and Its Pulsar Surveys*

The largest radio telescope in the world is now the Five-hundred-metre Aperture Spherical Telescope (FAST), located in China. This was built as a possible SKA design to demonstrate one element of a small array of very large diameter collectors (large D—small N array technology). In the first year of routine operation with its 19-beam focal plane receiver, it has a pulsar discovery rate which exceeds all previous radio telescopes (see Fig. 5.20).

**Fig. 5.19** Image of the polar ring galaxy NGC4632 showing the anomalous HI component observed in the ASKAP WALLABY HI survey (diffuse purple structure). The anomalous HI is superposed on an optical image from Subaru Hyper Suprime-Cam. The disc HI has been removed. Science credit: N. Deg et al., WALLABY Survey, CSIRO S&A/ASKAP, NOAJ/Subaru. Image credit: Jayanne English (U. Manitoba)

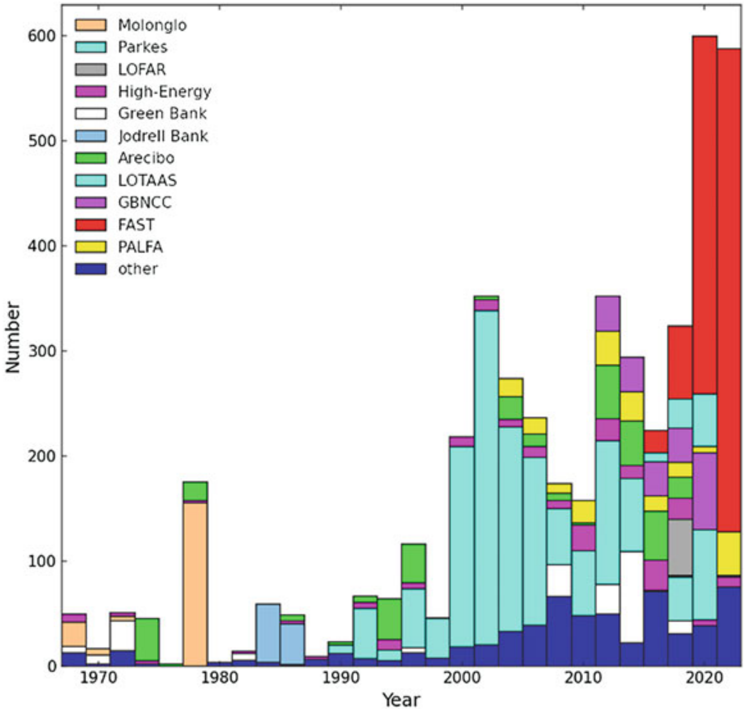

**Fig. 5.20** Pulsar surveys of time using different radio telescopes based on the ATNF Pulsar Catalogue (V1.70). The Chinese FAST SKA pathfinder with its 19 beam focal plane array is now dominating the pulsar discovery rate. Credit Dick Manchester (CSIRO) and Di Li (NAO, China) for updates

### *5.12.6 Discovering the Unknown*

As we have already discussed in Sect. 5.11.1 the SKA precursors and pathfinders have already made significant new discoveries. One example is a new class of radio source never seen before. The wide-field-of-view of the ASKAP precursor included some unusual sources called Odd Radio Circles (ORC). This discovery was confirmed with the higher resolution and higher sensitivity MeerKAT data and is thought to be the result of a violent explosion one million years ago in the central faint and distant galaxy (Norris et al., 2022) (see Fig. 5.21).

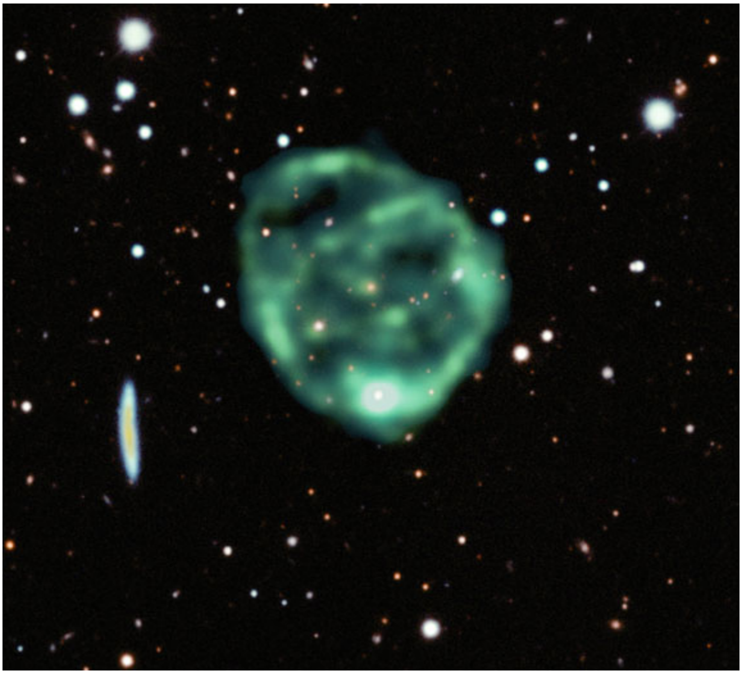

**Fig. 5.21** ORC (Odd Radio Circle) composite image observed with ASKAP and MeerKAT superposed on a Dark Energy Survey (DES) optical image. Science Credit: R. P. Norris (Western Sydney U.), ASKAP-EMU/CSIRO, MeerKAT, DES-NSF/AURA. Image Credit: Jayanne English (U. Manitoba)

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# Chapter 6
# Innovation Meets Reality: The SKA Design

This book describes the roles of many factors: persistence, management, luck, competition, cooperation, and politics. The way the SKA came together represents a global first among international science projects, even in the time horizon of this book, and in the end will indeed result in two next-generation radio telescopes. This chapter traces the evolution of the roles of innovation, technical development and engineering approaches, alongside the other chapters that describe the many other aspects required to make the SKA happen. The story of the winnowing of technology provides a lesson that it is not easy to accomplish the twin goals of changing established technology at the same time as successfully funding and building a major new facility.

The originators of the SKA idea in the 1990s understood that a next-generation radio telescope was needed, but also realised that breakthroughs in technology or techniques would also be needed to achieve their vision. The SKA began with a serious attempt to transform the design of radio telescopes to enable a next generation that would surpass the performance of the then current generation by 100 times at an affordable cost. Although sounding extremely ambitious, this was known to be possible in other fields, such as particle physics and the miniaturisation of electronics. These aspirations triggered a period of invention, adaptation, and innovation, and inspired a global pool of hundreds of talented engineers and scientists. It also attracted sponsorship by governments and funding agencies.

Innovation, used to capture all the above, takes many forms and is difficult to capture precisely. It is usually considered very disruptive if it completely obviates current methods or existing technology, but this is rare. Most innovations are mildly disruptive, and some are just incremental improvements on existing technology. For example, while the invention of the laser was much more than mere innovation, it provided opportunities for thousands of innovations which emerged. The most important innovations incorporate the concept of a platform, a framework which supports many capabilities. As will be illustrated, this concept applies to general-purpose radio telescopes too, in the sense of enhancing the likelihood of new discoveries, which by definition cannot be specifically designed for. Almost all the

R. T. Schilizzi et al., *The Square Kilometre Array*, Historical & Cultural Astronomy,
https://doi.org/10.1007/978-3-031-51374-9_6

new approaches to the design of the SKA were directed to enhancing discovery space.

Innovation cannot be predicted or planned for, but circumstances can be created in which its probability is enhanced. In the case of the SKA in the late-1990s and early-2000s, the circumstances were ripe for new approaches to radio telescope design.

Initially, innovations tend not to work as well as existing approaches or designs. This is a natural barrier, which can delay or even halt their usage. It is conceivable that some of the many new ideas that were explored for the SKA were halted prematurely and some might even become practical in the future if additional developments occur. This is because an innovation period can last only so long before some retrenchment is in order. As described in Chaps. 3 and 4, the need for a proven design became more pressing as funding agencies became interested. At that point the SKA had to make a transition from focussing on innovative designs to the engineering required to deliver a realistic next-generation telescope. However, the design path was not straightforward, and this chapter tells the story of how it occurred.

Although every project is unique, it is hoped that this chapter might also shed light on age-old themes that seem to pervade highly technical projects, as they have manifested in the SKA project. Cross references to the following points are made throughout the chapter.

(A) *The role of optimism.* Where is the line between boundless optimism and that which is necessary to propel innovation? A famous quotation from Robert Noyce frames the issue[1]: “Optimism is an essential ingredient of innovation. How else can the individual welcome change over security, adventure over staying in safe places?” A balance must be struck, because optimism to the point of not recognising challenges will eventually lead to poor results. Optimism played a definite role in driving the SKA project forward.

(B) *The role of discovery space in the design of large scientific facilities.* In radio astronomy almost all major discoveries have been unexpected outcomes of observations with telescopes not designed to make such observations (e.g., Fast Radio Bursts (Lorimer et al., 2007)) (see Sects. 1.2.2 and 5.3.7). Widening parameter space, increasing flexibility, and promoting agility in the final design all enable larger discovery space. But these design approaches are usually expensive, and their usefulness cannot be predicted in advance. In contrast, a goal-oriented design sets out to answer a specific scientific question. Threading the needle between these extremes created a consistent underlying tension in the years leading up to a stable design between maintaining a high degree of flexibility and achieving a practical, affordable design.

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[1] The exact time and place of this quote is obscure. According to an article in Forbes Magazine by Carmine Gallo, Gordon Moore said “Every time I walked onto the Intel campus, I was greeted with a quote above the doors that welcomed employees and visitors”.

(C) *The psychology of cost and cost projections.* In a subject related to the previous two, realistic projections of cost and risk, if made too early, are likely to kill a project in the eyes of all but the most sophisticated national funding agencies. Sensitivity to costs was intensified by the need for funds to build large prototypes to fully test SKA antenna concepts. It is conceivable that some SKA concepts might have borne fruit if sufficient funds and time were available to develop them to maturity, which would then enable accurate cost estimates (see Sects. 6.4.4.2 and 6.4.6). The progression of cost and schedule targets for the SKA project is discussed in Sect. 4.6.1.

(D) *Born Global.* SKA started as a global project without a single major sponsor providing most of the resources and driving decisions. This is unusual in astronomy. What specific lessons can be learned from the SKA project, especially in its formative years? Projects as large as the SKA tend to force international collaboration because most nations cannot afford the cost. But international collaboration almost always costs more than one carried out efficiently under one sponsor, and as described in Chaps. 1, 4 and 11, it takes much longer. Also, although technical risk is likely to increase because there are 'too many cooks', the risk of cancellation is likely to decrease, because the risk of one sponsor withdrawing is diluted (see Chaps. 4 and 11).

(E) *Complex Project.* As described in a series of workshops by Gary Sanders (California Institute of Technology),[2] most global projects exhibit the characteristics of complex projects: multiple resource bases, political interference, clashes of institutional cultures, and several others. National interests have the potential to trump everything in international complex projects, sometimes to the detriment of lowest cost or best performance possible. Constant independent scrutiny is clearly needed. There are likely to be many similar complex projects in the future. Will the SKA survive complexity? The SKA project has clearly survived the challenges of complexity up to the time of writing, including during the period covered in this book (see Chaps. 1 and 11).

(F) *Non-science benefits.* Excellent science is a necessary condition for institutional funding and support, but governments and funding agencies also value benefits to industry, employment, the potential for innovation and access for their scientists. Unless there are identifiable economic benefits, prospects for support are diminished. While involving industry directly is mainly beneficial, issues with intellectual property can also hinder progress by impeding essential dissemination of information.

(G) *Evolution of technology.* As discussed in Sect. 1.3, Livingston curves (Livingston, 1954), log-plots based on the evolution of particle accelerator energy, were used by analogy to illustrate the evolution of radio telescope sensitivity in the formative years of the SKA and to promote innovation and the project in general. Moore's law (Moore, 1965) and the growth of optical fibre

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[2] hba.skao.int/SKAHB-143 Complex *Projects,* Sanders, G., presentation at the Project Science Workshop, 19 January 2002.

communication, resulting from the invention of the laser, are examples of exponential growth as well (see Chap. 1 and SKASUP1-1). Underlying inventions or discoveries are required to set the scene for these developments. Even if underlying origins are present, mature technology often presents a barrier to innovation that must either be overcome or tunnelled through (See Sect. 11.4.3).

(H) *Helpful technology diffusion.* Technology developments occurred after 2000 that enabled the SKA to reach its current construction stage (e.g., optical fibre data transmission). Further developments are likely to be needed to proceed to the originally envisioned SKA Phase 2. Would any of the innovations investigated in the SKA's formative stages survive if they were re-started today?

(I) *Unhelpful technology diffusion.* The accelerating utilisation of the radio spectrum for other uses may gradually choke off its use for astronomy. More recently, the capability to launch thousands of small satellites for the first time has resulted radio frequency interference directly in the look-direction of radio telescopes. Weak spectral lines and highly redshifted spectral lines will be most at risk. Will the SKA be the last major ground-based telescope to access a scientifically useful fraction of the radio spectrum for astronomy? (See Sect. 6.2.2.12).

(J) *The need to deliver.* Once it has become clear that there is limited time available to fully develop more risky innovations, large project management and system engineering processes must take hold. This discipline will generally slow down change in the project design and architecture, sometimes to the detriment of science goals. Did this happen at the right time for the SKA? (See Chap. 11).

(K) *Project Management and System Engineering.* Do the disciplines of project management and system engineering also lead to a form of tunnel vision, especially projects that take more than a decade to build? This is their intent. Otherwise, the design will never converge, and there is no other method of managing a large-scale project involving many parties and people. Achieving a balance between creative change and accountable management is a complex problem.

## 6.1 Design Goals for a General-Purpose Radio Telescope

The SKA has always been considered a next-generation general-purpose telescope for all of metre and centimetre wave astronomy. This role is arguably held now by the Jansky Very Large Array (JVLA) in the USA, which was commissioned in 1980 under the name, Very Large Array (VLA), and upgraded over a period from 2001 to 2012 (Perley et al., 2009, 2011). Although scientific goals were elucidated in its funding proposals, it is a general-purpose telescope, not designed to carry out specific science experiments. Its capabilities are broad, and its record of scientific achievement is amazing.

The key aspects of the upgrade in the early 2000s were continuous frequency coverage (1–50 GHz), increased sensitivity, increased instantaneous bandwidth and higher frequency resolution. The upgrade provided greater access to new discovery space, primarily new frequencies.

The design of the SKA follows a similar general-purpose philosophy. Its most important design aspects incorporate the concept of a platform, i.e., a framework which supports many capabilities. The approach is to produce a constrained maximisation of discovery space by retaining flexibility wherever possible. Flexibility is abandoned only when it strikes limitations of technical feasibility and cost at the time of its design. As will be described in this chapter, many innovations were explored in depth, all of which were intended either to reduce cost so that “more telescope” could be afforded or to directly increase discovery space.

For a radio telescope, one can describe the capabilities of the platform as a multidimensional parameter space, each of which confers a significant capability, but to describe this space in detail is beyond the scope of this book. In terms of capabilities, the important parameters enable the telescope to make 3-D radio images (two dimensions on the sky and one frequency dimension) with high sensitivity and resolution, so that narrow spectral lines can be traced in the frequency dimension. Moreover, the telescope must be able to capture all the spatial scales in complex images while at the same time covering large regions of sky. Because much of the sky contains polarised radio emission, it is also important to be able to measure polarised radio emission in the images. Finally, there are time-variable sources of radio emission whose time scales vary from milliseconds to years.[3] These capabilities were all driven from what was perceived as the most important science questions in astronomy (see Chap. 5), while recognising that historically, the most important discoveries have been unexpected. In such cases a telescope happened to detect a phenomenon for which it was not designed. Chapter 11 discusses the recent example of the CHIME telescope, which has found most of the phenomena of Fast Radio Bursts, despite being designed for something completely different.

To span the required range of frequencies with this set of capabilities required two separate telescopes now under construction in Australia and South Africa. By 2012, the end of the period covered in this book, the design had incorporated design improvements in almost all the capabilities described above, which are not available in today’s telescopes.

## 6.2 SKA Innovation History

The history of major telescope developments from the 1950s to 1990 is covered in detail in Chap. 2. This history of this period illustrates the mind-sets of radio astronomers which converged from several independent threads of thought circulating in the global community. Interferometry, utilised as arrays of antennas in various

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[3] Through very accurate time-keeping and repeated observations, these phenomena must be tracked for at least a decade.

forms, could provide high resolution. But because radio astronomy signals are very weak, especially the ubiquitous hydrogen line at 1420 MHz, radio telescopes also needed high sensitivity to progress the science. Sensitivity, especially at relatively high radio frequencies, was difficult to obtain at reasonable cost. More subtly, obtaining good radio imaging requires a continuous representation of interferometer spacings in array designs. This thinking was on display in 1990 at the IAU Colloquium 131 on Radio-Interferometry (Cornwell & Perley, 1990) but it took until 1993 for it to consolidate (see Sects. 2.4.3–2.5). This chapter briefly covers events of the 1990s, with increasing detail from 2000 to 2007, yet more detail from 2008 to 2012, and in some cases extending a bit further. As at the time of writing the SKA is under construction, there will be much more to tell in the future.

Figure 6.1 is a guide to the technical history of the project and provides a link to other chapters in this book (see also Figs. 3.1 and 4.1). Exploratory technical discussions took place from the early 1990s to 2002, during which major prototypes were built and performance tests carried out. Table 6.1 is a companion to Fig. 6.1, and contains a table of important documents along with notes as to their significance.

## *6.2.1 1993–2007: The Pre-PrepSKA Period*

### 6.2.1.1 Beginnings of Engineering Coordination

Initiatives to develop new technology and engineering approaches to the design of the SKA had been taking place in the most prominent institutes around the world since 1993, cooperating and communicating through the URSI Large Telescope Working Group (LTWG) (see Sect. 3.2.1). More formal cooperation was put in place in 1996 (see Sect. 3.2.2) with a Memorandum of Agreement which was signed by eight globally- distributed[4] institutions to cooperate in a technology study program leading to a future very large radio telescope.[5] As described in detail in Chap. 3, the International SKA Steering Committee (ISSC) was established in 1999 and met approximately every 6 months, ending in 2007. A key event occurred on January 1, 2003, the establishment of the International SKA Project Office (ISPO) with Richard Schilizzi as its director.

From a technical perspective, the ISSC set itself a goal of increasing telescope sensitivity by a factor of 100. Not only did subject matter experts believe that this ambitious goal could be achieved, they also each had in mind innovations to achieve it. But only after the establishment of the ISSC did serious critical examination of the various proposals begin to take place.

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[4] The ‘born global’ theme (see point {D} in Chap. 6 introduction) had taken hold and was frequently mentioned in presentations, especially by Ron Ekers.

[5] hba.skao.int/SKAHB-142 Memorandum *of an Agreement to Cooperate in a Technology Study Program Leading to a Future Very Large Radio Telescope,* Directors of eight global astronomy institutes, 1996.

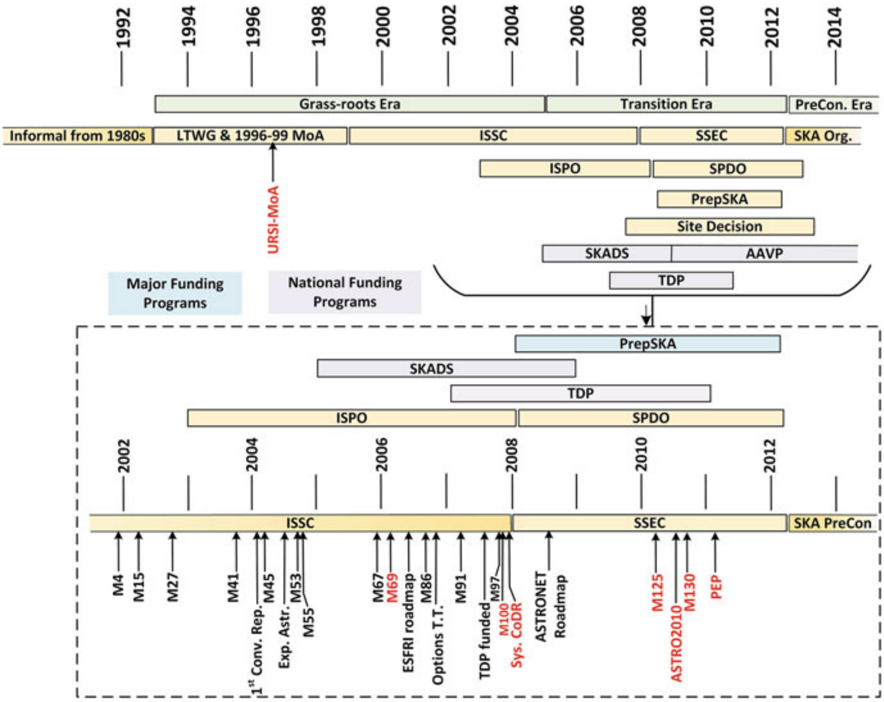

**Fig. 6.1** A timeline of the technical development of the SKA (Acronyms and Abbreviations. PreCon: Pre-construction, LTWG: Large Telescope Working Group, URSI: International Union of Radio Scientists, MoA: Memorandum of Agreement, ISSC: International SKA Steering Committee, SSEC: SKA Science and Engineering Committee, ISPO: International SKA Project Office, SPDO: SKA Program Development Office, PrepSKA: Preparatory phase for the Square Kilometre Array, SKADS: SKA Design Study, AAVP: Aperture Array Verification Program, TDP: Technology Development Project (USA), 1st Conv. Rep.: First Convergence Report, Exp. Astr.: Experimental Astronomy, ESFRI: European Strategy Forum on Research Infrastructures, Options T.T.: Options Tiger Team, Sys. CoDR: System Concept Design Review, ASTRONET: network of European funding organisations, ASTRO2010: the 2010 report from the US Decadal astronomy survey in 2010, PEP: Project Execution Plan). The top part illustrates the context of governance and funding (see Chaps. 3 and 4). The bottom part shows the dates of publication of SKA Memos and other papers that were influential in subsequent technical developments. The red-coloured items denote major turning-point documents. The Mxx notation stands for SKA Memo xx

The goal was solidified in a synopsis of technical specifications assembled by Ron Ekers[6] in late-2001, based on science and engineering discussions in preceding years. These specifications, rooted in science, provided more specific engineering direction.

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[6] hba.skao.int/SKAMEM-4 SKA *Technical Specifications,* Ekers, R. D., SKA Memo 4, December 2001.

**Table 6.1** Documents representing major turning-points in SKA development

| Doc. | 1st Auth. | Date | Reference | Notes |
|---|---|---|---|---|
| URSI-LTWG | Braun | 1993 | SKAHB-123 | Minutes of the 1st meeting of the LTWG |
| MoA | Directors of major institutes | Q4, 1996 | SKAHB-6, SKAHB-142 | Memorandum of an agreement to cooperate in a technology study program leading to a future very large radio telescope (see Chap. 3) |
| Memo 4 | Ekers | Dec. 2001 | SKAMEM-4 | Early technical specifications |
| Memo 18 | USSKA | 2002 | SKAMEM-18 | Large N - small D design for the SKA |
| 1st convergence report | Schilizzi | 13 Jan. 2004 | SKAHB-147 | Summary of the first SKA design convergence workshop—Hybrid proposals |
| Memo 45 | Jones | 26 Feb. 2004 | SKAMEM-45 | SKA science requirements: Version 2 (actually technical requirements) |
| Memo 53 | Schilizzi | Sep. 2004 | SKAMEM-53 | Summary of the second SKA design convergence workshop |
| SKADS funding | | Jul. 2005 | SKAHB-335 | SKA design study (SKADS) funded for four years through the European Commission's sixth FP6 |
| ESFRI road map | | Mid-2006 | https://www.esfri.eu | European strategy forum on research infrastructures—Recognition of SKA as major European project—See Chap. 4 |
| Memo 69 (reference design) | ISPO | 27 Jan. 2006 | SKAMEM-69 | Reference design for the SKA. The culmination of Tiger-team work leading to a down-select of technologies in late 2005 |
| Options Tiger team | Schilizzi | 19 Mar. 2007 | SKAHB-149 | Engineering decisions for the SKA 2007–2014 |
| Memo 97 | Cordes | 27 Sep. 2007 | SKAMEM-97 | The SKA as a radio synoptic survey telescope: Widefield surveys for transients, pulsars and ETI (time domain astronomy) |
| US TDP funded | Cordes | Oct. 2007 | SKAHB-230 | U.S. technology development project for the SKA:<br>Revised work plan (Jan. 2007, funded Oct. 2007) |
| Memo 100 | Schilizzi | Dec. 2007 | SKAMEM-100 | Preliminary specifications for the square kilometre Array. |
| ASTRONET roadmap | | Nov. 2008 | (Bode et al., 2008) | ASTRONET infrastructure roadmap: a strategic plan for European astronomy—Critical milestone (see Chap. 4) |
| Transition from SKADS to AAVP | | Mar. 2010 | SKAHB-350 | As the SKADS program on developing aperture arrays for the SKA ended, work continued in a consortium-funded program, the aperture Array verification program (AAVP) |

(continued)

**Table 6.1** (continued)

| Doc. | 1st Auth. | Date | Reference | Notes |
|---|---|---|---|---|
| Sys CoDR report | Wild | 19 Mar 2010 | SKAHB-184 | Turning point for realism and provided licence to resist political pressures on technical decisions |
| Memo 125 | Garrett | Jun. 1, 2010 | SKAMEM-125 | A concept design for SKA phase 1 (SKA1)—An 'implementation' motivated by the results of the system CoDR |
| ASTRO2010 | Blandford | 13 Aug. 2010 | (Blandford et al., 2011) | US participation in SKA not supported in the 2010–20 decade—Technical aspect: Large, justified scepticism of SKA costs. |
| Memo 130 | Dewdney | 22 Nov. 2010 | SKAMEM-130 | Preliminary system description for SKA1. (basis for Baseline Design document in 2012/13) |
| PEP | Schilizzi | 17 Jan. 2011 | SKAHB-192 | Project Execution Plan (PEP): Detailed project plan |
| SKA1 system Baseline Design | Dewdney et al. | 12 Mar. 2013 | SKAHB-206 | Baseline design to begin the SKA1 Pre-construction period |

The meeting of the ISSC in August 2000 recognised the need to coordinate engineering effort. Based on a recommendation from the Five-year Management Plan and Technical Oversight Working Group, an Engineering Management Team (EMT) was established (later renamed International Engineering Management Team—IEMT). Their remit was all-encompassing: produce a technical audit of SKA technical activities, identify deficiencies, maintain an evolving SKA system definition document, foster information flow among project groups, and coordinate with a similar-level Science Advisory Committee on interacting issues. After some iterations, a group of interested but independent people were appointed.[7] Peter Hall (Australia Telescope National Facility) was appointed by the ISSC as chair. From then until about 2007, Hall dominated the leadership of the international SKA engineering scene.

Apart from the SKA Newsletter series, itself, this period is also covered by notes made from the newsletters,[8] which contains lists of events and technical meetings, as well as notes ordered by SKA-related entities (countries and EU-related organisations).

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[7] There was some variation in the EMT/IEMT membership. The members in 2002 were: S. Ananthakrishnan (India), Ren Gexue (China), Peter Hall—Chair (Australia), Dion Kant (The Netherlands), Peter Napier (USA), Ralph Spencer (UK), Richard Thompson (USA), Bruce Veidt (Canada). Later Nan Rendong (China) replaced Ren Gexue. Marco de Vos (The Netherlands) also participated later.

[8] hba.skao.int/SKAHB-153 *SKA Newsletters Notes*, Dewdney, P. E., Informal Notes, 30 April 2008.

**Table 6.2** SKA concepts in the 2001–2005 period

| SKA concept | Leading Country | Adopted | Notes |
|---|---|---|---|
| Cylindrical Reflector | Australia | N | Short lived—Dropped in 2003 |
| Luneburg Lens[a] | Australia | N | Short lived |
| The Large Adaptive Reflector (LAR)[b] | Canada | N | Large D–Small N (LDSN) concept |
| Kilometre-Square Area Radio Synthesis Telescope —KARST[c] | China | N | LDSN concept eventually built as a single dish. Site-specific coupling. Later became the 500-m Aperture Spherical radio Telescope (FAST) |
| Dense Aperture Array Tiles | The Netherlands | N | Decimetre wavelengths (Sect. 6.5.5) |
| Pre-loaded Parabolic Dish | India | N | Not practical for high frequencies (Sect. 6.4.4.3) |
| Large N–Small D Array | USA | Y | Eventually adopted with 15-m dishes and conventional feeds. A version adopted for MeerKAT for decimetre wavelengths (Sect. 6.4) |
| Dishes with Phased Array Feeds (PAFs) | Australia | N | Adopted for ASKAP (Sect. 4.3.3.1) |
| Decameter and Metre Arrays | The Netherlands | Y | Low-frequency array adopted but not the LOFAR[d] design (Sect. 6.5.3.1) |

[a] See hba.skao.int/SKASUP6-30—Luneburg Lenses

[b] See hba.skao.int/SKASUP6-28—The Large Adaptive Reflector (LAR)

[c] See hba.skao.int/SKASUP6-29—The Five-hundred-metre Aperture Spherical radio Telescope (FAST)

[d] LOFAR: The LOw-Frequency Array. A large low -frequency radio telescope in the Netherlands (van Haarlem et al., 2013)

#### 6.2.1.2 2003–2007, the International SKA Project Office (ISPO): Working Towards Engineering Coherence

In 2003, Schilizzi put forward an SKA Management Plan,[9] which formed the basis for management of the ISPO. This plan re-enforced the role of the IEMT as a key part of SKA Management but changed the emphasis to "conduct reviews of national and regional design studies" and "act in the capacity of (an) engineering working group". Table 6.2 contains a list of innovative receptor-concepts[10] being put forward by national groups. The role of the IEMT in the management plan was a step towards a tangible technical design for the SKA, while retaining the activity of winnowing options. In 2004, the IEMT was renamed the Engineering Working Group (EWG) .

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[9] hba.skao.int/SKAHB-146 *SKA Management Plan*, Schilizzi, R. T., ISSC Discussion Document—version 1.0, 03 August 2003.

[10] Receptor was used as a generic term for antennas or antenna arrays, which are the basis of the collecting area of the telescope. Collecting area is the raw area used to intercept radio waves, the most important measure of telescope sensitivity.

Table 6.3 Major engineering documents in the pre-PrepSKA period

| Doc. | 1st Auth. | Date | Reference | Notes |
|---|---|---|---|---|
| Memo 15 | Hall | 27 Mar. 2002 | SKAMEM-15 | Compendium of required information on design studies |
| Memo 27 | Hall | 1 Jan. 2002 | SKAMEM-27 | EMT comments on concept proposals |
| Memo 41 | Hall | 3 Oct. 2003 | SKAMEM-41 | IEMT assessments of SKA updated concepts and demonstrators |
| Exp. Ast. | Hall (ed.) | Jun. 2004 | (Hall, 2004a) | Vol 17, issue 1–3, June 2004 |
| Exp. Ast. | Hall | 4 Oct 2004 | (Hall, 2004b) | Engineering overview of the SKA |
| Memo 55 | Hall | 22 Sep. 2004 | SKAMEM-55 | Assessment of Demonstrators by the Engineering Working Group |
| Memo 56 | Veidt | Sep. 2004 | SKAMEM-56 | EWG Reviews of SKA Hybrid Proposals |
| Memo 67 | Hall | 1 Dec. 2005 | SKAMEM-67 | EWG assessments of SKA demonstrators |
| Memo 86 | Hall | 6 Oct. 2006 | SKAMEM-86 | SKA Demonstrators, Pathfinders and Design Studies—updates |
| Memo 91 | Hall | 14 Sep. 2007 | SKAMEM-91 | White Papers by the Task Forces of the IEWG |

Table 6.3 shows a trail of documents in which the EMT/IEMT carried out their mission to review the concepts in Table 6.2. After putting out a request for technical information,[11] the group produced the first comprehensive assessments of the design studies (SKA Memo 27).

One aspect of their assessment stands out: "The EMT is persuaded that independent, widely-placeable, multi-beams translate into a true sensitivity gain for a radio telescope." This was widely accepted at the time, but it is interesting to note that only at low frequencies has this been realised in the SKA design (i.e., wavelengths longer than about 1 m). The reasons are discussed in Sects. 6.4.5 and 6.5. Independently, John Bunton (Australia Telescope National Facility) attempted to evaluate the designs based on cost as a function of frequency,[12] which turned out to require many assumptions and succeeded only in highlighting some rough trends.

The assessments of late 2003, documented in SKA Memo 41 (see Table 6.3), carried out by working groups appointed by the IEMT, were impressively thorough. A key aspect was "hybrids" or "composite" solutions involving a combination of concepts. While noting that "No one concept provides optimal performance in both the high frequency and multi-fielding domains", they also cautioned that "The IEMT feels that investigation of hybrids, while important, should not de-focus efforts in

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[11] hba.skao.int/SKAMEM-15 Descriptions *of SKA Concepts—Suggested Form,* Hall, P. J., SKA Memo 15, 27 March 2002.

[12] hba.skao.int/SKAMEM-36 *SKA Station Cost Comparison,* Bunton, J. D., SKA Memo 36, 04 August 2003.

key development areas within each concept". The obvious hybrid was a frequency-split between two technologies. However, almost all technologies claimed high sensitivity from about 150 MHz to 10 GHz. Although work continued apace on most of these concepts, Luneburg Lenses[13] were dropped in 2004 after a review by the Australian SKA Consortium.

Based on the SKA meeting in Penticton, Canada in July 2004, a book was published in 2005 by Springer, edited by Hall (Hall, 2004a), who was now SKA Project Engineer. This volume contained a compendium of aspects of all the SKA demonstrator projects and many other SKA technical developments. Hall's overview paper (Hall, 2004b), summarising the status at time, pointed out that many specialised technologies needed to be refined, not just antennas. One concern, for example, bubbling below the surface, was that the cost of image processing[14] (see Sects. 6.6.5, 6.2.1.3, and 6.4.3.1) would scale as the inverse 8th power of antenna diameter.

The way forward was now seen as "convergence", another way of expressing the idea of a hybrid solution. The ISPO organised a workshop in South Africa in January 2004, explicitly set up to discuss options for hybrid designs and to "explore the parameter space of combined designs and narrow down the possibilities to a small number that can be focussed on in the future". Schilizzi's summary[15] re-enforced the emerging themes noted above, while stressing that cost must be contained to €1 billion and that "a mutually agreed single concept that is inclusive and engages the global community" was required. Several types of hybrids were identified, including a "site hybrid", which turned out in the end to be what took place.

The summary contained an important table illustrating the depth of expertise in the six countries participating at the time. For each of the 21 technical areas, there were at least three countries where significant expertise was present. In essence, this was a global dream team, which could capably explore all the innovative approaches if provided with appropriate resources. In the event, however, they never operated as a global team. Although there were a few exceptions, there was not much cross-fertilisation of ideas. Each country concentrated mainly on developing their own concepts, rather than supporting concepts elsewhere. Nevertheless, the IEMT did provide excellent feedback on the strengths and weaknesses of each concept, but that is a long way from actual participation. This is clearly one of the features of a complex project (see point {E} in Chap. 6 the introduction to this chapter).

In the meantime, SKA specifications were firming up and becoming more detailed.[16] However, sensing that primary goals might be lost, scientists stressed

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[13] See hba.skao.int/SKASUP6-30—Luneburg Lenses.

[14] See hba.skao.int/SKASUP6-15—Computing Challenges: CSIRO collaboration with South Africa.

[15] hba.skao.int/SKAHB-147 *Summary of the First SKA Design Convergence Workshop, 13 January 2004, Schilizzi*, R.T., ISPO document, February 2004.

[16] hba.skao.int/SKAMEM-45 *SKA Science Requirements: Version 2, Jones*, D. L., SKA Memo 45, 26 February 2004.

the need at the South Africa meeting to maintain sensitivity as the most important parameter, more so than complete frequency coverage, and the multi-fielding needed further investigation for scientific benefits.

Six months later, the initial convergence meeting was followed by another in which more detailed discussions and analyses of specific concepts and technical risks took place. The second summary[17] contains more detail, complete with the meeting presentations. Of particular importance was a presentation by Bruce Veidt (National Research Council of Canada, Dominion Radio Astrophysical Observatory), which contained a thumbnail analysis of each potential hybrid, and for the first time discussed the issue of technical risk[18] (see also Table 6.3). However, against the flow, Ken Kellermann (US National Radio Astronomy Observatory) expressed concern in a presentation at the meeting that hybrids would simply increase cost without yielding significant science benefits and was not sympathetic to keeping a broad spectrum of participants involved.[19]

These meetings were a turning point in the life of the SKA. Pressure was building to come to agreement on an SKA design. The winnowing process had begun in earnest, even though it was still below the surface.

In parallel with the engineering management activity, Hall also pioneered policy on the SKA relationship to industry.[20,21] This was important groundwork for later industry interactions (see Chap. 10). This work had political implications because the sponsors (governments) were keenly interested in economic benefits. The SKA presented many opportunities for such benefits, but also led to conflicting concerns over intellectual property (IP) (see point {F} in Chap. 6 introduction).

The EWG (renamed from the IEMT) continued IEMT practice, carrying out annual evaluations of the SKA demonstrator projects in 2004,[22] 2005[23] (Table 6.3) and 2006.[24] All were given a numerical score, based on a large list of criteria that included cost, risk, schedule, security of funding, project management

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[17] hba.skao.int/SKAMEM-53 *Summary of the second SKA Design Convergence Workshop,* Schilizzi, R. T. and Hall, P. J., SKA Memo 53, September 2004.

[18] hba.skao.int/SKAMEM-56 *EWG Reviews of SKA Hybrid Proposals,* Veidt, B., et al., SKA Memo 56, 18 November 2004.

[19] This presentation can be found in the summary report by Schilizzi and Hall (SKA Memo 53).

[20] hba.skao.int/SKAMEM-52 *The International SKA Project: Industry Interactions,* Hall, P. J., SKA Memo 52, 02 August 2004.

[21] hba.skao.int/SKAMEM-80 *The International SKA Project: Industry Liaison Models and Policies,* Hall, P. J. and Kahn, S., SKA Memo 80, 28 July 2006.

[22] hba.skao.int/SKAMEM-55 *SKA Demonstrators, 2004: An Assessment by the Engineering Working Group,* Hall, P. J., SKA Memo 55, 22 September 2004.

[23] hba.skao.int/SKAMEM-67 *SKA Demonstrators, 2005 Assessment by the Engineering Working Group,* Hall, P. J., SKA Memo 67, 01 December 2005.

[24] hba.skao.int/SKAMEM-86 *SKA Demonstrators, Pathfinders & Design Studies—EWG Comments on 2006 Updates,* Hall, P. J., SKA Memo 86, October 2006.

and responsiveness to questions. There were no stellar results. It continued to be obvious that many engineering challenges lay ahead.

A compendium of the work of the EWG (including the earlier work of the IEMT) through its task forces was published in 2007.[25]

#### 6.2.1.3 The Reference Design

As described in Sect. 3.4.1, the Heathrow meeting in June 2005 was a turning point for the SKA because it was now ‘on the radar’ of the funding agencies. But as the SKA project had equally weighted several different technical concepts, the funding agencies were concerned that the SKA was too immature to provide near-term support.

Possibly the lack of high marks for any of the alternatives by the EWG (see the previous section) and other indicators also led the ISSC to realise that the project was at an impasse. This was a fair assessment. Discussions in ISSC meetings subsequently led to the definition of a Reference Design for the SKA.[26] And following discussion at the November 2005 meeting, the ISSC instructed the Director to put together a ‘tiger team’ of ten prominent people to provide the Reference Design.[27] Their approach was that the design “should contain a substantial component of known technology in order to minimise risk yet should include an innovative component that enables access to new scientific parameter space, is challenging for the engineering community, and is attractive to policy makers and industry”.

For mid-frequencies, the reference design report notes that dish-based technologies are inherently more mature than aperture array technologies. Indeed, although not the final step, this was a dramatic step in the direction of abandoning some of the innovative ideas of the previous decade in favour of a buildable interferometric telescope within 5 years (i.e., lowish risk). This trend is traceable to the issues expressed more generally in the introduction to this chapter (see points {G}, {J} in Chap. 6 introduction).

The key features of the reference design were:

- Frequency coverage from 100 MHz to 25 GHz.
- An array configuration with baselines up to 3000 km, with half the collecting area in a central core of about 5 km in diameter.
- Small dishes (in contrast to Large Diameter) with “smart feeds”. These were very small dishes (about 10 m).

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[25] hba.skao.int/SKAMEM-91 *An SKA Engineering Overview: White Papers by the Task Forces of the International Engineering Working Group,* Hall, P. J., ed., SKA Memo 91, 14 September 2007.

[26] hba.skao.int/SKAHB-148 *On the Selection of the Reference Design for the SKA*, Schilizzi, R.T., ISSC14 paper, 23 August 2005.

[27] hba.skao.int/SKAMEM-69 *Reference design for the SKA, Discussion Document,* International SKA Project Office (ISPO), Version 2.2, SKA Memo 69, 27 January 2006.

- Aperture Array tiles in the core with multiple independent fields-of-view, covering 0.3–1 GHz.
- An 'Epoch of Reionisation'[28] (EoR) array also in the core area, like the LOFAR design.
- Supporting technologies such as data transport, processing, and software to be common to all forms of collecting area.

Recognising the nature of telescope arrays, a phased approach, with the first phase having about 10% of the total collecting area, was described in some detail. All the technologies were represented in the Reference Design apart from the EoR array, which was thought to be unnecessary, since a 10% version would have been no larger than LOFAR was planned to be. However, by 2007 this view had changed, when an EoR array was included in the SKA Phase 1 concept[29] (see Sect. 5.9.5).

Although the Large-N–Small-D (LNSD)[30,31] approach was a standard radio telescope design, the aim of the Reference Design was to avoid choking off innovation that might still be possible within the Reference Design framework, perforce deliberately entailing a large measure of risk. For example, the term "smart feeds" meant a combination of Phased Array Feeds (PAFs) (Sect. 6.4.7) and Wide-Band Single Pixel feeds (WBSPF) (Sects. 6.4.5 and 6.6.1.1). Both were considered "known technology". Although not as definitively, Dense Aperture Arrays (Sect. 6.5.5) were considered quite mature. Unfortunately, none of the projects, put forward over-optimistically as mature, managed a sufficiently convincing level of success to be incorporated into the final SKA design,[32] one of several instances of over-optimism (see point {A} in Chap. 6 introduction).

The selection of the LNSD approach to the SKA eliminated further consideration of the FAST (initially called Kilometre-Square Area Radio Synthesis Telescope (KARST)[33]) and LAR designs (see Table 6.2) for the SKA. The early background to FAST is described in Sects. 3.2.6.2, 3.3.3.3 and the China's proposal for the SKA site, utilising FAST-like antennas, in Sect. 7.3.5. A brief outline of the KARST/

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[28] A period in the early Universe just as stars and galaxies were forming, from which spectral signatures from highly redshifted atomic hydrogen (HI) might be detected. At the time of writing there has been no confirmed detection, but this possibility has always been one of the most important motivations for constructing the SKA (see Chap. 5).

[29] hba.skao.int/SKAHB-150 *Science with Phase I of the Square Kilometre Array,* SKA Science Working Group, 21 March 2007.

[30] hba.skao.int/SKAMEM-16 A Model for the SKA, Wright, M., SKA Memo 16, 21 March 2002.

[31] hba.skao.int/SKAMEM-18 The Square Kilometer Array Preliminary Strawman Design Large N–Small D, USSKA Consortium, SKA Memo 18, 2002.

[32] Some of these technologies such as PAFs and WBSPFs are actively being refined and could find their way into the SKA in the future, beyond Phase 1.

[33] hba.skao.int/SKAMEM-17 Kilometer-square Area Radio Synthesis Telescope—KARST, Nan Rendong, et al., SKA Memo 17, 2002.

FAST design is described in SKASUP6-29.[34] The LAR approach is described in SKASUP6-28.[35]

The US Technology Development Program (TDP) , funded in October 2007, formed an Antenna Working Group (AWG) to coordinate dish development (see Sect. 6.4.5). Although their funding proposal[36] was broader, the main emphasis was to pursue the LNSD design philosophy.

The 10-m dish diameter in the Reference Design was a compromise. US participants favoured 6.5-m dishes like those of the in the Allen Telescope Array (ATA), based on the idea that small dishes inherently have wide fields-of-view and high survey speed, a key science goal (Sect. 6.4.3.1). On the other hand, there was concern for the computing costs of wide-field imaging. Computing costs were thought to scale as $d^{-8}$, where d is the dish diameter.[37] Nevertheless, it did not prevent proposals for even smaller dishes, but only if intermediate beamforming were used to mitigate the computing cost[38] (Sect. 6.6.5).

#### 6.2.1.4 Goal Posts for the Future: Memo 100

Between the dissemination of the Reference Design in January 2006 and March 2007, the ISSC had assembled an 'options tiger team', chaired by Schilizzi, to deliver an options report,[39] building on the Reference Design, in which many design aspects were deliberately left open. The team identified five options, combinations of technologies to cover fundamental capabilities, such as frequency range, sensitivity, field-of-view (FoV), and transients. Despite stating that "FoV expansion technology (aperture arrays (AAs), PAFs, and multi-cluster feeds) . . . will be incorporated in the SKA design if and when it proves feasible", all the options contained these technologies, although AAs were included only as a transient monitor. It was also stated that no additional R&D was needed for the 100–300 MHz range, because this would be developed in the context of LOFAR, MWA or the LWA. Finally, it was noted that if dish cost or technology limited frequency coverage to less than 25 GHz, a second dish array would be required.

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[34] See hba.skao.int/SKASUP6-29—The Five-hundred-meter Aperture Spherical radio Telescope (FAST).

[35] See hba.skao.int/SKASUP6-28—The Large Adaptive Reflector (LAR).

[36] hba.skao.int/SKAHB-230 *The U.S. Technology Development Project for the SKA: Revised Work Plan,* Cordes, J. M., et al., Submission to the National Science Foundation for The U.S. SKA Consortium, 30 January 2007.

[37] hba.skao.int/SKAMEM-49 *SKA and EVLA computing costs for wide field imaging (Revised),* Cornwell, T. J., SKA Memo 49, June 2004.

[38] hba.skao.int/SKAMEM-61 *LNSD reconsidered—the Big Gulp option,* Cornwell, T. J., SKA Memo 61, July 2005.

[39] hba.skao.int/SKAHB-149 *Engineering decisions for the SKA 2007–2014, Schilizzi*, R. T., et al., Options Tiger Team Report, 19 March 2007.

Phasing the telescope construction was strongly emphasised, with the proviso stated in the options report, SKA Phase 1 “must perform as a science instrument in its own right and form a coherent steppingstone to the full SKA”. A timeline was included in the options report: SKA Phase 1 was to begin construction in 2012 and to take about 3 years. In March 2007, the ISSC formally adopted a resolution endorsing a phased implementation.[40]

As the phased approach was formally agreed and in light of the upcoming European ASTRONET Roadmap and US Decadal Review (see Fig. 6.1 and Table 6.1), it was decided that a formal set of revised specifications was needed, leading to a baseline implementation. A ‘specifications tiger team’[41] was assembled to provide these and a clearly defined route forward through SKA parameter space. The outcome was SKA Memo 100, “Preliminary Specifications for the Square Kilometre Array”.[42]

Cost issues were much more prominent now. Indeed, some of the innovations put forward were directed at reducing the cost of collecting area (e.g., mould-based reflectors (Sect. 6.4.4.2) and Preloaded Parabolic Reflectors (Sect. 6.4.4.3)), but these needed significant up-front funding and development time before costs could be estimated with reasonable accuracy (see point {C} in Chap. 6 introduction). The tiger team was cognisant of opposing considerations: nailing down SKA specifications and cost, while not dampening the optimism in the engineering community needed to continue working on the various concepts (see point {A} in Chap. 6 introduction).

Memo 100 was such a major step that it had to be independently reviewed. The SKA Specifications Review Committee (SSRC), chaired by Roy Booth (Onsala Space Observatory, Chalmers University of Technology), was formed, and forthwith issued its report.[43] Although the SSRC outlined many challenges to be met, PAFs and AAs were considered sufficiently mature and important enablers of high survey speed. A major recommendation was “. . . we suggest that the SKA project should have stronger interfaces with the pathfinder projects, and that many uncertainties may be alleviated through the actual use of the pathfinders like LOFAR and the EVLA.”.

A record of tiger team discussions[44] on the SSRC report provides a more concise view of their recommendations than the report, itself, and provides additional insight

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[40] hba.skao.int/SKAHB-151 *Phased implementation of the SKA,* International SKA Steering Committee, ISSC17 resolution, March 2007.

[41] Members were Paul Alexander, Jim Cordes, Peter Dewdney, Ron Ekers, Andy Faulkner, Bryan Gaensler, Peter Hall, Justin Jonas, Ken Kellermann, and Richard Schilizzi (chair).

[42] hba.skao.int/SKAMEM-100 *Preliminary Specifications for the Square Kilometre Array,* Schilizzi, R. T., et al., SKA Memo 100, December 2007.

[43] hba.skao.int/SKAHB-245 *Report of the SKA Specifications Review Committee,* Booth, R., et al., report commissioned by the ISSC, 30 January 2008.

[44] hba.skao.int/SKAHB-250 *Compendium of Tiger Team comments on SSRC Report,* Schilizzi, R. T., et al., Tiger Team internal discussions on the SKA Specifications Review Committee (SSRC) report, 26 March 2008.

into the collective thinking about future directions for the SKA. The SPDO, the US Technology Development Program (TDP) and others emphasised that they were already linking their activities with the pathfinder projects. However, in subsequent years the record was quite spotty in this regard for many different reasons: political, personalities and competition for resources (see point {E} in Chap. 6 introduction) (see also Sect. 4.5.2).

Without a doubt, Memo 100 is one of the most important documents in the history of SKA development. It summarised top-level science goals, laid out key technical specifications required to achieve each category of science, covered potential technologies available to enable the specifications, considered cost implications, and outlined the construction phases and anticipated a construction timeline. This was the first time that all of this was available in one place, a detailed elucidation of the SKA dream. Although many of the details turned out to be far too optimistic, the science goals and the general approach remain as the SKA is being constructed.

#### 6.2.1.5 The SKA Precursors: ASKAP, MeerKAT, MWA[45]

The Australian SKA Pathfinder (ASKAP, see Fig. 4.2 and Fig. 6.10) began gradually with early interest in phased array feeds (PAFs) for dishes. The story of PAFs is told from various perspectives in this book: Sect. 6.2.2.5 for the impact on SKA development, Sect. 6.4.4.1 for antenna design and Sect. 4.3.3.1 for ASKAP, itself.

MeerKAT (see Fig. 4.4) also began gradually, with early experiments on dish fabrication from composite materials, which is described in Sect. 6.4.4.2.2. Its impact on SKA development was different in character from ASKAP and is described in Sect. 6.2.2.5.

The Low Frequency Array (LOFAR) began as a named project in 2000 with a paper by Jaap Bregman (ASTRON) (Bregman, 2000), although development had already begun in 1998 (van Haarlem et al., 2013) (see Sect. 3.2.6.1). The Murchison Widefield Array (MWA, see Sect. 4.3.3.1) arose in about 2004 because of a split among the original promoters of LOFAR about its location. The radio astronomy group at MIT/Haystack led the initial design of the MWA (Lonsdale et al., 2000) (see also Sect. 6.5.3).

By 2006, sufficient progress on low-frequency arrays was made that further development specifically for the SKA was not considered important (i.e., in the context of the Reference Design or Memo 100 (Sects. 6.2.1.3 and 6.2.1.4)). It was also thought that design choices, which might have been controversial, were not needed.

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[45] hba.skao.int/SKAHB-153 *SKA Newsletters Notes,* Dewdney, P. E., Informal Notes, 30 April 2008.

#### 6.2.1.6 Aperture Array Development Programs for the SKA: SKADS and AAVP

After several years of planning, the SKA Design Study (SKADS) was funded for 4 years in July 2005 through the European Commission's Sixth Framework Program (FP6) for research, technological development and demonstration (see Sect. 3.3.3.4) and from national sources. As outlined in Chap. 4, the EC funding had a major unifying effect among the European SKA participants, and through wide international participation, provided significant momentum for the whole SKA project and significant technical training opportunities for young researchers. An outline of the technical progress made in the SKADS program is contained in Sect. 6.5.5.2.

It was clear in November 2009[46] that many challenges remained before dense AAs could be adopted for the SKA. Hence, development continued beyond SKADS, as dense AAs became the focus of the Aperture Array Verification Program (AAVP) (coordinated by ASTRON and funded partly by a consortium of mainly European institutions plus ICRAR in Australia and partly by the PrepSKA program[47]). Discussions of the plans to establish the AAVP as a formal collaboration independent of, but associated with, PrepSKA were already being held at the SPDO offices in Manchester in 2008.[48] Work formally began at a meeting in Zaandam in March 2010,[49] shortly after SKADS funding ceased.

### *6.2.2 2008–2012: The SPDO Period*

PrepSKA funding was a step change in the SKA project. It provided a serious level of funding on the basis that a buildable design would emerge at the end of three years (later extended to four). Although challenging, science goals were clear and impressive enough to attract the attention of the astronomy world and funding agencies. As already described, engineering and technical progress had been developing in associated institutions globally and had already attracted considerable funding in Europe. The enthusiastic flavour of all this is captured in the January 2008 SKA newsletter.[50]

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[46] hba.skao.int/SKAHB-343 AAVP*: The Next Step after SKADS, van* Ardenne, A., Proceedings of Science (https://pos.sissa.it/132/), SKADS Conf. Wide Field Science and Technology for the Square Kilometre Array (eds. Torchinsky, S. A., et al.), Château de Limelette, Belgium, 04 November 2009.

[47] hba.skao.int/SKAHB-350 Aperture *Array Verification Program (AAVP) Collaboration Agreement document outlining* an agreement to participate in the AAVP program, 04 March 2010.

[48] hba.skao.int/SKAHB-339 AAVP *Structure and Timeline: Discussion at the SPDO,* Faulkner, A. J., presentation at the SPDO, 23 October 2008.

[49] hba.skao.int/SKAHB-351 Kick *Off Meeting AAVP—AgendaAAVP document,* 10 March 2010.

[50] hba.skao.int/SKANEWS-13 *SKA Newsletter* Vol. 13, January 2008.

Now came the hard part, putting together a comprehensive design from everything that had gone before. Previous development progress led to expectations by individuals and institutions that what they had put forward would be integrated into the SKA system design. This integrative approach was embodied in the primary technical work package description in the PrepSKA proposal, Work Package 2 (WP2).

While this was an interesting principle, it turned out to be impossible, especially at the expected scale of the project. To develop a buildable design in four years, decisions and technology selections had to be made. Ideally, decisions would have been made at the engineering level because only at that level can feasibility and cost be properly assessed. In reality, engineering decisions are based on the balance of probabilities because not all information is available, and schedule pressures demand answers. For a project the size of the SKA in which none of the participants had direct experience, a conservative approach would have been warranted, but an overly conservative design would not have yielded the scientific advances required. This created constant tension in design discussions. Although common in many projects, this is a salient feature of complex projects (see point {E} in Chap. 6 introduction).

This section contains the story of the SKA Program Development Office (SPDO) from the engineering perspective, and how the architectural design of SKA Phase1 was finally brought together. The story has many threads, the most important of which concerned the technologies that were finally adopted for the design of SKA Phase 1, dishes and low-frequency aperture arrays. Significant innovations in dish designs were tried and discarded but the project did settle on a design that had not been used previously in radio astronomy.[51] Similarly, ambitious initial plans for aperture array technologies were pared down drastically but did retain new design aspects. The sagas that led to these results are told in Sects. 6.4 and 6.5.

The project managed to stay together despite clashing ambitions and heartbreaking decisions that had to be made to reach a practical, affordable design.[52] Given the global nature of the collaboration, major PrepSKA WP2 meetings were crucial. They were the glue that facilitated communication and mutual understanding among those working at the technical level.[53]

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[51] Plans in 2004 for the Allen Telescope Array (ATA) included small antennas with offset-Gregorian antennas, which had not previously been used. Afterwards, the SKA chose the same optical design for a much larger antenna. The MeerKAT project also adopted this design at a similar time.

[52] The only major participant to withdraw was the USA.

[53] Major WP2 Meetings: Manchester, November 2008. Manchester, October 2009. Oxford, October 2010. Manchester, October 2011. Typical attendance was 100 scientists and engineers.

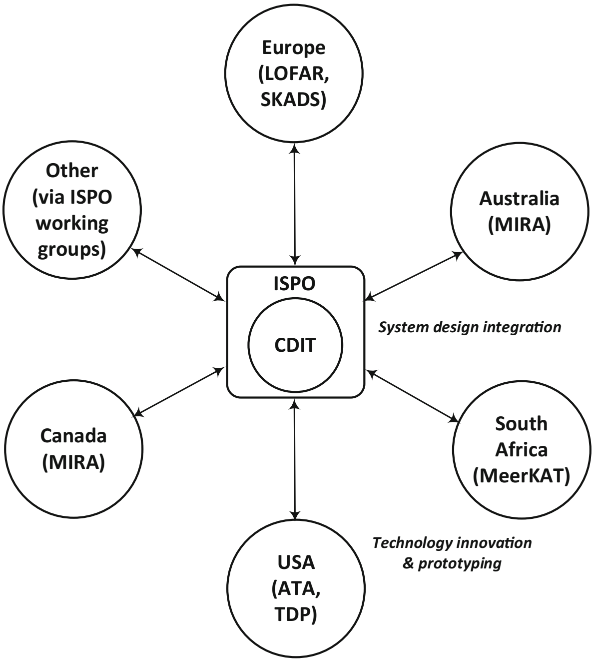

**Fig. 6.2** A schematic diagram showing the central role to be played by the ISPO-CDIT in taking the technology innovation and prototyping carried out by the design studies like SKADS in Europe and TDP in the USA and the pathfinder telescopes (ATA, EVLA, e-MERLIN, LOFAR, APERTIF, MeerKAT, and MIRA) to an integrated end design for the SKA (SKADS: SKA Design Study, TDP: Technology Development Project (USA), ATA: Allen Telescope Array, EVLA: Expanded Very Large Array, e-MERLIN: enhanced Multi-Element Radio Linked Interferometer Network, LOFAR: LOw Frequency ARray, APERTIF: APERture Tile In Focus (an upgrade of the Westerbork Synthesis Radio Telescope), MeerKAT: enhanced Karoo Array Telescope, and MIRA: Mileura International Radio Array). Credit: Peter Hall

#### 6.2.2.1 Inherited Directions from the ISPO and Grasping New Challenges

In 2007, the view on engineering and technology expressed in the PrepSKA proposal[54] was that "a Central Design Integration Team (CDIT) will be formed, . . . This team will have as its primary task the goal of integrating all the diverse strands of technology development from around the around the world to produce a detailed and fully costed design for Phase 1 of the SKA, and to develop a deployment plan for the full SKA." The approach was perfectly illustrated in Fig. 6.2 from the proposal and Memo 100.

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[54] hba.skao.int/SKAHB-152 *A Preparatory Phase proposal for the Square Kilometre Array (PrepSKA),* Diamond, P. et al., Proposal to 7th Framework Program for Research Infrastructure of the European Commission, 02 May 2007.

There was already a Reference Design (Sect. 6.2.1.3) and top-level specifications in Memo 100 (Sect. 6.2.1.4). Also, large-scale design studies[55] were in train or being planned, and numerous pathfinder and precursor telescopes[56] were committed to providing design information to the project. This was a good base from which to begin.

Specific objectives of WP2 were to produce (see also Chap. 4, hba.skao.int/SKASUP4-4):

(a) A costed top-level design for the SKA, and a detailed system design for SKA Phase 1,
(b) Advanced prototype SKA sub-systems specified as part of (a), the sub-systems to be based on technology development in the current regional pathfinders and design studies,
(c) Base receptor technologies for SKA Phase 1 and critical wide field-of-view design technology extensions,
(d) An Initial Verification System (IVS) which rolled together the most advanced SKA Phase 1 technology components and demonstrated the functionality, cost effectiveness and manufacturability of the adopted SKA Phase 1 design.

Although this was a very wide scope, PrepSKA managed to accomplish a significant fraction of these objectives. But towards the end of the PrepSKA period, it became clear that another phase of work (SKA Pre-construction) would be needed before readiness for construction could be demonstrated.

#### 6.2.2.2 Engineering Management: Changes in Direction

While the PrepSKA proposal clearly laid out the top-level organisation of work packages, including a breakdown of PrepSKA WP2 into smaller ‘programs’ (see Fig. 5.23), the first job of the SPDO was to analyse them and provide a plan for actually delivering a costed design using the available resources. As explained above, the general approach emphasised integrating all the diverse strands of technology development from around the world into a telescope design.

Over the ensuing months after the new Project Engineer, Peter Dewdney, joined the SPDO in April 2008, analysis revealed practical difficulties in managing the integration process described in the PrepSKA proposal. The root issue was that the SKA participants had long agreed on ambitious scientific goals and had each been

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[55] SKADS (Europe) (see Sect. 6.5.5.2) and the TDP (USA) (see Sect. 6.2.1.3).

[56] By definition, Precursors were on prospective sites, while Pathfinders were off-site projects of significance to the SKA. Precursors were ASKAP (Australia) and MeerKAT (South Africa). Pathfinders were LOFAR (The Netherlands), ATA (USA), MWA (Australia), LWA (USA), EVLA (USA), APERTIF (The Netherlands), eMERLIN (UK), MIRA (Australia, Canada).

**Fig. 6.3** An illustration of the complexity of stitching together devices which were developed with disparate interfaces and standards. Credit John T. McFarland

working on new technology solutions to enable them at modest cost.[57] But just integrating them into a coherent system was clearly going to be impossible without making some changes in the approach at the top engineering level.

While the previous 'integrative approach' never reached extremes, the greatest fear was that everything would be cobbled together with substantially different approaches to engineering and bespoke interfaces. This is epitomised in Fig. 6.3, used at the time to illustrate the point, for example in October 2010.[58]

The answer was to adopt a more formal system-engineering structure that would stand the test of time, enforce documented/verified decision-making and reviewed milestones, and provide a structure that could accommodate the scale of the SKA project. This last item was especially important because no one in the radio astronomy community had real experience with projects of this scale and access to this sort of expertise was limited. Scale changes everything!

This was the SKA response to two of the issues raised in the chapter introduction (see points {J} {K} in Chap. 6 introduction): *The need to deliver* and *Project*

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[57] Cohesion of technologies had partly set in with the agreement in 2006 on the Reference Design based on the Large-Number—Small-Dish (LNSD) concept, but much was left open (see Sect. 6.2.1.3).

[58] hba.skao.int/SKAHB-189 *Refining the DRM & Deriving Technical Requirements,* Dewdney, P. E., presentation to WP2_delta Design Review, 27 October 2010.

*Management and System Engineering*. To avoid the tunnel-vision effect noted in {K}, it was important to avoid an overly restrictive form of project management. Several promising innovative, but high-risk, approaches were kept on board, but subject to standardised reviews.

A key aspect of the system-engineering approach was deriving technical requirements from science requirements, which is covered in Sect. 6.2.2.7. While previously this had been done informally in SKA Memo 100 (see Sect. 6.2.1.4) and other places, a more precise approach was needed. Formal experience with system engineering existed in the South African engineering community and had been employed in the design and construction of the South African Large Telescope (SALT), an optical telescope. With South Africa being an active partner in SKA development and vying for the SKA site, there was a ready-made opportunity to exploit their experience. It was therefore not surprising that the SPDO System Engineer appointed in 2008, Kobus Cloete (SKA South Africa), came from South Africa.

The SKA project certainly followed the definition of complex project as defined by Sanders,[59] so complex that its prospects were considered extremely uncertain. This was all the more reason to adopt a more rigorous approach where possible.

Thinking theoretically along system engineering lines was a long way from convincing the participating institutions to follow the approach or to develop a detailed plan. An analysis of the tasks and how each participating institution was planning to contribute led in November 2008 to the Guiding Principles document.[60] The analysis breakdown is illustrated in the figure in SKASUP6-1,[61] in which all 40 tasks were organised into Programs (P1–P10), and each task was managed by a Lead Institution, leading as many as nine contributing institutions for a given task.

Some important observations as quoted from the Guiding Principles document were:

> "The work involved is complex for four reasons:
>
> 1. The project contains research elements and unknowns and is not like any projects that the contributors have carried out before.
> 2. There is a highly fragmented network of contributors, even to the individual task level.
> 3. The locations of the contributors are globally dispersed.
> 4. The resources of the SPDO are insufficient to take up any slack left by the contributors."

> "It is obvious by inspection of the task grid[62] that while the tasks are challenging in themselves, the project is additionally complex because of the number and diversity of contributors. In some cases, there are so many institutions involved in some tasks (e.g., Tasks P9T5 and P9T6, which each contain ten contributors) that communication may involve more effort than the work."

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[59] hba.skao.int/SKAHB-143 Complex *Projects,* Sanders, G., presentation at the Project Science Workshop, 19 January 2002.

[60] hba.skao.int/SKAHB-155 *Guiding Principles, Activities and Targets for PrepSKA Work Package 2, Dewdney*, P., SKA Project Office Report, 02 November 2008.

[61] hba.skao.int/SKASUP6-1—WP2 Description of Work as a Matrix of Tasks and Programs.

[62] hba.skao.int/SKASUP6-1—WP2 Description of Work as a Matrix of Tasks and Programs.

The complexity of the network of contributing institutions was brought about because most of the institutes had some expertise over a broad range of skills and wanted the chance to contribute, but also to get as large a slice of the project as possible. Also, the SPDO was new in 2008 and needed time to gain the trust of experts in the contributing institutes. Each thought that they should be involved in almost everything. Clearly this is also a hallmark of a complex project (see point {E} in Chap. 6 introduction).

Some of the complexity was foreseen in the original PrepSKA proposal, which suggested the appointment of Liaison Engineers in the institutes (see SKASUP6-2). They would have been required in any sensible organisation with many contributing organisations but were also helpful in mitigating the obvious management complexity described above. In the Guiding Principles document, they were described as "senior engineering managers, part of normal management structure—not necessarily experts in the technologies associated with each task, but sufficiently knowledgeable to understand and support multiple tasks if required."

As described in Sects. 3.3.1.3 and 4.4.2.1, the previous engineering working group (EWG/IEMG) continued during the PrepSKA period, alongside other working groups (e.g., Science WG, Site Characterisation WG, Simulation WG, Operations WG, Outreach WG), each with its own chair.[63]

The Guiding Principles document and a draft Project Management Plan were in place for the PrepSKA WP2 Kick-Off Meeting held in Manchester in November 2008.[64,65,66] This was an optimistic time for the project. Individual participants were pleased that their home institutions were supporting the project and that most would be able to continue their own participation. An initial plan had been circulated from the SPDO, so that most participants had a good idea of their roles. SPDO had hired a project engineer, a nearly complete complement of domain specialists, a project scientist, a system engineer, and a site engineer. In addition, the Project Scientist had already introduced the first cut at the development of science requirements.[67] Nevertheless, participants had doubts about the change to a system engineering approach, doubts which persisted for a long time afterwards and never really went away. Final development of revised work plan[68] took another year to be finalised, an indication of the length of time needed to change direction.

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[63] hba.skao.int/SKASUP6-2—SPDO staff members, Liaison Engineers, and Working Group Chairs.

[64] hba.skao.int/SKAHB-158 *PrepSKA WP2 Kick-off meeting,* Schilizzi, R. T., presentation at the PrepSKA WP2 Kick-Off Meeting, 10 November 2008.

[65] hba.skao.int/SKAHB-155 *Guiding Principles, Activities and Targets for PrepSKA Work Package 2*, Dewdney, P., SKA Project Office Report, 02 November 2008.

[66] hba.skao.int/SKAHB-160 *A System Approach to Designing the SKA,* Cloete, K., presentation at the PrepSKA WP2 Kick-Off Meeting, 10 November 2008.

[67] hba.skao.int/SKAHB-159 *SKA Reference Science Mission,* Lazio, J., presentation at the PrepSKA WP2 Kick-Off Meeting, 10 November 2008.

[68] hba.skao.int/SKAHB-168 *Revised Approach to the WP2 Work Plan and Timeline,* Dewdney, P. and Cloete, K., SKA Project Office Report, 08 October 2009.

#### 6.2.2.3 International Engineering Advisory Committee (IEAC)

The need for an engineering advisory committee had already been realised and its terms of reference for the IEAC were first drafted for the ISSC meeting in Guiyang (2005) and subsequently revised.[69] Its purpose was to provide the ISSC (subsequently the SSEC) with external expert advice on SKA technical progress by annually reviewing past engineering progress, and near and longer-term plans. Members[70] were selected to cover the technical breadth of the SKA. The IEAC was asked to review documentation provided by the SPDO, reports from design reviews, project management reports, presentations on up-coming technical issues, and reports from precursor and pathfinder projects.[71]

The report from the first meeting in April 2009 was prescient in many ways. Almost all the findings[72] continued to be issues throughout the PrepSKA period and beyond: for instance, very challenging timescales, efficiency in coordinating a globally distributed engineering project, and the need for consensus from the institutions and regional development groups on rules for PrepSKA decision-making. On the more technical side, obtaining acceptance of the proposed dish verification program (DVP), coupling between the design and the choice of site, a method for ranking the pathfinders for performance/cost ratios (emphasising sensitivity and controlling systematic errors), and isolating critical technology path(s), and figuring out how to proceed to SKA Phase 2.

The second meeting[73] (June 2010) was held after the System CoDR (see Sect. 6.2.2.9). Although they endorsed the SKA Phase 1 concept definition following the CoDR, they noted that a System delta-CoDR would be required and strongly recommended that “any further changes to (the) concept definition be made on the advice of the SPDO, after due analysis of performance—cost considerations and other engineering issues.”

The third meeting[74] (June 2011) noted additional progress, especially in executing several sub-system CoDRs, areas of new governance structure, selection of a

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[69] hba.skao.int/SKAHB-424 *Terms of Reference: International Engineering Advisory Committee (IEAC)*, SPDO, SPDO paper for the SSEC, 05 November 2008.

[70] IEAC membership: Alan Rogers (MIT) (chair), Tony Beasley (NRAO), Roy Booth (Hartebeesthoek Radio Obs.), Peter Hall (Curtin University), André Hoogstrate (Dutch Organisation for Applied Scientific Research (TNO)), Peter Napier (NRAO), Marco de Vos (ASTRON), Wolfgang von Rueden (CERN). Peter Napier replaced Alan Rogers as chair, and Jaap Baars (Arcor, Germany) and Noriyuki Kawaguchi (NAO) replaced Rogers and Booth at the second meeting.

[71] This volume of information was more than could be handled by the members and resulted in expressions of concern by some members that the IEAC could not properly fulfill this role.

[72] hba.skao.int/SKAHB-274 *International Engineering Advisory Committee Report*, Rogers, A., et al., SKA Document, 30 September 2009.

[73] hba.skao.int/SKAHB-286 *Report of the SKA International Engineering Advisory Committee*, Napier, P., et al., SKA Document, 30 June 2010.

[74] hba.skao.int/SKAHB-292 *Report of the SKA International Engineering Advisory Committee*, Napier, P., et al., SKA Document, 14 June 2011.

new headquarters location, site selection progress and the review of the Project Execution Plan (PEP))[75] (see Sect. 6.2.2.14).

This committee, now the SKA Engineering Advisory Committee (SEAC), continues with a similar mandate at the time of writing.

#### 6.2.2.4 Recruitment and Staffing the SPDO

There was great concern among some participating institutions that recruitment at the SPDO would rob them of their best talent, hobbling their other activities and rendering them less competitive in promoting their favourite technology. In other cases, they were simply concerned about growing requests for funds over which they might have little control. The directors of these institutions and some of the funding agencies represented in the FAWG and later the ASG[76] made it clear that the SPDO had to be a small group who could design a system from what they had to offer.

Although this could have been a disaster, it did not turn out that way. There were some advantages to recruiting people from outside the radio-astronomy field, who had experience in large, international projects (e.g., potentially from large companies) to balance those from the relatively small numbers of people in the field globally. In other words, it was difficult (or unrealistic) to find persons with long experience in radio astronomy technology who also had large project experience. Some existed but were not available because they were well established elsewhere or for other reasons.

The terms of employment were a big impediment. Applicants had to move to Manchester[77] for a job with only a four-year term, and if the project could not continue, and if they were not EU citizens, they would have to leave the UK.

In the end, most came from the UK and the others from the participating countries. The result was a staff complement with a mixture of backgrounds, and several without strong connections to radio astronomy. It was gratifying to be able to find people who believed that scientific progress also meant taking risks with their careers. SKASUP6-2[78] contains a list of SPDO staff from 2008 to 2012 (see also Fig. 4.6).

Another problem was simply one of numbers. The complex nature of the SKA project (see Sect. 6.2.2.2 and Sect. 11.3.2) required a larger staff complement to manage and coordinate activities than could be funded at the central office. Secondment from participating organisations was an alternative but this did not

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[75] hba.skao.int/SKAHB-192 *Project Execution Plan: Pre-Construction Phase for the Square Kilometre Array (SKA)*, Schilizzi, R. T., et al., SKA Document MGT-001.005.005-MP-001, 17 January 2011.

[76] "Funding Agencies Working Group" and "Agencies SKA Group", respectively.

[77] This was relaxed to some extent in some cases.

[78] hba.skao.int/SKASUP6-2—SPDO staff members, Liaison Engineers, and Working Group Chairs.

materialise to any substantial extent. Although the Liaison Engineer solution did help, it was not sufficient to manage the project effectively. Liaison engineers, themselves, had 'day jobs' in their home institutes and were not always able to spend the required time on the SKA.

Nevertheless, with a few bumps in the road and some muddling through, most of the SPDO staff continued to the end of PrepSKA and some went on in 2012 to the next stage in the SKA saga, the Pre-construction era. A sense of optimism (see point {A} in Chap. 6 introduction) and a belief in the project's vision, to build the world's largest radio telescope, carried them through (see Sects. 11.3.5 and 11.3.6).

#### 6.2.2.5 Other Challenges

*The impact of SKA Pathfinders and Precursors*[79]*:* These projects played a complex role in the SKA's engineering development with both positive and negative effects in the 2006–2012 period. On the positive side, the SKA provided motivation for the participating countries and organisations to develop their own expertise and projects in what was seen as an important field of astronomy. The development of expertise in particular had a lasting effect on the SKA's prospects at the end of PrepSKA, as it entered the pre-construction and construction phases.

On the other hand, in the participating countries, the most likely route to successfully raising national funds was to propose institute or national SKA-related projects, in addition to annual contributions to the SPDO operating costs.[80] National and institutional funds were then spent locally. With the consequent requirement to satisfy local deliverables, there was a tendency for national priorities to take precedence over the global project. From a central project office perspective, a less than positive side-effect was to utilise people and resources that otherwise could have been directed in a more-focussed way towards the global project itself.

Throughout PrepSKA, the (perceived winner-takes-all) competition for the SKA site created a hyper-competitive atmosphere in the project that had its effects on the large precursor projects, ASKAP and MeerKAT. Statements that carried an implication that a particular technology being developed in one or the other precursor might already be discounted or left out were very sensitive.

The large precursor telescopes (ASKAP and MeerKAT) impacted the SKA project in a similar way as noted above. But their motivations were completely different[81]:

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[79] By definition, Precursors were on prospective sites, while Pathfinders were off-site projects of significance to the SKA. Precursors were ASKAP (Australia) and MeerKAT (South Africa). Pathfinders were LOFAR (The Netherlands), ATA (USA), MWA (Australia), LWA (USA), EVLA (USA), APERTIF (The Netherlands), eMERLIN (UK), MIRA (Australia, Canada).

[80] See Sects. 4.3.3.1 and 4.3.3.2 for a recounting of the paths towards the Precursors, ASKAP and MeerKAT.

[81] National motivations are discussed in Ch 11.3.11.

- Australia had a long, storied history in radio astronomy going back to the beginning, having already built a suite of scientifically productive telescopes. Therefore, the motivation for ASKAP was to build on that past and to progress the field in a fundamental way. It was initiated as a vehicle for technology development and to showcase Australia's position as a world-leading supplier of innovative technology for radio astronomy and the SKA. But it later became a showpiece to highlight the Australian site and a fall-back if its site were not selected.
- South Africa heretofore had only a small role in radio astronomy, with one small telescope, used primarily for VLBI. But South Africa had selected astronomy as one of four science fields to emphasise[82] (see Sect. 3.3.3.7) and needed a project to show the world that South Africa could build a major radio telescope as more established countries had done in the past. Although not really a vehicle for technology development, they did this in spades, at the same time highlighting the deep reservoir of engineering talent in the country. As the site competition heated up, MeerKAT also provided a fall-back position for a role in radio astronomy, whatever the decision.

*Cultural Differences:* In general, different styles of work in different organisations, one of the aspects of a complex project, is inevitable but does make it difficult to design an integrated project (see point {E} in Chap. 6 introduction). Contrasts between the engineering and science cultures were evident between Australia and South Africa. Just as great were contrasts in approach between Europe and the USA. The European approach of consultation and compromise, to counter a legacy of centuries of war, was partly responsible for keeping the SKA project afloat through formative periods (see Chap. 4). In the USA, the more competitive and combative approach was partly responsible for its withdrawal from the project in 2011 (see Sect. 4.5.3). Both have their strengths and weaknesses, but in the case of the SKA, the European approach was far more productive.

*Communication and documentation:* Communication in a such large project, whose participants were spread over several time zones, was always going to be a challenge. The annual large engineering meetings (see Sect. 6.2.2) were critically important in maintaining contact among the community of engineers across the globe, but a year is a long time between updates in a four-year project.

One remedy for communication challenges was thought to be good written documentation that could be reviewed and passed back and forth among participants, ultimately becoming the only source of corporate memory. The SPDO developed

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[82] From Walker et al. (2019). "By 2002, astronomy was clearly positioned by the Department of Science and Technology (DST) as one of four fields of scientific research in which South Africa was seen to have a strongly competitive geographic advantage, the others being human palaeontology, biodiversity and Antarctic research."

detailed standards for documentation.[83,84] However, many of the institute laboratories were not used to writing project documentation, often resorting to Power Point presentations at meetings with little follow-up. Academic institutions are motivated by career progression and grant applications to produce peer-reviewed papers in journals. However, these usually take months to become available and are much less detailed than project documents. In the development stage of a project, it is important in documentation to relate what did not work, not just what worked.

In retrospect, the project's expectations were probably too high. Detailed documentation takes a great deal of work to produce. Despite these shortcomings, when it came to design reviews, the documentation produced for them provided a sufficient legacy to allow the project to track progress for several years and eventually to make sensible decisions.

*The Effect of US Withdrawal:* Scientists from a broad cross-section of US astronomy were leading participants in the SKA project until the 2010/11 era and played a key role in developing the technical definition of the SKA in its early stages and during the first part of the PrepSKA era.

When the report from the ASTRO2010 Decadal Survey of astronomy (Blandford et al., 2011) contained only mild support for US involvement in the SKA, the National Science Foundation (NSF) declined to participate further (see Sect. 4.5.3). Very high cost-estimates from the Aerospace Corporation (see Sect. 4.5.3.5), which have never been revealed in detail, also played a role. The consequence was that the deep reservoir of engineering and scientific talent in the USA was ultimately lost to the project.

As US astronomers were primarily interested in astronomy at the high end of the frequency range of the SKA, they concentrated mainly on defining SKA-Mid. The NSF-funded Technology Development Program (TDP) was the primary vehicle for supporting dish development. Its impact on dish development is discussed in detail in Sect. 6.4.5.1. The US expectation for the SKA was to build a third telescope in the USA for frequencies well above 10 GHz, which was then referred to as SKA Phase 3.

Although opening new discovery space (see point {B} in Chap. 6 introduction) (e.g., in the time domain) was not a major part of the SKA science case, it did play a role, denoted by Exploration of the Unknown (see Sect. 6.2.2.8). However, the US funding system is not receptive to this (see Sect. 4.5.3.4) and building flexibility into a design for the sake of enhancing discovery potential was not seen as a valid argument, as discussed in Sect. 4.5.3.4. Nevertheless, it was mainly US astronomers who promoted discovery space in the time domain.[85,86]

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[83] hba.skao.int/SKAHB-167 *PrepSKA WP2 and WP3 Documentation Standards, Handling and Control,* Cloete, K., SKA document MGT-040.010.010-MP-001-C, 02 April 2009.

[84] hba.skao.int/SKAHB-188 *Approach to SKA Documentation,* Dewdney, P. E., presentation to WP2_delta Design Review, 27 October 2010.

[85] hba.skao.int/SKAMEM-6 Radio Transients, Stellar End Products, and SETI Working Group Report, Lazio, J., et al., SKA Memo 6, 22 March 2002.

[86] hba.skao.int/SKAMEM-97 The *Square Kilometer Array as a Radio Synoptic Survey Telescope: Widefield Surveys for Transients, Pulsars and ETI, Cordes*, J., SKA Memo 97, 21 September 2007.

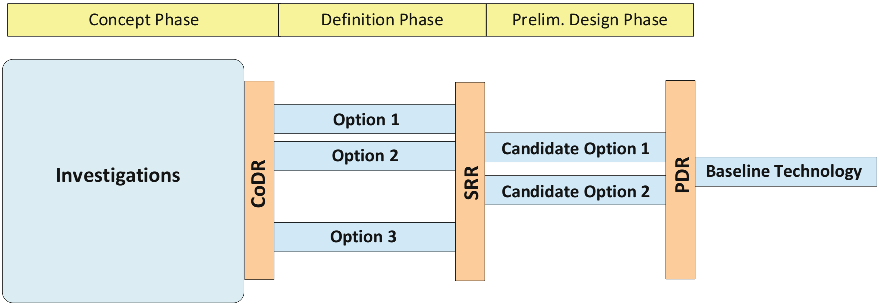

**Fig. 6.4** A schematic view of the reduction of potential technical options available, through a series of reviews

#### 6.2.2.6 Design Reviews

The PrepSKA design review process was not particularly new or innovative, but it was relatively new to radio astronomy projects. Design reviews are a formal process that brings together all the aspects of a project as it moves through various stages. For PrepSKA, this was spelled out in the System Engineering Management Plan.[87] Figure 6.4 is a simplified view of how technical options were to be narrowed down through a series of reviews. An initial set of system requirements were developed,[88] and plans were made for a System Requirements Review (SRR),[89] intended to ensure that requirements were well understood and suited to the project. Project review practice varies, but during PrepSKA most of the reviews were conducted at the Concept Design Review (CoDR) level. The PrepSKA review process required between 10 and 20 documents for each review.

Supplementary material[90] provides details on how the reviews were carried out.

#### 6.2.2.7 Developing Technical Requirements from Science Requirements

The work of the URSI Large Telescope Working Group (LTWG, see Sect. 3.2) in the 1990s was devoted to developing the initial science requirements for the SKA and discussing the technical specifications to deliver the science. In 2001, based on this work and other national efforts, Ron Ekers summarised the then current

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[87] hba.skao.int/SKAHB-169 *SKA System Engineering Management Plan,* Cloete, K., SKA Document WP2-005.010.030-MP-001, 20 January 2010.

[88] hba.skao.int/SKAHB-170 *SKA System Requirements Specification,* Cloete, K., SKA Document WP2-005.030.000-SRS-001, 12 February 2010.

[89] hba.skao.int/SKAHB-299 *Towards Phase 1 SRR,* Stevenson, T., presentation at the WP2 Engineering Meeting, Manchester, 17 October 2011.

[90] hba.skao.int/SKASUP6-3—SKA Design Reviews during the PrepSKA Era.

technical specifications for the SKA.[91] This was updated by Dayton Jones (Jet Propulsion Laboratory) in 2004[92] (see also Sect. 5.7).

One of the first orders of business for PrepSKA was to extend the work of Memo 100 (see Sect. 6.2.1.4) and produce more formal connections between the science goals of the SKA, and the technical requirements which embody the scope of the telescope design in top-level terms. This was easier said than done because for a general-purpose telescope like the SKA, the science is open-ended and diverse. This contrasts with some astronomy projects, typically space missions, which are designed to answer a small number of important, well formulated science questions and no more.

A school of thought circulating at the time was: "Why not just improve the capabilities of each generation of telescope along the 'fundamental performance axes': resolution, sensitivity, frequency coverage, time-domain resolution, field-of-view, polarisation and spectral coverage/resolution?" But which axes to choose was the question? A partial answer lay in the concept of the SKA in the first place, "Improve sensitivity by two orders of magnitude!". This was partly because in radio astronomy, very high-resolution imaging through Very Long Baseline Interferometry (VLBI) had already been achieved (see Sect. 2.3), demonstrating that it was possible to build telescopes with effective diameters up to near-Earth orbit, and routinely the diameter of the Earth. With the collecting area available there was only enough sensitivity to detect extremely bright non-thermal objects, principally quasars.

Still a debating point, another fundamental performance axis was frequency range. The early proponents of the SKA were mostly interested in decimetre wavelengths and longer. But the SKA also attracted a large contingent of potential observers that wanted centimetre wavelength coverage.

Naturally, cost and technical feasibility (see the green box in Fig. 6.5) constrained the design process. To obtain tangible information in these two areas, the key line in Fig. 6.5 is Case Studies. Scenarios were selected to capture the *upper performance envelop*e that would progress existing science in directions commensurate with SKA science goals. These provided the guidance needed to incorporate that capability into the design requirements (see SKASUP6-4[93] for further discussion). Cost models of the entire SKA system are also discussed in Sect. 6.4.6.

At a high level, SKA science had long been targeting Key Science Projects) (KSPs),[94] broad categories of science for which radio astronomy could deliver unique or complementary results to all of astronomy. Case studies were particularly

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[91] hba.skao.int/SKAMEM-4 SKA *Technical Specifications,* Ekers, R. D., SKA Memo 4, December 2001.

[92] hba.skao.int/SKAMEM-45 *SKA Science Requirements: Version 2, Jones*, D. L., SKA Memo 45, 26 February 2004.

[93] hba.skao.int/SKASUP6-4—Developing Technical Requirements from Science Requirements.

[94] These were (1) Probing the Dark Ages (2) Galaxy Evolution, Cosmology, & Dark Energy (3) Strong Field Tests of Gravity Using Pulsars and Black Holes (4) The Cradle of Life/Astrobiology. In addition, Exploration of the Unknown (see Chap. 5 and Sect. 6.2.2.8).

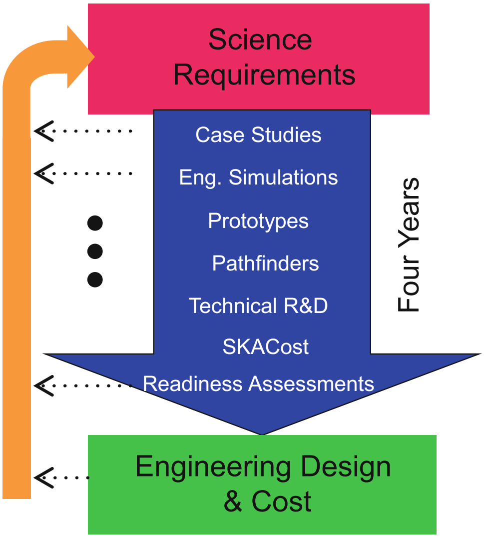

**Fig. 6.5** A diagram used in a presentation by Dewdney at the SKA Forum in Perth in 2008 (hba.skao.int/SKAHB-154 *The SKA—Opportunities & Challenges for Industry,* Dewdney, P. E., presentation at the SKA Forum in Perth, April 9 2008) to represent the approach to deriving a design from science requirements

important in these areas. This began with a draft set of such studies in 2008[95] and a presentation by Joe Lazio, the new SKA Project Scientist, at the PrepSKA kick-off meeting.[96]

This process cannot operate without feedback from the prospective observer community. The SPDO and the Science Working Group developed a Reference Science Mission (RSM) through 2009,[97] and in 2010 this document became the Design Reference Mission (DRM).[98]

Although the DRM provided guidance to the design, a simple flow-down of requirements to technology selections was not possible in 2010. The SKA project was not ready to permit a simple approach to selecting technologies for the design (i.e., establishing a design baseline). However, this was established in March 2011, a month after the System Concept Design Review (CoDR) (see Sects. 6.2.2.9 and 4.5.2).

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[95] hba.skao.int/SKAHB-157 *Use Case Strawman Science to Technical Requirements,* Dewdney, P. E. and Lazio, J., SKA Project Office Report, 05 November 2008.

[96] hba.skao.int/SKAHB-159 *SKA Reference Science Mission,* Lazio, J., presentation at the PrepSKA WP2 Kick-Off Meeting, 10 November 2008.

[97] hba.skao.int/SKAHB-163 *The Square Kilometre Array Reference Science Mission,* Lazio, J., et al. Report from the SKA Science Working Group, SKA Document, 05 January 2009.

[98] hba.skao.int/SKAHB-175 *The Square Kilometre Array Design Reference Mission (DRM): SKA-Mid and SKA-lo,* Lazio, J., et al., SKA Document V1.0, 02 February 2010.

In parallel with preparations for the System CoDR, a method to guide the selection of technologies was developed using an 'evaluation hierarchy' to evaluate potential SKA system implementations.[99,100] (See the second figure and the discussion in SKASUP6-4[101]).

#### 6.2.2.8 Exploration of the Unknown

A historically important goal of the SKA was "The Exploration of the Unknown". Most of the major discoveries in astronomy have been unexpected or accidental, relying on the perspicacity of observers and some luck. There is no design method that can uniquely capture this goal. Informed judgement plays a key role on whether to spend resources on a design aspect that could convey additional design flexibility or agility to widen discovery space (see point {B} in Chap. 6 introduction). An important early analysis of discovery space was described by Jim Cordes,[102] in which various aspects of discovery potential are discussed. In particular, he illustrated the size of the time-luminosity phase space covered by the relatively small number of known transient phenomena, about 20 orders of magnitude on each axis.

An important aspect of the SKA's approach to discovery space was to ensure continuous frequency coverage within the overall boundaries set by the major goals of the telescope. In the case of the Expanded Very Large Array (EVLA) for example, continuous coverage had a dramatic influence on the number and quality of new phenomena (discoveries) made after the VLA was equipped with receivers that covered its entire accessible frequency range.

A design aspect related to discovery space is ensuring continuous, smooth coverage of telescope sensitivity over its range of accessible scale sizes. During the development of the SKA array configurations, there was much discussion of this point (see Sect. 6.2.2.10). A related concept is spatial dynamic range, which is a measure of the range of scale-sizes on the sky that can be recovered from the observations. As an example, for some types of radio sources, a so-called wide-shallow survey of a large area of sky can yield more discoveries than a survey with higher sensitivity on a smaller area of sky, in the same amount of observing time.[103] All these aspects are ultimately linked to survey speed (see Sects. 6.4.1 and 6.5.1).

Historically, the design or operation of many telescopes have effectively discarded discovery space by, for example, using long integration times, imaging

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[99] hba.skao.int/SKAHB-176 *SKA Science-Technology Trade-Off Process,* Dewdney, P. E., SKA Document WP2-005.010.030-MP-004, 15 February 2010.

[100] hba.skao.int/SKAHB-182 *Observing Time Performance Factors in Carrying Out SKA Trade-offs,* Dewdney, P. E., SKA Document WP2-005.010.030-PR-001, 15 March 2010.

[101] hba.skao.int/SKASUP6-4—Developing Technical Requirements from Science Requirements.

[102] hba.skao.int/SKAMEM-85 *Discovery and Understanding with the SKA,* Cordes, J., SKA Memo 85, October 2006.

[103] hba.skao.int/SKAHB-205 *Pulsars and Transients*, Macquart, J.-P., presentation, AAVP Workshop, Dwingeloo, The Netherlands, 13 December 2011.

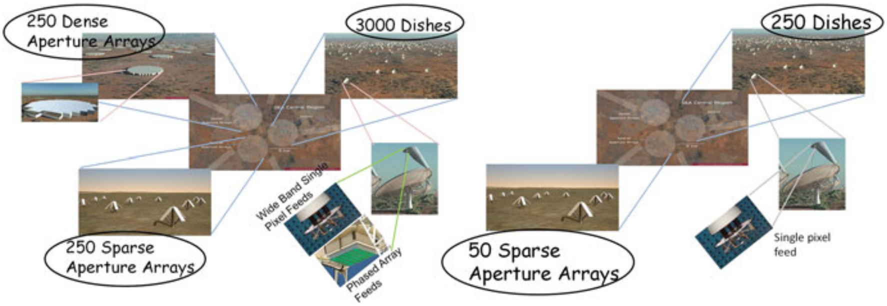

**Fig. 6.6** A compact system view of the SKA telescope. Left: The technologies associated with the SKA before the System CoDR. Right: The technologies associated with the SKA after the System CoDR and the definition of SKA Phase 1. Credit: The authors using material from Swinburne University of Technology, Melbourne, Australia

over a narrower field than the antenna beam or simplifying polarisation observations. The design of the SKA was intended to capture all the available information from the telescope so as to maximise discovery space. Further examples of this are given in SKASUP6-5.[104]

#### 6.2.2.9 The System Concept Design Review (February 2010)

A major transition during PrepSKA occurred because of the System Concept Design Review (CoDR). Up to that point, the only accepted view of the telescope design included ‘everything’. Figures 6.6 (left) and 6.7 (right) illustrate the scope of the issue.

In late 2009, frustration had been building at the SPDO (see Sect. 4.5.2). It was proving very difficult to select technologies, regardless of the rigour of the design process (see Sect. 6.2.2.7). Each of the national participants strongly believed that their approach to technology was the best. It was also evident that managing the project and completing its goals would likely be impossible without acceptance by the participants that choices had to be made to achieve the required focus.

It became obvious that the only way to proceed was to hold a review with senior independent experts on the Review Panel who had experience in similarly large (or larger projects), where technology had been selected.[105] Although this might

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[104] hba.skao.int/SKASUP6-5—Supplementary Material: Exploration of the Unknown.

[105] Wolfgang Wild (chair), ALMA, European Southern Observatory, Garching bei München, Germany; Jim Yeck, Icecube Neutrino Observatory, Madison, USA; John Webber, ALMA, National Radio Astronomy Observatory, Charlottesville, USA; Robin Sharpe, External advisor, Ex Philips Semiconductors, Winchester, UK; Lyndon Evans, Large Hadron Collider, CERN, Geneva, Switzerland.

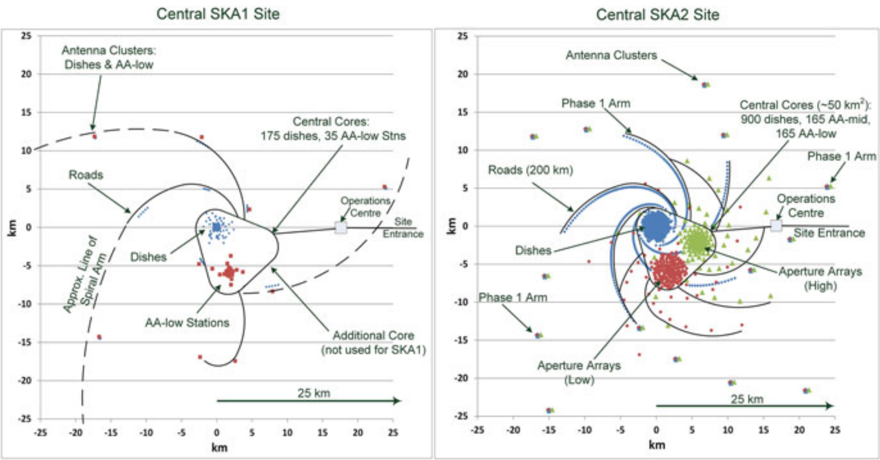

**Fig. 6.7** The proposed layout on the ground of the central part of the SKA site for the original SKA (right) and SKA Phase 1 (left). Note the presence of antenna clusters rather than single antennas

have put the project at risk of cancellation if the review went badly, it was felt that in the medium term the project was at risk anyway.

A three-day CoDR meeting was organised in mid-February 2010 around a review plan.[106] The review was based on a comprehensive set of documents, provided by the SPDO and national participants, which the latter had an opportunity to review before they went to the Review Panel.

The key documents were the Design Reference Mission,[107] the High-Level System Description,[108] the Science Operations Plan,[109] Strategy to Proceed to the Next Phase,[110] the Risk Register,[111] and the Risk Management Plan.[112] There was also a presentation on cost, but because of the uneven development states of the technologies involved, a definitive report on cost was difficult to produce.

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[106] hba.skao.int/SKAHB-180 *SKA System Concept Design Review Plan,* Cloete, K., SKA Document WP2-005.020.010-PLA-001, 23 February 2010.

[107] hba.skao.int/SKAHB-175 *The Square Kilometre Array Design Reference Mission (DRM): SKA-Mid and SKA-lo,* Lazio, J., et al., SKA Document V1.0, 02 February 2010.

[108] hba.skao.int/SKAHB-178 *High-Level SKA System Description,* Dewdney, P. E., et al., SKA Document WP2-005.030.010-TD-001, 15 February 2010.

[109] hba.skao.int/SKAHB-174 *The SKA Science and Technical Operations Plan,* Kellermann, K., et al., SKA Operations Working Group Report, WP2-001.010.010-PLA-001, 29 January 2010.

[110] hba.skao.int/SKAHB-177 *SKA Strategy to Proceed to the Next Phase,* Cloete, K., SKA Document WP2-005.010.030-PLA-001-D, 08 February 2010.

[111] hba.skao.int/SKAHB-179 *Risk Register,* SPDO, SKA Document MGT-090.010.010-RE-002, 15 February 2010.

[112] hba.skao.int/SKAHB-171 *Risk Management Plan,* Cloete, K., SKA Document MGT-040.040.000-MP-001, 03 August 2009.

As expected, the Review Panel found that the project was not ready to proceed. Among the key findings[113,114] were:

- SKA in its present setup tries to push technology limits on pretty much all fronts. Some parameters are pushed orders of magnitude beyond state-of-the-art. Even things that traditionally have been minor problems are now an issue (e.g., power, computing, signal transport and processing, etc.). Given current time and cost constraints the Review Panel felt that the combination of scope, timeline, and cost was in general overambitious and in several areas unrealistic.
- Given current timeframe and assumed funding constraints, the science covers too large a parameter space and includes requirements which imply differing optimal design decisions, . . . .
- The Review Panel did not see stable requirements which would allow a stable design for SKA.
- SKA is ready to move into the definition phase (Fig. 6.4). This transition is essential to support the proposed timeline for a construction start (with a redefined scope), to arrive at an SKA concept, and to ensure that additional resources are focused on activities that truly support the SKA schedule.

As explained in Sect. 4.5.2, the impact was immediate. In response,[115] the SKA Science and Engineering Committee (SSEC) convened a sub-committee to define the science goals and a concept technical baseline for SKA Phase 1 with the aim of stabilising the design requirements as soon as possible. In other words, detailed design work would proceed for SKA Phase 1 only. The sub-committee produced a brief, influential report, SKA Memo 125,[116] that set a new direction for the SKA. It refined the science goals, the technical baseline, and cost and schedule targets. It also established an Advanced Instrumentation Program (AIP), which provided a mechanism to continue to develop less mature technologies (Phased Array Feeds, Wideband Single Pixel Feeds and Aperture Arrays, see later sections in this chapter) in the expectation that they could be used in SKA Phase 2. The new approach was embodied in the Project Execution Plan (PEP))[117] generated in late 2010 (see Sect. 4.5.3.7). It retained the momentum of the project and the need to deliver (see point

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[113] hba.skao.int/SKAHB-181 *SKA System CoDR Panel Initial Feedback,* Wild, W., et al., presentation at the System CoDR Review, 26 February 2010.

[114] hba.skao.int/SKAHB-184 *SKA System CoDR_Panel_Review_Report,* Wild, W., et al., SKA Document, System CoDR Review Report, 19 March 2010.

[115] hba.skao.int/SKAHB-185 *SPDO Response to the Panel Report on the SKA System CoDR_Panel_Review,* SPDO staff, SKA Document System CoDR Review Response, 24 May 2010.

[116] hba.skao.int/SKAMEM-125 *A Concept Design for SKA Phase 1 (SKA1),* Garrett, M.A., et al., SKA Memo 125, August 2010.

[117] hba.skao.int/SKAHB-192 *Project Execution Plan: Pre-Construction Phase for the Square Kilometre Array (SKA),* Schilizzi, R. T., et al., SKA Document MGT-001.005.005-MP-001, 17 January 2011.

{J} in Chap. 6 introduction). The resulting system is depicted in Figs. 6.6 (right) and 6.7 (left).

The technical baseline consisted of low-frequency sparse aperture arrays and a dish-array of 15-m antennas equipped with single-pixel feeds. However, it did not entirely stick because, as a part of the site decision process in 2012 (see Sect. 8.6.3), an additional array of dishes with Phased Array Feeds (an AIP element) became included in the technical baseline until it was removed in 2015.

As a result of Memo 125, the SKA adopted mainly proven technology for the SKA Phase1 technical baseline. This was the moment which inspired the title of this chapter: "Innovation Meets Reality".

#### 6.2.2.10 Intertwined: Array Configuration, Infrastructure and Topology

Even after a suitable site has been identified, the design of a large telescope array like the SKA requires consideration of many interacting, practical factors. Antennas must be placed on solid ground where service access is available, where the sky is not blocked by local topology, and in the case of antennas far away from the core, where the climate is acceptably benign. Cost plays a significant role. In contrast, the ideal array configuration from the perspective of telescope performance is not likely to be compatible with these practical constraints, and a compromise must be reached. Figure 6.8 shows the many aspects considered in the design of the SKA array configuration.[118]

An array configuration based on a spiral pattern on the ground had been accepted as the best available basic configuration for the SKA, although previous major telescope arrays had used a Y-shaped configuration. SKASUP6-6[119] explains how the spiral configuration influences telescope performance and the factors used in assessing performance. One of the dominant factors in deciding on the configuration was the cost, which was in large measure dependent on the number of spiral arms and number of "stations" (assemblies of multiple antenna elements) along the arms.

A Configuration Task Force (CTF)[120] was set up by the SPDO in April 2008[121] to optimise the array configuration, including "matching the 'ideal' configuration to the

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[118] hba.skao.int/SKAHB-199 *SKA Configurations—Approach and Strategy,* Dewdney, P., presentation to the International Engineering Advisory Committee (IEAC) meeting, 13 June 2011.

[119] hba.skao.int/SKASUP6-6—The Influence of Array Configuration on Telescope Performance.

[120] hba.skao.int/SKAHB-165 *Site Characterisation Working Group SCWG—PrepSKA WP3*, Millenaar, R., presentation at the Configuration Task Force Kick-off Meeting, Manchester, 11 March 2009.

[121] The Site Characterisation Working Group (SCWG) was chaired by the Site Engineer, Rob Millenaar, under which the Configuration Task Force (CTF) was established. Members were Millenaar (chair), Rosie Bolton, Anna Scaife and Mattieu de Villiers.

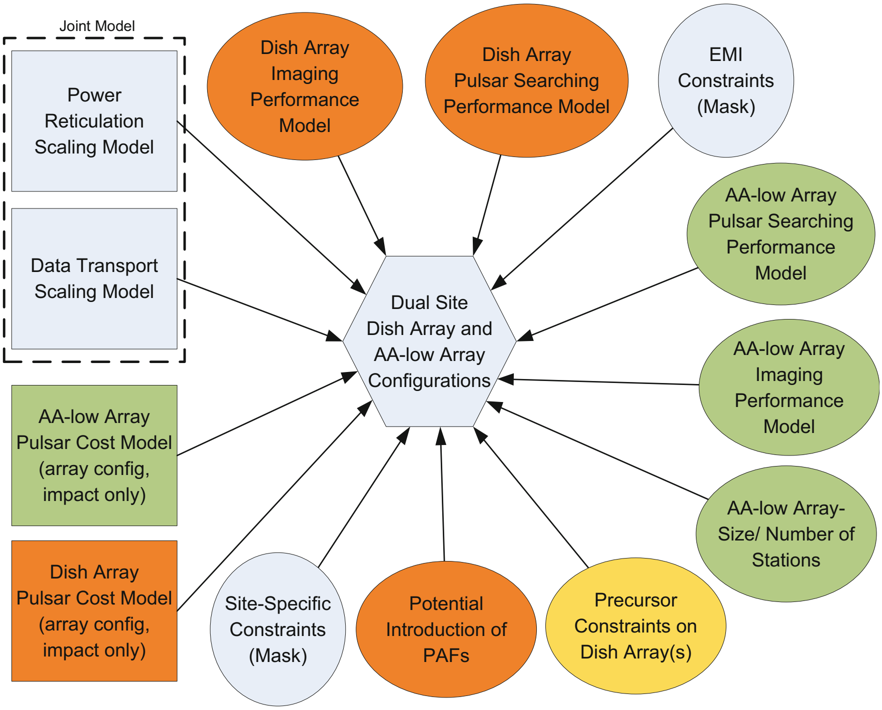

**Fig. 6.8** A context diagram showing all the influences and aspects of the design of the SKA array configuration

geographical realities of the two short-listed sites"[122] (see SKASUP6-6 and Sect. 8.4.4).

Once a spiral approach was adopted, there were not many avenues of optimisation of the spiral, itself: the number of arms, the wrap of arms, the spacing of antennas on the arms, and the fraction of antennas in the core. For example, once cost minimisation is considered, the number of arms is affected. Figure 6.7 (right) shows a five-arm spiral, which is better than a three-arm spiral, but costs more. But was a three-arm spiral good enough? This could only be judged against the science goals. A prominent cost-driven issue was whether antennas could be clustered on spiral arms, rather than spreading them out along the arms.[123] This would reduce servicing cost but produce redundant samples in the *u*-*v* plane, instead of providing more distinct samples.

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[122] hba.skao.int/SKAHB-183 *Site Characterisation Working Group Roadmap of Activities, 2010 and 2011, Millenaar*, R., SPDO Document, 18 March 2010.

[123] hba.skao.int/SKAHB-166 *Practical Determination of SKA Configuration,* Dewdney, P. E., presentation at the Configuration Kickoff Meeting, 12 March 2009.

Collaborating with the Science Working Group, the Simulation Working Group, and other members of the SPDO, the CTF adopted figures-of-merit (FoM), based on earlier work,[124] for evaluating the imaging capabilities of proposed configurations after they were subjected to some of the practical site constraints described above.[125] The SPDO also produced a model for the site selection process[126] in 2011–12, which contained considerable technical information on site requirements (see Sect. 8.3.7).

Once the dual site decision was made in 2012, the job of optimising the SKA array configurations became much easier, but this was not finalised until after 2012. A UK branch of the company, Parsons-Brinckerhoff,[127,128] with experience in large infrastructure projects was commissioned by the SPDO to assess the feasibility and cost of the proposed infrastructures on the two sites, based on the model configuration in the Request for Information document (see Sect. 8.3.7).

### 6.2.2.11 Site Power Provision

The cost of supplying electricity to a remote SKA site had been recognised from the beginning as an important factor in the SKA capital and operating costs. In February 2009 the SPDO set up a Power Investigation Task Force (PITF), co-chaired by Peter Hall (Australia) and Bernie Fanaroff (South Africa)[129] to assemble experts and understand the impact on power requirements of various possible telescope technologies.[130,131]

There was much discussion of ‘green energy’ for the SKA at the time, and various emerging industries were interested in providing both solar power arrays and battery storage. However, the SPDO was concerned that this could be a major distraction

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[124] hba.skao.int/SKAMEM-107 *Array configuration studies for the SKA—Implementation of Figures of Merit base on Spatial Dynamic Range,* Lal, D. V., et al., SKA Memo 107, December 2008.

[125] hba.skao.int/SKAHB-191 Figures *of Merit for SKA Configuration Analysis,* Millenaar, R. P. and Bolton, R. C., SKA Document WP3-050.020.000-TR-001, 07 December 2010.

[126] hba.skao.int/SKAHB-197 *Model of the SKA for Site Evaluation Purposes,* SPDO contributed to the SKA Siting Group (SSG), Annex to Request for Information from the Candidate SKA Sites, 31 May 2011.

[127] hba.skao.int/SKAHB-202 *Assessment of the Australia-New Zealand Submission—Basic Infrastructure,* Parsons Brinckerhoff, SKA Document, Parsons Brinckerhoff Consultancy Report, November 2011.

[128] hba.skao.int/SKAHB-203 *Assessment of the South Africa Submission—Basic Infrastructure,* Parsons Brinckerhoff, SKA Document, Parsons Brinckerhoff Consultancy Report, November 2011.

[129] hba.skao.int/SKAHB-164 *SKA Power Investigation Task Force: Opening Remarks,* Hall, P. J., SKA Document Agenda and key presentations, Cape Town, S.A., PITF meeting, 17 February 2009.

[130] hba.skao.int/SKAHB-172 *Power_Investigation_Task_Force_(PITF)_meeting,* SPDO, SKA Document Agenda and key presentations, PITF meeting, 23 October 2009.

[131] hba.skao.int/SKAHB-190 *Power System Design Issues: Demand Projections and Uncertainty,* Dewdney, P. E., presentation to the Power Investigation Task Force, 30 October 2010.

from the focus on the science and the design of the telescope, and these initiatives were not taken up at the time.

Radio Frequency Interference (RFI) from power systems had been a longstanding concern. In South Africa, where inexpensive power was available from the grid, the MeerKAT group developed methods for building low-emissions power lines.[132]

The potential cost of power distribution on the extended sites engendered discussion of clustering or clumping of dishes,[133] as well as generating power at remote sites instead of distributing it via power lines. Clustering was eventually taken up for the low frequency telescope in Australia, but not for the mid-frequency telescope in South Africa.

In September 2011, the SPDO took formal responsibility for interfacing with the power industry.[134] This work was then led by Phil Crosby, who was already the SPDO Industry Participation Manager.

The on-going cost of power in the operating phase might have been a major limiting factor on just how much sensitivity and angular resolution could have been afforded for the SKA, because providing power to distant antennas is very expensive if it is not available locally. But, at the time of writing, the SKA ‘power problem’ is gradually resolving itself as SKA Phase1 construction proceeds. The emergence of relatively low-cost solar power and rapid reductions in the cost of battery storage, have come to the rescue. Even in South Africa, where grid power has been unreliable for many years, locally produced solar power is likely to be competitive with grid power.

#### 6.2.2.12 Radio Frequency Interference and Mitigation

Radio frequency interference (RFI) from human-caused radio emissions has a strong negative impact on ground-based radio astronomy. Man-made radio emissions, the sources of RFI, have always been a driving factor in locating radio observatories on sites that are as remote as possible from population centres. Figure 6.9 is a dramatic illustration of the efficacy of locating radio telescopes in remote regions. Remoteness is clearly the first line of defence for a ground-based radio telescope.

While there are several other technical and scientific aspects to choosing a site for a new telescope (see discussion in Sects. 7.3 and 8.3.7), remoteness is a vital factor, which comes at a substantial cost for the construction of the observatory: infrastructure, operations staff, and electricity. The cost of establishing the SKA in remote

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[132] hba.skao.int/SKAHB-173 *An RFI Quiet Transmission Line,* Tiplady, A., presentation to the Power Investigation Task Force meeting, 23 October 2009.

[133] hba.skao.int/SKASUP6-6—The Influence of Array Configuration on Telescope Performance.

[134] hba.skao.int/SKAHB-201 *Advice to Wind Up the Power Investigation Task Force (PITF),* Hall, P. J. and Fanaroff, B., email exchange of messages between the SPDO and PITF chairs, 27 September 2011.

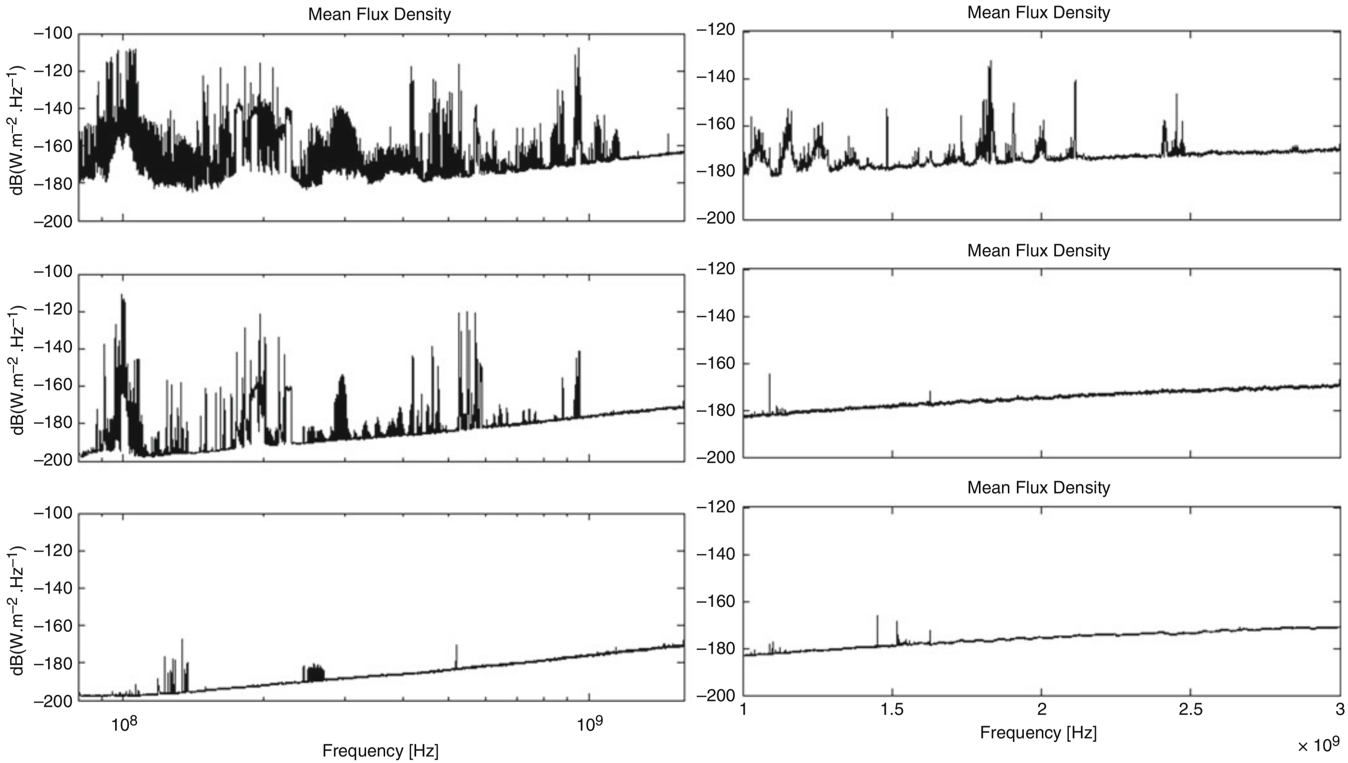

**Fig. 6.9** RFI emission spectrum measurements at three locations in Australia. Left: frequencies from 70 MHz to about 1800 MHz. Right: frequencies from 1000 to 3000 MHz. Note that the vertical scale is different in the left and right panels. Top: Sydney (population, four million). Middle: Narrabri near the Australia Telescope (pop. 6000). Bottom: Mileura, Western Australia at a remote station (pop. 4). (Measurements were made with an HF Coaxial Dipole, omnidirectional, vertical polarisation). Credit: CSIRO Radio Astronomy Image Archive CRAIA-SKA007

locations represents a large fraction of the total cost. Every radio telescope in history has had to deal with this issue.

However, the benefits of a remote location in terms of its RFI environment is not guaranteed. Over the years, as previously remote sites have been encroached upon by population centres, operators of radio telescope sites have gradually been able to obtain legal recognition of 'radio quiet zones (RQZ)',[135] which provide a modest level of protection in the long term (see point {I} in Chap. 6 introduction and the discussion of mitigation below).

While astronomy in general benefits greatly from the march of technology (see point {H} in Chap. 6 introduction), radio astronomy is so greatly affected by the growth of radio-spectrum usage that observations will be increasingly difficult. This is the most prominent example of unhelpful technology diffusion for radio astronomy (see point {I} in Chap. 6 introduction).

In particular, there has been a recent proliferation of hundreds to thousands of low-Earth orbit satellites that provide internet and other services to almost arbitrary locations on the ground. Although space-based emissions have been present for decades in bands allocated for radio astronomy (e.g., Argyle et al., 1977), these space-based emissions, even outside the radio astronomy bands, are the most harmful form of RFI. At 11 to 12 GHz, radio astronomy observations are already impaired.

A report commissioned by the SPDO in late-2011,[136] as part of the site selection process (see Sect. 8.3.6), provided a look at the long-term evolution of the RFI environment generally in the two site countries, considering the increased uses of the spectrum and the intensification with population growth. The main conclusion was that the use of the spectrum in the SKA bands will gradually increase worldwide, affecting both Australia and South Africa.

Aperture synthesis telescopes, consisting of arrays of antennas, are fundamentally more resistant to ground-based sources of RFI because they employ correlation. RFI emanating from sources near the horizon tend to de-correlate, reducing their effect, especially between antennas that are far apart. For example, this effect was invoked in discussions of RFI masks on potential SKA sites.[137]

In the rapidly changing RFI environment, mitigation strategies were recognised as being of critical importance in the SKA design and in the international spectrum management sphere. That remains the case at the time of writing. Hopefully the technical measures taken in the design, most of which are common to many modern radio telescopes, but critically important for the SKA, will ensure a long future for

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[135] hba.skao.int/SKAMEM-94 *Spectrum Protection Criteria for the Square Kilometre Array: SKA Task Force on Regulatory Issues,* Baan, W. A., SKA Memo 94, November 2005.

[136] hba.skao.int/SKAHB-204 *Study on the long-term RFI environment for the SKA radio telescope,* Analysys Mason Ltd., SKA Document, Report for the SKA Program Development Office, 23 November 2011.

[137] hba.skao.int/SKAHB-187 *EMI considerations in the area beyond the SKA skirt region: 13–180 km*, Nicolson, G. D., SKA South Africa Document, 11 October 2010.

the SKA. We discuss some of the RFI mitigation strategies in the following paragraphs.

### RFI Mitigation

RFI mitigation strategies are employed primarily on two fronts, spectrum management and technical design (e.g., see early recognition of this in (Ekers & Bell, 1999)). Fundamental to this approach is establishing a quantitative reference set of measurements of RFI levels at prospective telescope sites. These can be used to plan technical mitigation measures and to make the national and global spectrum-management cases to protect radio telescopes from other users of the radio spectrum.

Reference measurements were carried out for the SKA by Rob Millenaar, the SKA Site Engineer from 2008 and colleagues; these measurements formed part of PrepSKA WP 3 on Site Characterisation. Knowledge of the RFI environment at each of the SKA prospective sites was one of the most important selection factors for both the shortlisting and site decision stages in 2004–5 (Sect. 7.3.2) and 2008–2011 (Sect. 8.4.2 and SKASUP8-2), respectively. RFI played a significant role in the final site decision as discussed in detail in Sect. 8.6.3.

1. Spectrum Management: The ISSC established a task force on spectrum regulation in 2004, which covered issues related to site selection,[138] but also of a more general nature, such as a fully fleshed-out definition of a radio quiet zone (RQZ) . The need to establish an RQZ to protect the observatory site had already been discussed early in the SKA project.[139] RQZs must be established through national and local government regulations, and some have been established around existing radio observatories.[140] The SKA RQZ was expected to have international impact, especially since the SKA was expected to transit national boundaries. Specialised conferences were held throughout this period, which included discussion of the SKA's relationship with the International Telecommunications Union (ITU).[141] Although the SKA could not be represented officially on international spectrum management bodies during the PrepSKA years, Millenaar maintained a presence, for example, at meetings of the Committee on Radio Astronomy Frequencies (CRAF).[142]

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[138] hba.skao.int/SKAMEM-94 *Spectrum Protection Criteria for the Square Kilometre Array: SKA Task Force on Regulatory Issues,* Baan, W. A., SKA Memo 94, November 2005.

[139] hba.skao.int/SKAMEM-2 Considerations *for Radio-Quiet Zones/Reserves,* Baan, W., SKA Memo 2, 2001.

[140] A particularly effective radio quiet zone, 160 km on a side, protects the radio telescopes of the National Radio Astronomy Observatory in Green Bank, West Virginia, USA.

[141] hba.skao.int/SKAHB-380 The SKA, RFI and ITU Regulations, Gergely, T., white paper and presentation at the RFI2004 meeting, Penticton, 16 July 2004.

[142] hba.skao.int/SKAHB-419 CRAF News—The newsletter of the ESF Expert Committee on Radio Astronomy Frequencies, van der Marel, H., et al., Publication of the European Science Foundation, July 2013.

2. Technical Measures: Coping with environmental RFI is one of the largest cost drivers for radio telescopes and has substantial impact on the design of the telescope (see also Sect. 5.8.2). There are multiple dimensions to the RFI 'space': radio frequency, signal strength, signal bandwidths, signal direction, signal polarisation, time-duration, repetition rate, and spectrum usage-development, among others. As the sophistication of telescopes increases, for example, to accommodate the astrophysical time domain, the full suite of factors becomes important.

   Among the many technical measures for mitigating RFI, a few important ones are discussed here. These directly impact the cost and capabilities of the SKA.

- *Dynamic range of RFI and natural signals.* Natural signals from the Universe are typically a million to 100 million times weaker than those in most communication systems. The apparatus in radio telescopes that carries the signals (the signal chain) must be capable of carrying both the strong and weak signals without distortion. In terms of bits, only 2 or 3 bits per sample are needed to retrieve the underlying radio astronomy information in the absence of RFI. The presence of RFI signals requires many more bits per sample to accurately retrieve the radio astronomy signal. The cost of separating the weak signals from strong RFI signals increases directly as the number of bits per sample needed to do this effectively, and as RFI signal levels increase more bits will be required. However, there is probably a bit-limit above which this method is no longer effective, especially if large segments of the radio spectrum contain RFI. Modern telescopes require approximately 10 bits to operate properly in the current RFI environment. Although this approach is effective if a significant fraction of the radio spectrum is free of RFI, the spectrum is expected to gradually 'fill up' with human-caused signals.
- *Avoiding self-generated interference.* Radio telescopes contain the same sort of electronics as most industrial equipment. All devices near the site require very high levels of metal shielding to avoid contaminating the radio telescope site. The SKA has also taken the approach of transmitting signals over optical fibre, which does not generate RFI.
- *Development of mitigation algorithms.* This large collection of techniques is a combination of exploiting the signatures of RFI signals to remove them and exploiting the nature of interferometers to reject signals arising from directions far away from where the science signals originate (summarised in the early SKA era by Albert-Jan Boonstra[143](ASTRON)). For example, most RFI arises from the horizon around the telescope sites. Both antennas and processing algorithms can in principle provide suppression in those directions[144] (e.g., see Sect. 6.5.1 for experiments using Aperture Arrays). Algorithms to take into account satellite

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[143] hba.skao.int/SKAHB-381 Radio Frequency Interference Mitigation in Radio Astronomy, Boonstra, A-J., Thesis, Technical University of Delft, 14 June 2005.

[144] hba.skao.int/SKAMEM-34 *Spatial Nulling for Attenuation of Interfering Signals,* Thompson, A. R., SKA Memo 34, 08 July 2003.

orbits and emission spectra so that observations can be ‘flagged’ using this a-priori information will need to be developed further.

Although there are data processing algorithms (Offringa et al., 2010; ITU, 2013) that partly expunge RFI from radio telescope data, they are not as effective at removing subtle effects from RFI as human intervention. This will be impossible for SKA because of the huge data volume. In the future it is likely that machine learning and artificial intelligence (AI) will play a role. ‘Training’ these algorithms to recognise RFI in radio astronomy data is already a research topic at the time of writing.

In conclusion, RFI is complex to quantify and changes rapidly with time. This means the attempt to quantify its impact on the long term and mitigate its effects, while critically important, is fraught with difficulty.

#### 6.2.2.13 Operations Planning

Chaired by Ken Kellermann of NRAO until 2010, the Operations Working Group (OWG) was formed in 2004. Its first report[145] was a sensible combination of NRAO’s views on operations and the experience of other large science facilities already operating. Its primary recommendations are contained in Box 6.1. None of these suggestions were particularly new or unknown to the SKA proponents, but they were time-tested goals for most such projects. Some of them were adopted in more detail in subsequent documents. An exception is the “open skies” policy, which was never adopted by the SKA, despite its long history in astronomy[146] (see Chap. 1 and Sect. 4.2, Box 4.1).

**Box 6.1 Recommendations of the Operations Working Group in 2004**

- Expending capital during the building phase is well worthwhile if it can save operations funding in the future.
- Adopt a ‘multi-tier’ approach to system support and data reduction, similar to that of the Large Hadron Collider.
- Be wary of cost increases resulting from a system of juste retour that is implemented badly (i.e., “avoids potentially inflated contracts from partners who expect their entitlement”).
- As much as possible, a system should be adopted whereby member countries second their staff to serve under the SKA Director.

(continued)

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[145] hba.skao.int/SKAMEM-84 *Report of the SKA Operations Working Group,* Kellermann, K., et al., SKA Memo 84, October 2006.

[146] hba.skao.int/SKAHB-141 The *Future of Astronomy,* Pickering, E. C., Popular Science Monthly, August 1909.

**Box 6.1** (continued)

- Options for power provision, including solar, wind, and geothermal sources, should also be explored in relation to operational issues.
- Because software development is so expensive it will be important that the resources be made available to make software easily portable to new computing hardware.
- An "open skies" policy with peer reviewed assessment of the scientific quality of proposals will give the best science returns for the SKA.

In 2010 the OWG presented a broad-brush, but comprehensive, plan[147] for SKA operations for the System Concept Design Review (System CoDR). This was an updated follow-up to the principles outlined in Box 6.1. Although it was based on a single-site model with a large, in-country headquarters, many of the concepts have survived to the present. However, as in the previous OWG document, there is a strong emphasis on anticipating and controlling operations costs. The emphasis on governance style, in which the Observatory Director would be vested with full responsibility in day-to-day operations, is less practical for the current multi-site model.

As part of the site selection process, an SPDO analysis of the staff required for operations[148] was included in the 2011 Request for Information from Candidate Host Countries to allow estimates of infrastructure requirements for the full SKA (SKA Phase 2) on a single site by the candidate sites. On-site staff were almost entirely maintenance staff, while observatory operations staff were off-site. Staff numbers were roughly based on failure statistics of components and the numbers of components in the system. The numbers startled many people and led to criticism that there was no way that these staffing levels would be needed, because modern remote operations would be brought to bear on the problem. However, it was more likely an indication of the ambitious scale of the full SKA system. In the future, this will be tested on a small scale with SKA Phase 1 on two sites.

A more forward-looking operations concept document was written for the delta System CoDR, which followed the System CoDR, in 2011.[149] This became the basis for subsequent work and presented a more detailed description of Regional Science Centres.

As a postscript to the long-running development of an operations plan, under the chairmanship of Douglas Bock, the OWG produced a comprehensive top-level operations plan in 2013 that was written to be a parallel to the SKA Baseline

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[147] hba.skao.int/SKAHB-174 *The SKA Science and Technical Operations Plan,* Kellermann, K., et al., SKA Operations Working Group Report, WP2-001.010.010-PLA-001, 29 January 2010.

[148] hba.skao.int/SKAHB-194 *Initial Model for Maintenance and Operations Staffing for SKA2, Dewdney*, P. E., SPDO Document in support of SKA site selection, 11 February 2011.

[149] hba.skao.int/SKAHB-195 *SKA Operational Concepts,* Dewdney, P. E., SKA Document WP2-001.010.010-PLA-002, 21 February 2011.

Design[150] document. However, the SKA Organisation Board of Directors was not ready for such detail, and asked that it be reduced to a set of operational principles. After many iterations, the principles document[151] was accepted and a revised edition of the more complete document[152] was eventually released.

### 6.2.2.14 Outcomes

As a result of the reports from the System CoDR in March 2010 (see Sect. 6.2.2.9), things moved rapidly over the next year:

1. In August 2010, the SSEC revised the overall SKA plan to build the SKA in two phases, outlined major science goals and a technical baseline for SKA Phase 1 in SKA Memo 125[153] (see Sects. 4.5.2 and 6.2.2.9).
2. This was fleshed out over the next few months in SKA Memo 130, a Preliminary System Description[154] for SKA Phase 1, based partly on the earlier High-Level Description document[155] (see Sect. 6.2.2.9). This document pulled together the array configurations (Fig. 6.7), the receptors, the signal chains, the signal processing (correlators) and the software required for imaging and pulsar observations in a single overview of the two telescopes envisaged in SKA Memo 125. It also provided tables and graphs of expected performance, which could be used by the science community to consider the impact on science of the phased approach. The emphasis was very much on SKA Phase 1 as a brief transit-point to the full SKA, and procedures were broadly outlined for how this could be done, while also incorporating the outputs of the Advanced Implementation Program into the full SKA.
3. In the meantime, an all-encompassing document, the Project Execution Plan,[156] (see Sect. 4.6.2) was being prepared. This was both an almost final, detailed report for PrepSKA and a plan for the next step, the pre-construction Phase of the SKA. At the system level, it covered management strategies, science drivers,

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[150] hba.skao.int/SKAHB-206 *SKA1 System Baseline Design*, Dewdney, P. E., et al., SKA Document SKA-TEL-SKO-DD-001, 12 March 2013.

[151] hba.skao.int/SKAHB-207 Top-level *Principles of the SKA Concept of Operations,* Bock, D., et al., paper approved by the SKA Board, 25 July 2013.

[152] hba.skao.int/SKAHB-208 *Concept of Operations for the SKA Observatory,* Bock, D. C. et al., SKA Document SKA-TEL-SKO-DD-001, 29 October 2013.

[153] hba.skao.int/SKAMEM-125 *A Concept Design for SKA Phase 1 (SKA1),* Garrett, M.A., et al., SKA Memo 125, August 2010.

[154] hba.skao.int/SKAMEM-130 *SKA Phase 1: Preliminary System Description,* Dewdney, P. E., et al., SKA Memo 130, 22 November 2010.

[155] hba.skao.int/SKAHB-178 *High-Level SKA System Description,* Dewdney, P. E., et al., SKA Document WP2-005.030.010-TD-001, 15 February 2010.

[156] hba.skao.int/SKAHB-192 *Project Execution Plan: Pre-Construction Phase for the Square Kilometre Array (SKA),* Schilizzi, R. T., et al., SKA Document MGT-001.005.005-MP-001, 17 January 2011.

system engineering, a system technical description, science operations and a description of work for pre-construction. It also covered options for a future governance structure, staffing, outreach, relations with industry (including intellectual property), and the contributions from the SKA pathfinder, precursor and design study projects.

The breadth and thoroughness of this document was instrumental in obtaining the support needed to continue into the pre-construction phase.

4. For completeness, a delta CoDR was held in February 2011. This time it passed with only minor comments from the review panel[157].

At the system architecture level, this led in 2012/13 to a new baseline for SKA Phase 1,[158] a much more detailed description of the two telescopes, which by that time were to be established on two sites in Australia (SKA1-Low) and South Africa (SKA1-Mid). At that point the SKA project continued on a roll after the end of the PrepSKA era.

## 6.3 Historical Analysis of Individual Technology Innovations for the SKA

The purpose of the following sections is to describe the stories behind the development of essential parts of the SKA, concentrating on apertures (arrays of antennas) and on critical supporting technologies. Most of the development effort was devoted to innovative antenna designs, and the road to winnowing down selections was tortuous at times. Some designs were discarded by the developers, themselves, but others were selected by judgement calls using the advice of experts. In general terms, selections were guided by the science in the form of the Reference Science Mission[159] document. Cost, performance, and maturity played major roles. The title of this chapter, Innovation Meets Reality, illustrates the trend, especially towards 2012, the end of the PrepSKA program.

Critical supporting technologies were not subjected to the same rigour as apertures. It was recognised that many of these could not be fully selected until the aperture types were selected. Also, the rapid advances of optical and digital technologies meant that freezing selections too early would result in inferior designs.

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[157] hba.skao.int/SKAHB-196 *SKA Delta System Concept Design Review (dCoDR), Report of the Review Panel,* Wild, W., et al., SKA Document System dCoDR Review Report, 04 March 2011.

[158] hba.skao.int/SKAHB-206 *SKA1 System Baseline Design,* Dewdney, P. E., et al., SKA Document SKA-TEL-SKO-DD-001, 12 March 2013.

[159] hba.skao.int/SKAHB-159 *SKA Reference Science Mission,* Lazio, J., presentation at the PrepSKA WP2 Kick-Off Meeting, 10 November 2008.

## 6.4 Dishes for the SKA

The key to the success of the SKA at mid frequencies was clearly a new generation of dish designs. Traditional designs had evolved only slightly over the years. Until the Very Large Array (VLA) antennas were constructed, dishes were needed only in small numbers. While these dishes were optimised for the task, the structural design was fairly rudimentary.[160]

Most importantly for the SKA, the cost of the dishes would be overwhelmingly the largest fraction of the budget. In 2007, a summary of dish costs, contained in SKA Memo 100 (see Sect. 6.2.1.4), indicated that they would be much more than half the total construction cost, even though their cost was underestimated at the time. This provided motivation to develop new techniques and designs for the SKA antennas and explains the dedication of time and resources during the PrepSKA period towards this end (see Sect. 6.4.5).

This led to a long period of innovation and development in two principal areas: structural design (Sects. 6.4.4 and 6.4.5) and sampling of the 3D space at the focus (two spatial and one frequency dimension) (Sect. 6.4.7). Although an enormous amount of progress was made and large resources poured in, none of these innovations made it into the final SKA telescope design. The risk was simply too high by the time the funding agencies were ready for the next phase and wanted a low-risk, secure design (see Sect. 4.6.2).

A reflector technology related to dishes is parabolic cylinders. Although abandoned as an option for mid and high frequencies in the early 2000s, they were studied intensively.[161] However, they later came back into their own in the CHIME telescope (Amiri et al., 2018) consisting of (at the time of writing) four 100 × 20-m cylinders at the Dominion Radio Astrophysical Observatory (DRAO) site in Canada. It has been extraordinarily successful at detecting fast radio bursts, an example of “exploration of the unknown” (see Sect. 6.2.2.8).

### 6.4.1 Dish Technology: A Thumbnail Sketch

Parabolic reflector antennas (‘dishes’) have been the mainstay of radio telescopes since pioneer Grote Reber built the first one in his back yard in 1937. Many examples of dishes are portrayed in Chap. 2. It might be assumed that their design

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[160] An exception was the Effelsberg Telescope, constructed in 1971, which utilised the principle of homology. The idea is to compensate for the gravitational deflection of the parabolic surface that must change with elevation angle while pointing the dish. The support structure can be designed so that a new paraboloid is formed at each elevation angle, with a slightly different location of the focal point. All that is needed is a mechanism to track the position of the focal point for different elevation angles.

[161] hba.skao.int/SKAMEM-23 Cylindrical Reflector SKA, Bunton, J. D., SKA Memo 23, 11 July 2002.

has been refined over the following decades to the point where little more could be improved. Variations of reflector antennas including those with circular cross-section instead of parabolic (e.g., the Arecibo telescope), and parabolic cylinders (e.g., the Molonglo telescope, an SKA pathfinder [162]) have also been used for radio astronomy. [162].

Surprisingly, the antenna designs for the most recent array telescopes, the SKA and the next-generation VLA (ngVLA)[163], have adopted designs that are unusual in radio astronomy. On the other hand, the designs for extremely large antennas used as single-dish radio telescopes have evolved separately and remain very different from those designed for arrays.

Among the thousands of articles on reflector antennas in the literature, the basics can be found most easily on Wikipedia. This is taken further in SKASUP6-7,[164] which discusses the operating principles of a radio reflector antenna. While dishes have a myriad of uses in communications, radar and in space, the radio astronomy receiving applications are by far the most demanding because the parameter space is large compared to more specialised applications.

In the early innovative period of the SKA developments, attempts were made to replace dishes at medium to high frequencies with other kinds of receptors, such as dense Aperture Arrays (Sect. 6.5.5) and Luneburg Lenses,[165] but the project always came back to dishes.

Later, several important attempts were made to radically reduce the cost of dishes while also improving performance. The story of why they were not adopted will be told here. Because the final design for the SKA dishes was adopted long after the time horizon of this book, this will be only briefly described.

### 6.4.2 Early Developments in SKA Dishes

In the early SKA context, the URSI Large Telescope Working Group (LTWG) discussed options for large reflector antennas (see previous section) in their first meeting.[166]

The Allen Telescope Array,[167] originally called the 1-Hectare Telescope (1HT) and constructed at Hat Creek in California, was one of the earliest and most

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[162] hba.skao.int/SKANEWS-9 *SKA Newsletter Vol.* 9, January 2006.

[163] hba.skao.int/SKAHB-318 *Next Generation Very Large Array, Memo No. 5 Science Working Groups, Project Overview,* Carilli, C., et al., National Radio Astronomy Observatory (NRAO), ngVLA Memo 5, 28 October 2015.

[164] hba.skao.int/SKASUP6-7—The Operating Principles of a Radio Telescope Antenna.

[165] See hba.skao.int/SKASUP6-30—Luneburg Lenses.

[166] hba.skao.int/SKAHB-212 *Draft Minutes, URSI Large Telescope Working Group (SKAHB123), Braun, R.,* First Meeting, Jodrell Bank, 21 March 1994.

[167] Originally developed jointly by the SETI Institute and the Radio Astronomy Laboratory at the University of California, Berkeley. It was sponsored mainly the Paul G. Allen Family Foundation and subsequently by others as well.

innovative of radio telescopes at the time and now (DeBoer et al., 2004; Welch et al., 2009). The first ATA Memo in 1998[168] captures the flavour of the discussions happening before it was first funded in 2001. It was the prototypical Large-Number—Small-Dish (LNSD) SKA architecture, championed in the US and adopted as a concept for the SKA. It bears a resemblance to the Radio Schmidt telescope that was proposed in the 1980s[169] but never constructed (see Sect. 2.2.2.4). The innovations of relevance to the SKA were: Continuous frequency coverage over a very wide band (0.5–11 GHz) using Wide-Band Single Pixel Feeds (WBSPFs); offset Gregorian dish optics; a novel mould-based antenna construction; and an 80 Kelvin cryogenically-cooled feed and low-noise amplifier. Although only the offset Gregorian optics design was adopted for the SKA in the end, the ATA provided design guidance with real system-level evidence in a way that other prototypical systems could not.

### *6.4.3 Dish Design Challenges in the SKA Context*

Despite the simplicity of the basic reflector design, there are many design choices and parameters to be optimised. For SKA-Mid, a critical consideration is cost. As described in SKA Memo 100 in 2007 (see Sect. 6.2.1.4), the estimated number of 15-m dishes needed was between 500 and 600 for SKA Phase 1 and 2000–3000 for the full SKA (SKA Phase 2). The resulting $A_e/T_{sys}$ figures of merit were 2000 $m^2$/K for SKA Phase 1 and 12,000 $m^2$/K for the full SKA. One could therefore simplify the goal to maximise $A_e/T_{sys}$ per unit of currency for each antenna and hence also for the whole telescope array. In SKA Memo 100, the cost per 15-m dish was estimated to be about €300,000, including all components but not the associated infrastructure. Such mass production of radio astronomy reflector antennas had never been done or even contemplated before. Economies of scale were clearly part of the picture.

The following sections explain the key challenges and design choices that had to be made for the SKA dishes. Because there are many interlocking priorities, the design choices cannot be optimised separately; they must be optimised jointly, which leads to a compromise design for each of the important parameters. In subsequent sections, attempts to develop innovations that would break the traditional design-paradigm will be explained.

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[168] hba.skao.int/SKAHB-213 *Astronomical Imaging with the One Hectare Telescope,* Wright, M., ATA Memo 1, December 1998.

[169] hba.skao.int/SKAHB-210 *The Radio Schmidt Telescope—Proceedings of a Workshop held at Penticton held 1989 Oct 11–12, Dewdney*, P. E. and Landecker, T. L., published by National Research Council of Canada, Herzberg Institute of Astrophysics, Dominion Radio Astrophysical Observatory, June 1991.

#### 6.4.3.1 Diameter of the Dishes in the Architecture of the Telescope

One of the most contentious aspects of the SKA1-Mid design was the dish diameter. In the beginning both very large dishes (e.g., the LAR[170] and FAST[171,172] and very small dishes (e.g., ATA dishes (DeBoer et al., 2004; Welch et al., 2009)) were proposed. The dish diameter clearly determines the number of dishes needed to create a specified total collecting area. Note that both the effective area, $A_e$, and the field-of-view, Ω, are proportional to the square of the diameter, $D^2$; for a given system temperature, $T_{sys}$. Both figures-of-merit ($A_e/T_{sys}$ and survey speed $(A_e/T_{sys})^2 \cdot \Omega$) increase with diameter. The opposite driver is the cost-per-unit-area versus diameter.

Based on historical data, there were attempts to create cost versus diameter curves. However, it is exceedingly difficult to obtain sufficiently accurate cost information for antennas that were built over decades. The widely assumed curve relationship was $C_D \propto D^{2.7}$, where $C_D$ is the dish cost. If this were correct, the sensitivity per unit cost would decrease for increasing diameter for an individual dish, but this is not the full story for system cost.

The primary qualitative factors affecting the choice of diameter for a many-dish array of specified total collecting area are:

1. Large antennas can accommodate large feed packages, including cryogenic feeds which lowers $T_{sys}$ dramatically. This is even more important if PAFs are included as options (see Sect. 6.4.7).
2. Small antennas require structural support pedestals and mounts for each one, which do not directly contribute to collecting area.
3. Small antennas have comparatively large fields-of-view, leading to higher survey speed.
4. Antenna maintenance cost is primarily per item. Many small antennas will increase maintenance costs proportionately.
5. Small antennas are easier to design for accurate pointing, surfaces, and alignment.
6. The signal and data-processing challenges for an array of many small antennas can be extreme[173] (see Sect. 6.6.5).

Small dishes are still prized for their inherent field-of-view and ease of manufacture. For example, the Canadian Hydrogen Observatory and Radio-transient Detector

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[170] See hba.skao.int/SKASUP6-28—The Large Adaptive Reflector (LAR).

[171] See hba.skao.int/SKASUP6-29—The Five-hundred-meter Aperture Spherical radio Telescope (FAST).

[172] Although the Large Adaptive Reflector (LAR) project was wound down in about 2006, the Five-hundred-meter Aperture Spherical radio Telescope (FAST) was completed in 2016 and is the world's largest filled aperture telescope.

[173] hba.skao.int/SKAMEM-49 *SKA and EVLA computing costs for wide field imaging (Revised),* Cornwell, T. J., SKA Memo 49, June 2004.

(CHORD),[174] under construction in Canada at the time of writing, utilises technology developed for the SKA (see Sect. 6.4.4.2.1) for a 640-dish array (a 512-dish core and two 64-dish distant outriggers). This is a specialised telescope designed to 'catch' radio transients and to map the distribution of atomic hydrogen in the Universe over a large area of sky up to redshift 4.

### 6.4.3.2 Frequency Range

Another contentious aspect was the frequency range. The original motivations for the SKA were based on observations of the red-shifted spectral line of atomic hydrogen (HI-line) in galactic and extra-galactic radio sources (see Chap. 5), which is emitted by the source at a wavelength of 21 cm (corresponding to a rest frequency of 1420 MHz). Red-shifting, due to the recession velocity of the observed object, increases the wavelength of observation. As more astronomers became interested in the concept of a next-generation radio telescope, the science broadened, and initially the upper frequency was set to 3 GHz ($\lambda = 10$ cm) and later became 10 GHz ($\lambda = 3$ cm). Noting the rules of thumb outlined in SKASUP6-7,[175] the surface and pointing accuracies required for these frequencies are easily achieved by antenna fabrication methods.

However, projections for the SKA's unparalleled sensitivity contained in SKA Memo 100 (see Sect. 6.2.1.4) brings another factor into play; wide-field imaging dynamic range.[176] Dynamic range refers to the capability of the telescope to image extremely weak objects in the presence of strong ones, rather like attempting to see a faint star near the Sun. Although this type of imaging is not the only scientific goal requiring high sensitivity, it is important to be able to detect and count radio sources emitting from the earliest stages of evolution of the Universe, which are inherently extremely weak.

For the SKA, the required dynamic range in the 15–30 cm wavelength range is approximately $10^7$, meaning that is possible to detect objects in the images that are 10 million times fainter than the strongest objects in the image. This will not be tested until the SKA is fully built.

Heuristically, it was argued that the shape of the antenna beam must be very stable to achieve sufficient dynamic range, translating directly into surface and pointing accuracy, even for long wavelengths. Tightening the rules-of-thumb by about an order of magnitude was required. Hence if that were the case, then

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[174] hba.skao.int/SKAHB-326 *The Canadian Hydrogen Observatory and Radio-transient Detector (CHORD),* Vanderlinde, K., White Paper submitted to the Canadian Long Range Plan process, 05 November 2019.

[175] hba.skao.int/SKASUP6-7—The Operating Principles of a Radio Telescope Antenna.

[176] It is usually possible to achieve high dynamic range imaging in a small field-of-view surrounding the pointing direction of the dish, but many times more difficult to achieve this over the entire field-of-view of the dish, which is usually taken as the region of the dish beam where the sensitivity drops by a factor of two (i.e., the half-power point).

extending the frequency range of the antennas would come along for the ride. A 10-GHz requirement remained the upper frequency limit until 2012/13; this governed the goals for the innovation programs described in Sect. 6.4.4.2.

20 GHz ($\lambda = 1.5$ cm) the final upper frequency requirement for SKA antennas was adopted in the SKA Baseline Design,[177] just at the end of the period covered by this book. In 2014–15, a survey of potential users of the SKA revealed that scientific interest in the highest frequency observing band (approximately 8–15 GHz) was ranked second behind the 21-cm wavelength band.[178,179]

### 6.4.3.3 Noise[180]

The introductory paragraphs to Sect. 6.4.3 explain the importance of limiting the value of $T_{sys}$, and as noted in SKASUP6-7,[181] the primary method of controlling amplifier noise is cryogenic cooling. Other sources of noise are spillover and scattering[182] (see Chapter 7). Early design considerations assumed that cryogenic cooling would be too expensive to operate because of the electrical power required and high maintenance costs, but a full cost-benefit analysis[183] was not done until 2013/14, but by that time the benefits of cryo-cooling had informally been recognised.

Initially this left the antenna diameter unconstrained at the small end, although the ATA design (Welch et al., 2009), with 6-m dishes, used a clever combination of ultra-wide band feed with a cryogenic cooler to bring the amplifier temperature down to about 80 K, rather than the preferred 10–20 K. More generally, however, a set of cryogenic feeds of standard design establishes a soft lower limit to the antenna diameter in the 10-m range.

Spillover noise and noise from scattering are controlled mainly by the selection of the optical design of the antennas. This is considered in Sect. 6.4.3.4.

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[177] hba.skao.int/SKAHB-206 *SKA1 System Baseline Design*, Dewdney, P. E., et al., SKA Document SKA-TEL-SKO-DD-001, 12 March 2013.

[178] hba.skao.int/SKAHB-320 *SKA1 Observing Bands: Scientific Context,* Braun, R., et al., SKA Document SKA-TEL-SKO-0000417, 28 October 2015.

[179] hba.skao.int/SKAHB-312 *SKA1 Science Priority Outcomes,* Braun, R., et al., SKA Document SKA-TEL-SKO-0000122, 25 September 2014.

[180] System noise is the sum of all sources of noise (i.e., from the sky, itself, as well as the telescope). Noise units are usually in Kelvins, the equivalent temperature of a resistor that produces the same noise. In terms of a radio signal, noise comprises random fluctuations of voltage, current or power.

[181] hba.skao.int/SKASUP6-7—The Operating Principles of a Radio Telescope Antenna.

[182] These sources of noise are from pickup of the surrounding ground noise, which is at a temperature of about 300 Kelvin, in contrast to the sky which is less than 10 Kelvin at the frequencies of SKA-Mid. Spillover and scattering are dependent on the ‘optical’ and electromagnetic designs of the dish.

[183] hba.skao.int/SKAHB-310 *Cryo-Cooling Analysis for SKA1-Mid, Dewdney*, P. and Tan, G.H., SKA document SKA-AG-DSH-RPT-00001, 09 March 2014.

#### 6.4.3.4 Optical Design

As one would expect, the choice of optical design, illustrated in SKASUP6-7, affects both performance and cost. For the ultra-sensitive SKA, apart from the diameter and frequency range, one aspect of the design stands out, scattering of the incoming radiation by the antenna structure. At the long-wavelength end, there will be components of the feed structure and focus assembly whose size is similar to a wavelength. This can result in resonant scattering, which is much stronger than normal at specific wavelengths. At the short wavelengths, scattering less important. Also, these two structural components block incoming radio waves. Both these effects subtly change the shape of the beam in ways that are difficult to predict and will certainly influence the imaging dynamic range. These considerations strongly argue for an offset design.

A major concern is the sensitivity of the antenna far away from the pointing direction, known as far-out sidelobes. RFI (see Sect. 6.2.2.12) can enter the signal path if it is not strongly rejected by the antenna beam. Scattering acts like an ‘omnidirectional antenna’; although its collecting area is small, RFI is extremely strong compared with natural signals from the sky. As the radio spectrum gets more and more crowded with man-made signals, the importance of reducing scattering increases. While not such a concern at the time when the SKA antenna design was being considered, new sources of RFI are now in the sky, itself, which increases the need to suppress signals far away from the pointing direction.

Measuring the polarisation of radio waves is a scientifically important aspect of radio astronomy. The polarisation performance of symmetrical dishes is usually considered better than off-axis dishes because the symmetry causes cancellation of undesired leakage between the two polarisation states of the incoming radiation. However, by structuring the optical design according to a method worked out by Mizusawa and Mizuguchi in the mid-1970s, an offset optical design with properties equivalent to a symmetrical paraboloid can be found.[184] This approach was used in the SKA antenna design.

On the other hand, an offset design is structurally unbalanced and requires the sub-reflector and feed assembly to be supported by a cantilevered structure. This is significant because, ignoring its self-weight, the deflection of a cantilevered beam loaded at one end scales as the cube of its length ($L^3$).

Another cost-driven consideration of an offset design is that the primary reflector has an elliptical outline. But the projection of the reflector in the pointing direction is circular. Hence, more physical area must be built than can be used as collecting area, adding to the cost. For example, the primary reflector of the SKA dishes is 15 × 18 m, but the projected collecting area is only a 15-m diameter circle. Moreover, the traditional method of building the reflector is to tesselate the surface with triangular or four-sided panels. A symmetric design has fewer different panel

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[184] hba.skao.int/SKAHB-270 *Dual Offset Reflector Antenna Optics Design using Misusawa’s Condition,* Cortés-Medellín G., TDP Memo, 14 July 2009.

shapes than the elliptical reflector in an offset design; therefore, manufacturing cost of a design that uses panels is increased.

In summary, the structure of an offset antenna is significantly more expensive than a symmetrical antenna for the same collecting area. But the advantages of the offset design were considered so significant that they became a requirement for the ultra-sensitive SKA to be built. This is especially true for the 10–50 cm wavelength range. Hence the offset design was selected, and for additional technical reasons, the offset Gregorian optics was decided upon (see Sect. 6.4.5).

SKASUP6-8[185] contains a summary of the desirable properties ultimately agreed upon for the SKA.

### 6.4.4 Ambitious Innovations in Antenna Structural Design[186]

The traditional structural form for the antenna consists of a small number of components (see the Box in SKASUP6-7[187]): a pedestal, a mount (turnhead) which contains the axes of motion and motors, a back-up structure which supports the panels, and feed arms which support the sub-reflector and feed assembly.

Because they are large structures, often in an open environment,[188] dishes are subject to so-called load cases, the primary mechanisms of structural distortion. These are gravity, wind, solar illumination, and temperature. Less important are rain, humidity, flooding, etc. The timescales on which the load cases act are important: wind can act on time-scales of 10s of seconds to minutes, whereas solar illumination is minutes to hours, and temperatures are longer. Of course, gravity is static, but its influence on the structure changes with pointing direction. All greatly affect and even drive the antenna design.

The following sections and SKASUP6-9[189] describe numerous attempts to break this design paradigm in a drive to both reduce the cost of antennas and to adapt to the requirements traceable to SKA science goals. A helpful aspect was the number of large antennas to be produced, an opportunity that had never previously arisen. Initially the full SKA would have contained about 3000 antennas, but this was later whittled down to 200 in the first phase of construction. Nevertheless, the potential savings from quasi-mass-production promised to be significant if the designers were clever enough to take advantage of it. Cost reduction is best measured in terms cost per unit of sensitivity (€ per unit of $A_e/T_{sys}$ or € per unit of survey speed).

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[185] hba.skao.int/SKASUP6-8—Properties of the Ideal SKA Reflector Antenna.

[186] An expanded version of this section can be found in hba.skao.int/SKASUP6-9.

[187] hba.skao.int/SKASUP6-7—The Operating Principles of a Radio Telescope Antenna.

[188] Some dishes are housed in a radome to protect them from the environment.

[189] hba.skao.int/SKASUP6-9—Detailed Version: Ambitious Innovations in Antenna Structural Design.

**Fig. 6.10** The ASKAP antennas under construction. The third axis of rotation is located just under the reflector. Credit: CSIRO Radio Astronomy Image Archive CRAIA-SKA011

#### 6.4.4.1 Sky-Mount Antennas

The emergence of ‘sky-mount antennas’, a term coined in Australia, was strongly coupled with the development of phased array feeds (PAFs) (see Sect. 4.3.3.1). These feeds are a compact array of small antennas which are combined in a way that is similar to an aperture array (see Fig. 6.19 and the box in SKASUP6-11[190]). While the method is based on sampling the electromagnetic field around the focus, the effect is to produce a grid of beams on the sky in the place of a single beam, hence increasing the field-of-view by a factor of the number of beams (typically 36). This dramatically increases the survey speed of the telescope if the $A_e/T_{sys}$ component of survey speed can be maintained (Sect. 6.4.3.1). But to work properly for an aperture synthesis telescope, the pattern of beams must be fixed to the sky. As explained in Sect. 6.4.5, this was done by adding a third axis, orthogonal to the reflector, to counteract the rotation of the reflector against the sky (see Fig. 6.10). CSIRO, the lead radio astronomy institution in Australia, was keen to develop these ideas for the SKA.

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[190] hba.skao.int/SKASUP6-11—Detailed Version: Principles of Phased Array Feeds (PAFs).

By 2009, ASKAP had become a major facility project (DeBoer, 2009) carrying a large scientific program, well beyond the concept of merely testing PAFs. By this time CSIRO had a great deal of confidence in PAFs and how to build the supporting infrastructure, such as beamformers, for a reasonable cost. More detail on ASKAP as a whole is contained in Sect. 4.3.3.1.

#### 6.4.4.2 Mould-Based Reflectors

The most ambitious innovations were to fabricate the entire primary reflector in one piece by forming it over a mould. This approach began in three different places, probably independently: Canada, USA, and South Africa. Although the approaches differ in detail, they followed a common theme: a convex mould was constructed over which the reflector material was formed by compressing the material against the mould. The concave reflector part was released from the mould as a complete reflector.

There were several potential attractions to this approach:

- Rapid fabrication in mass production: Although some methods require a cure time of a few hours, the complete reflector is available after it is released from the mould.
- Repeatability: With adequate control over the fabrication environment, the reflectors will be nearly identical. No adjustments are necessary.
- Accuracy: The accuracy of the reflector is determined by the accuracy of the mould. Very accurate reflectors are possible.
- Variety of shapes: Asymmetric shapes or bi-lateral reflector symmetries (or any dual-curvature shape) can be fabricated as easily as symmetric shapes. In contrast, panelled reflectors are much easier to make for symmetric reflectors, but more expensive for offset reflectors.
- Partly Self Supporting: Because of its continuous surface, the reflector can be designed to carry most of its own weight with much less underlying structure than panelled reflectors, especially if it is highly curved.

Mould-based fabrication of large reflectors for the huge number of radio telescopes being planned (for SKA Phase 1 and the much larger SKA Phase 2), promised an enormous impact on cost and feasibility. While retaining the tried-and-true advantages of reflectors, comparatively frequency-independent and passive collecting area, mould-based reflectors might have revolutionised the field. Sadly, it was not to be.

In Canada and South Africa, fibre reinforced plastic (carbon fibre and fibreglass, respectively) was used to build prototypes. In the USA, hydro-formed aluminium was used for the ATA antennas (for examples of mould-based reflectors, see Figs. 6.11, 6.12, 6.13 and 6.14). These efforts are described in more detail in SKASUP6-9.[191]

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[191] hba.skao.int/SKASUP6-9—Detailed Version: Ambitious Innovations in Antenna Structural Design.

**Fig. 6.11** Left: Vacuum Infusion of the 10-m Mk2 reflector at the Dominion Radio Astrophysical Observatory in Canada on June 4, 2008. Credit: National Research Council of Canada. Right: The reflector with the (PHAD) feed completed in October 2008. Credit: The National Research Council of Canada

**Fig. 6.12** Left: The XDM telescope mould under construction at Hartebeesthoek Radio Astronomy Observatory in South Africa in 2007. Right: The XDM with all subsystems installed, integrated and tested in 2009. Credit: South African Radio Astronomy Observatory (SARAO)

### 6.4.4.2.1 Mould-Based Reflectors in Canada: Carbon Fibre Reinforced Plastic (CFRP)

The Canadian project began in early 2006 as an outgrowth of the Large Adaptive Reflector (LAR) project,[192] when the National Research Council of Canada hired

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[192] See hba.skao.int/SKASUP6-28—The Large Adaptive Reflector (LAR).

**Fig. 6.13** The KAT-7 fibreglass dishes under construction in the Karoo district of South Africa in 2009. Right: The completed KAT-7 dishes being installed in 2009 on what is now the site for MeerKAT and SKA1-Mid

**Fig. 6.14** Left: The first ATA reflector on the factory floor. Right: A completed antenna. Credit: David DeBoer

Gordon Lacy in 2004 to work at DRAO. With a background in composite fibre construction techniques in the marine industry,[193] he was hired to design a lightweight support for the suspended LAR feed, which was based on PAF technology (see Sect. 6.4.7.1.1). The feed support was to be made from Carbon Fibre Reinforced Plastic (CFRP).

The project began with the production of a mere 1-m offset reflector. It progressed to two 10-m symmetrical versions, the second of which displayed a root mean square (rms) surface accuracy of 500 microns,[194] sufficient for high efficiency at 20 GHz, confirmed with a laser tracker and holography in October, 2008 (Fig. 6.11). The next

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[193] hba.skao.int/SKAHB-228 *Composite Construction Techniques*, Lacy, G., presentation, 11 October 2006.

[194] hba.skao.int/SKAHB-253 *HIA Breaks the Mold: the Latest High-Performance New-Technology Reflector,* Dougherty, S., NRC/DRAO announcement, 09 October 2008.

in the series was Dish Verification Antenna 1 (DVA-1), a prototype designed to the SKA specifications at the time. This played a major role in the history of SKA dish design for several years, as told in Sect. 6.4.5.

#### 6.4.4.2.2 Mould-Based Reflectors in South Africa: Fibreglass Reinforced Plastic

Planning in South Africa began in early 2006 for the Karoo Array telescope (KAT), the first of which was a 15-m diameter prototype (XDM) erected at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) (Fig. 6.12). The XDM prototype was part of a larger plan funded by the South African government for up to US$50 M, among other things to build and equip the dish with state-of-the-art receivers and digital back-end devices. Plans were also laid to build 20 dishes on the Karoo site in the Northern Cape region, which had been selected for the South African bid for the entire SKA.[195] This was later trimmed to 7 dishes, becoming the KAT-7 project (Fig. 6.13).

The KAT-7 array was commissioned by the end of 2010, but by that time the SKA had adopted 15-m offset reflectors as the SKA standard. Also by that time, it had become clear that MeerKAT antennas were unlikely to use the simple mould-based method developed for the XDM and KAT-7, which was restricted to building only symmetric antennas.

#### 6.4.4.2.3 Hydroformed Aluminium Reflectors in the United States

As outlined in Sect. 6.4.5, the TDP program was funded in late 2007 (see Sect. 6.2.1.3) and had assembled an Antenna Working Group (AWG) to globally coordinate dish development. They also planned to carry out innovative dish development themselves, concentrating on the hydroforming process.

The ATA (DeBoer et al., 2004) was the first radio astronomy telescope that had used a hydroforming process for fabricating its 6-m diameter reflectors (Fig. 6.14). Little has been published about the proprietary process[196] used to make the ATA reflectors or the so-called Deep Space Network Breadboard reflectors.[197,198] The process was similar to one widely used in industry (Leuthesser & Fox, 1955) for making small reflectors for satellite television reception, sheet-metal parts for

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[195] hba.skao.int/SKANEWS-9 *SKA Newsletter Vol.* 9, January 2006.

[196] Used by Andersen Manufacturing of Idaho Falls, USA, to make the ATA and DSN antennas. Andersen no longer makes antennas.

[197] The NASA Deep Space Network (DSN) purchased three 6-m hydroformed antennas to evaluate for proposed deep space tracking array.

[198] hba.skao.int/SKAHB-217, Imbriale, W.A., et al., National Aeronautics and Space Administration (NASA), The Interplanetary Network Progress Report, Vol. 42-157, 15 July 2004.

automobiles, etc. The method employs a high-pressure fluid (not necessarily water as implied by the name) to deform a flat metal sheet over a mould, resulting in a sheet that has taken the shape of the mould.[199]

In 2004, prior to TDP funding, the US SKA community proposed a symmetrical 12-m hydroformed design with a 2-m mesh extension (Schultz et al., 2004) which would yield a 16-m antenna. By 2009, this proposal had evolved to 12-m hydroformed antennas with either symmetric or offset Gregorian optical designs[200] without extensions. This was smaller than the 15-m antennas adopted by the international project as the optimum size for minimum overall system costs.

A major impediment to further development of the hydroforming approach for the SKA dishes was the up-front capital cost[201] required to carry out a full investigation of a 12-m hydroformed design and to build a prototype (see point {C} in Chap. 6 introduction). It was this cost and the limitations to the maximum antenna diameter possible with hydroforming that led to it being discontinued for the SKA. Instead, the TDP moved to joint development of mould-based 15-m CFRP antennas together with the Canadians and other partners around the world (see Sect. 6.4.5.1).

#### 6.4.4.3 Preloaded Parabolic Dish (PPD): Tension Structure Reflectors

First proposed for the SKA in 2002,[202] the Raman Research Institute began an experiment to construct a PPD dish in 2003 using the principles of preloaded structures, based on a design from the Tata Institute of Fundamental Research in Pune, India.[203] As they described it (Shankar, 2008), "The preloaded concept is based on the principle that if a structure has an initial stored strain energy, then under certain conditions, it has the capacity to offer a larger stiffness for the same weight to additional external loads.".

A 12-m prototype PPD dish was completed in 2008 and measured photogrammetrically,[204] yielding rms deviations from an ideal surface of about 20 mm (Fig. 6.15). Because these dishes were suitable only for low frequencies, it became clear that they could not be adopted for SKA-Mid, especially after preliminary specifications were published in December 2007 (SKA Memo 100, see Sect.

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[199] A similar process that does not require a mould has even been proposed specifically for parabolic reflectors (Gray & Lahey, 1988).

[200] hba.skao.int/SKAHB-264 *Hydroformed Metal Reflector Production Cost Estimate,* Fleming, M., TDP Antenna Design Note, 28 April 2009.

[201] hba.skao.int/SKAHB-249 *Hydroformed Reflector Time & Materials Cost Estimate*, Fleming, M., Antennas Working Group Meeting, San Francisco, 13 March 2008.

[202] hba.skao.int/SKAHB-215 *Preloaded Parabolic Dish Antennas for the Square Kilometre Array,* Swarup, G. and Shankar, N.U., SKA White Paper, 17 June 2002.

[203] hba.skao.int/SKANEWS-9 *SKA Newsletter Vol.* 9, January 2006.

[204] hba.skao.int/SKAHB-257 *Photogrammetric Measurements of a 12-metre Preloaded Parabolic Dish Antenna,* Shankar, N.U., National Workshop on the Design of Antenna & Radar Systems (DARS), 13 February 2009.

**Fig. 6.15** The fully equipped PPD antenna at the Gauribidanur Radio Observatory. Credit: The Raman Research Institute

6.2.1.4). And for low frequencies, more flexible aperture arrays were a better match to requirements over dishes.

### 6.4.5 Historical Twists and Turns in Dish Development

As previously noted in the introduction to the section on SKA dishes (Sect. 6.4), the cost of the dishes would be overwhelmingly the largest fraction of the budget. Beginning in late 2007, the basic specifications for SKA dish antennas had been roughly outlined in SKA Memo 100. Almost all the detailed parameter space was still open, but the expectations were clear:

- The frequency range for dishes, initially based on the science, was also influenced by the technology it was paired with. If paired with dense Aperture Arrays covering frequencies from 0.5 to 1.5 GHz, dishes needed only to cover frequencies above 1.5 GHz. Otherwise, the lower limit for dishes would be between 0.3 and 0.5 GHz. The upper limit considered was either 3 or 10 GHz, depending on cost.

- Three types of feeds were discussed: (1) Wide-band single-pixel feeds (WBSPFs, see Sect. 6.6.1.1), which cover a frequency range from 0.5 to 10 GHz (20:1 range), were assumed to be on the near-term horizon for development. (2) Traditional feed systems consisting of several switchable feeds with only a 2:1 frequency range were also a possibility, but cost and feasibility were clearly a problem, especially for small dishes. (3) PAFs (see Sect. 6.4.7), which are arrays of small antennas designed to produce multiple beams on the sky. PAFs greatly expand the instantaneous field-of-view of a single antenna, thus ‘reusing’ the collecting area of the antennas, but the beam-pattern had to be stabilised on the sky (see Sect. 6.4.4.1).
- Cryo-cooling of the first stage of amplification was widely used in dish antennas. Innovative techniques for single-pixel feeds were assumed to be possible using Stirling cycle devices, a cost-effective compromise able to cool to 80 Kelvin instead of the usual 20 K. There was also a hint that uncooled amplifiers might be developed that would not require cryo-cooling. However, for PAFs, which had to be very large at mid-frequencies, the possibility of cryo-cooled amplifiers was considered remote.

None of the SKA Memo 100 specifications stuck in the end, but the boundaries of parameter-space were clear, and under the aegis of PrepSKA, its exploration was quickly systematised, beginning in 2008. Above all, it was also clear that priority had to be given to reducing the cost of antennas.

In November 2008, a plan[205,206] was formulated to systematise all PrepSKA work packages: organise deliverables, assign roles and responsibilities, and to conform to system engineering principles (see Sect. 6.2.2.2). A parallel document,[207] setting out the rationale for dish development, specifically covered dishes in the context of an integrated approach to the entire SKA telescope system.

In the rationale document, four model development programs were defined: (1) An “optimised ‘single-pixel feed only’ antenna” to deliver the baseline described in SKA Memo 100 using optimised but well understood technology. This was the design against which the other three designs, containing more advanced technology, were to be measured. The other models were essentially optimised differently and designed to handle both WBSPFs and PAFs. (2) An Alt-Az Mounted Antenna with on-axis feeds to provide the lowest cost model that could accommodate both types of

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[205] hba.skao.int/SKAHB-155 *Guiding Principles, Activities and Targets for PrepSKA Work Package 2, Dewdney*, P., SKA Project Office Report, 02 November 2008.

[206] hba.skao.int/SKAHB-168 *Revised Approach to the WP2 Work Plan and Timeline,* Dewdney, P. and Cloete, K., SKA Project Office Report, 08 October 2009.

[207] hba.skao.int/SKAHB-254 *Rationale for Re-Organizing PrepSKA WP2 Work Packages related to Dish Design and RF Systems,* Roddis, N. and Dewdney, P., SKA SPDO Memo, 26 October 2008.

feeds. (3) The sky-mount design (see Sect. 6.4.4.1) to provide a model that did not emphasise the clean-beam design (i.e., normal scattering), but did emphasise freezing the parallactic rotation[208] of beam patterns on the sky. The third axis was introduced to produce counter-rotation, thus freezing the antenna pattern on the sky. (4) An offset optics antenna to provide the best scattering performance.

Each development was to be led by a 'lead institution', but contributions from all the SKA participating institutions were to be made to all four models in a kind of matrix organisation. Standard system engineering processes were invoked. A Work Breakdown Structure (WBS) and a schedule were developed, ending in June 2010. Based on the design work, the goal was to eliminate two of the models and to build jointly funded prototypes of the remaining two.

In fact, no lead institutions were formally appointed. In the case of dishes, a TDP report to the SKA Science and Engineering Committee (SSEC) in February 2009[209] contained a statement: "Decision that the TDP will serve as a clearinghouse for antenna work done around the world, consolidating information for use by the international SKA project. Close collaboration between TDP and DRAO on composite reflectors, mounts, and phased array feeds. DRAO participation in TDP industrial studies.". This was accepted by the SSEC.

The TDP had already formed an Antenna Working Group (AWG) (see Sect. 6.2.1.3). The first meeting was held in San Francisco in March 2008 at which the PrepSKA work packages were described in detail[210] by Peter Dewdney, the International Project Engineer: overview of SKA science goals and top-level system specifications; review of proposed stages of build out; cost drivers; and detailed discussion of reflector antenna specifications. This was followed by detailed discussion and negotiation of the design processes at the TDP, mindful of their roles as both clearing house and proponent of a specific design.[211,212] Participants from the ATA were especially Influential in this group and strong proponents of very small dishes.

In an important side-meeting at the San Francisco event, top-level specifications for SKA dishes were worked out between the SPDO, DRAO and TDP

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[208] Parallactic angle is the angle subtended at the antenna pointing direction by a great circle passing through this point and the zenith, and another great circle passing through the same point and the North or South pole. The practical effect, for antennas like that in the figure in the Box in hba.skao.int/SKASUP6-7 is to cause the reflector to rotate against the sky. The beam formed by the reflector is not normally perfectly circularly symmetric, so the apparent amplitude of an emitting object that is not centred in the pointing direction will fluctuate as the reflector rotates. If the antenna is designed to form a grid of beams, then the grid pattern will also be fixed to the sky.

[209] hba.skao.int/SKAHB-255 *TDP report to SSEC2, Summary and Status of the U.S. SKA Technology Development Project,* Cordes, J., Cape Town, South Africa, 03 February 2009.

[210] hba.skao.int/SKAHB-247 *SKA Specifications and Reflector Antennas,* Dewdney, P., Antennas Working Group Meeting, San Francisco, 13 March 2008.

[211] hba.skao.int/SKAHB-244 *Meeting Summary, Antennas Working Group Meeting,* Baker, L. and Cordes, J., San Francisco, 13 March 2008.

[212] hba.skao.int/SKAHB-246 *Index and Outlines of Talks, Antennas Working Group Meeting TDP* Antenna Working Group, San Francisco, 13 March 2008.

representatives.[213] This eventually became the accepted basic design for the SKA-Mid antennas, although it took a long time to be fully accepted.

#### 6.4.5.1 The Saga of DVA-1: The SKA Prototype Dish

The Large-Number—Small-Dish (LNSD) antenna array concepts had been defined as part of the SKA Reference Design in early 2006. In the 2 years following, pressure mounted to define the actual dish design, and nail down what was clearly the largest single cost-component of the SKA. A high specification, low-cost design was needed if the SKA were to come even close to meeting the projected cost targets. As described above, it was considered that traditional designs could not deliver this combination, and so a great deal was riding on the mooted potential innovation aspects and on the decision-making process.

As described above, beginning in 2008 the TDP's task was to act as a clearing house for antenna design, in addition to their own program, which called for the development and production of an SKA prototype antenna. The broad outline was discussed at the San Francisco meeting in March, 2008.[214,215] Most of the TDP effort between mid-2008 and 2009 was devoted to (1) dish optics studies[216,217,218] (2) the design[219,220,221] and (3) performance and cost.[222] An offset-Gregorian optics design clearly had had momentum for a long time, but questions of the diameter, implementation and cost remained. As described in Sect. 6.4.3.4, the cost of an offset antenna was higher than a symmetric design, but not so much that the difference could not be afforded, especially considering the higher $A_e/T_{sys}$ performance metric

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[213] hba.skao.int/SKAHB-282 *Summary of a Group Discussion after Main DVA1 Meeting: Design Choices,* Baker, L., 15 April 2010.

[214] hba.skao.int/SKAHB-244 *Meeting Summary, Antennas Working Group Meeting,* Baker, L. and Cordes, J., San Francisco, 13 March 2008.

[215] hba.skao.int/SKAHB-246 *Index and Outlines of Talks, Antennas Working Group Meeting TDP* Antenna Working Group, San Francisco, 13 March 2008.

[216] hba.skao.int/SKAHB-266 *Choosing Offset Gregorian Optics for the SKA/TDP Prototype - Discussion Summary and Rationale,* Baker, L., TDP Memo 13, 2009-06.

[217] hba.skao.int/SKAHB-268 *Diffraction Analysis of a Preliminary Dual Shaped Reflector Design for the SKA/TDP Prototype Antenna,* Baker, L. and Holler, C., TDP Memo 11, 29 June 2009.

[218] hba.skao.int/SKAHB-272 *SKA Offset Optics Design (Progress Update),* Cortés-Medellín, G. and Imbriale, W., T.

[219] hba.skao.int/SKAHB-262 *TDP Antenna Specification: Structural Mechanical Portion,* Fleming, M., TDP Memo 8, Rev. B, April 2009.

[220] hba.skao.int/SKAHB-267 *TDP Antenna Optics Design Possibilities,* Fleming, M., TDP Memo 14, June 2009.

[221] hba.skao.int/SKAHB-283 *Hydroforming Process—Short Description,* Fleming, M., DVA1 Meeting, Arlington, Virginia, 15 April 2010.

[222] hba.skao.int/SKAHB-264 *Hydroformed Metal Reflector Production Cost Estimate,* Fleming, M., T.

for offset antennas. In parallel with work on other aspects, work on comparing dish costs continued to the end of 2010.[223]

Meanwhile, the SPDO was focussed mainly on bringing the SKA dishes into a system engineering framework (see Sect. 6.2.2.2) as part of the larger SKA-Mid design.[224] The resulting analysis was described in an SPDO Memo[225] and in documents that defined a Dish Verification Program.[226,227]

In February 2009, the SPDO drafted a TDP/DRAO/SPDO agreement[228] to (lightly edited) "carry out a joint program of work on PrepSKA WP2 Tasks according to an agreed timescale and with agreed deliverables and follow an agreed project management methodology—as outlined in the Guiding Principles document" (see Sect. 6.2.2.2). It is not certain that this agreement was ever signed, but it did provide a mutual understanding of the roles and responsibilities of the parties, a detailed work-breakdown structure, and a timeline.

The question of the diameter (see Sect. 6.4.3.1) had been unresolved for some time and a solution had to be found to make progress with a prototype, although even this was questioned by the TDP which argued that several prototypes would be required and the diameter of the first prototype would not need to be final. The TDP favoured a 12-m diameter, mainly because they probably would not be able to carry forward the hydroforming option for a 15-m antenna. Also, they were not really making progress on a 12-m hydroformed antenna, mainly due to the huge cost of tooling.

The SPDO favoured a 15-m antenna, based on an analysis of capital and operational costs (e.g., maintenance) for a smaller number of antennas.[229] This analysis was validated separately in a discussion document on choosing 12-m or 15-m dishes.[230] Nevertheless, it was not absolutely clear to anyone that any 15-m mould-based antenna could be prototyped, but it seemed probable that a mould-

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[223] hba.skao.int/SKAHB-288 *Antenna Configuration Cost Comparison,* Fleming, M., TDP Antenna Design Note, 21 December 2010.

[224] hba.skao.int/SKAHB-155 *Guiding Principles, Activities and Targets for PrepSKA Work Package 2, Dewdney*, P., SKA Project Office Report, 02 November 2008.

[225] hba.skao.int/SKAHB-254 *Rationale for Re-Organizing PrepSKA WP2 Work Packages related to Dish Design and RF Systems,* Roddis, N. and Dewdney, P., SKA SPDO Memo, 26 October 2008.

[226] hba.skao.int/SKAHB-260 *Dish Verification Program: Rationale and Implementation,* Roddis, N. and Dewdney, P., SKA SPDO Memo, 17 April 2009.

[227] hba.skao.int/SKAHB-276 *Dish Verification Program,* Dewdney, P., et al., SKA SPDO Memo, 09 December 2009.

[228] hba.skao.int/SKAHB-256 *TDP-DRAO-SPDO Agreement (MoA) on PrepSKA Work Package 2 Activities SPDO* Document, 06 February 2009.

[229] hba.skao.int/SKAHB-279 *SKA System Costs vs Antenna Diameter for Fixed Collecting Area in 12–15 m Diameter Range,* Dewdney, P. and Roddis, N., SKA SPDO Memo, 12 February 2010.

[230] hba.skao.int/SKAHB-284 *12 m or 15 m Dish Choice for the SKA—Discussion Document,* McCool, R. and Colegate, T., SKA SPDO Memo, April 2010.

based composite carbon fibre reflector (see Sect. 6.4.4.2.1) could be built. As a fall-back, a traditional panelled dish would be pursued.

The positions of the TDP and the SPDO were made clear in an interchange of notes[231] in which the SPDO outlined their key requirement: the deliverable had to be a "near-production prototype dish that had been carefully tested". The TDP was inclined to view the dish verification program as consisting of a "first prototype of a small converging series of prototypes", DVA-1, DVA-2, possibly with different diameters. Also, the SPDO emphasised that the diameter should be based on system cost and performance, not on the cost of a prototype. The TDP was very concerned that abandoning hydroforming would undercut their credibility with the US National Science Foundation, which was funding them.

The over-riding consideration was the timescale. The PrepSKA program had to demonstrate a costed, tested dish design. By the end of 2009, the TDP and other proponents of dish designs realised that much closer collaboration was necessary. The TDP put forward a draft Dish Verification Plan,[232] which identified potential partners including NRC/DRAO which could provide reflectors, NRAO which could provide a test site, CETC54 in China which could provide entire antennas, and the South African SKA Project Office which was interested in collaborating on antennas. It was emphasised that the selection of the basic design parameters would need to be made early in 2010.

In the meantime, the South African group approached NRAO with a collaboration proposal involving NRC/DRAO for which NRAO would provide design, testing expertise and a test site, while NRC/DRAO would provide its mould and composite dishes. However, NRAO expressed a general concern that the whole dish development effort would be fragmented. In fact, fragmentation did happen briefly but shortly afterwards, a group consisting of the SPDO, TDP and DRAO coalesced without NRAO and South Africa. Tentatively, they agreed to build a 15-m prototype if the funds could be found, otherwise a 12-m prototype[628].

A major DVA-1 meeting was held in Arlington, Virginia in April 2010 to discuss all aspects and alternatives for the DVA-1 design, including alternatives from potential suppliers, such as CETC54. The result was not definitive, but a smaller group led by the TDP arranged a side meeting at which a more detailed description, "Selected Baseline Design", was hammered out.[233] This was a 15 × 18-m, shaped[234] offset design with a 4-m sub-reflector with space at the focus for a variety of feeds,

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[231] hba.skao.int/SKAHB-280 *SPDO-TDP Position Statements on SKA Antenna Diameter,* Dewdney, P., Roddis, N., Schilizzi, R., Cordes, J., Interchange of Notes, 15 January 2010.

[232] hba.skao.int/SKAHB-275 *Dish Verification Program, Preliminary Program Plan,* Baker, L., draft v0.5, October 2009.

[233] hba.skao.int/SKAHB-282 *Summary of a Group Discussion after Main DVA1 Meeting: Design Choices,* Baker, L., 15 April 2010.

[234] On a dual reflector antenna, it is possible to tweak the shape of the reflectors to direct more signal power to outer areas of the dish so that there is a more uniform illumination of the primary. This maximises the efficiency of the dish but results in reflector surfaces that are no longer conic sections, although they usually only deviate slightly from elliptic or parabolic cross-sections.

including WBSPFs. What remained to decide is whether the feed should be mounted above the reflector (‘feed-up’) or below (‘feed-down’).

Although at arm’s length, since it did not control the national funding involved, the SPDO continued to stress the need for system engineering rigour and produced a top-level specifications document for DVA-1[235] which specified the size and optical configuration but was agnostic on the fabrication method. This had to be kept general because there were still competing visions for the SKA dishes. A Dish Conceptual Design Review (CoDR) was held in Socorro in February 2011, with review-panel members that were acknowledged experts in antenna design. The project plan presented at this CoDR consisted of the fabrication of a 15-m composite reflector by the DRAO team, to be built on the ALMA antenna test site at the NRAO VLA site in New Mexico (see below). Although the panel expressed concerns over the technical risk of the rim-supported composite reflector and a lack of a clear management structure, it concluded that the project was ready to proceed to a more detailed, preliminary design stage.

The SPDO and others were concerned about qualifying and testing the prototype if it were just a single dish at the DRAO site. A test plan involving the construction of DVA-1 (or a copy) on the VLA site had been put forward in 2009 by the SPDO.[236] This would involve a battery of single-dish tests, followed by tests using the Expanded -VLA (EVLA) antennas in interferometer mode with the prototype. Most of the proposed tests would require only a few VLA antennas, but one or two tests would require the entire array for a short time. Several people in the US questioned whether the interferometry segment of the plan would work. Nevertheless, it was eventually agreed that even single-dish testing at the EVLA site would be very useful and bringing in expertise from NRAO would be important.

During mid-2011, a Letter of Intent was being circulated that established a framework for the design, construction and testing of DVA-1. After delays resulting from legal concerns, it was signed by Cornell University, the Herzberg Institute of Astrophysics (NRC in Canada), NRAO, and the University of Manchester (representing the TDP, DRAO, NRAO and the SPDO, respectively). This group formed a Management Board for the DVA-1 project, chaired by Bob Dickman of NRAO. An engineering team led by a Project Engineer from the University of California (Berkeley), a Project Manager from NRAO, and technical experts were assembled using a combination of funds and contributed personnel.[237] Their near-term goal was to bring the project to meet the criteria for a Dish Subsystem Preliminary Design Review.

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[235] hba.skao.int/SKAHB-298 *Outline Specification for the DVA1 Dish,* Dewdney, P. and Roddis, N., SPDO document WP2-020.045.020-RS-001, 16 September 2011.

[236] hba.skao.int/SKAHB-269 *Dish Verification Program, Test Plan,* Dewdney, P. and Roddis, N., SKA SPDO Memo, 29 June 2009.

[237] hba.skao.int/SKAHB-305 *DVA1 Project Management,* Ford, E., presentation DVA1 PDR meeting, 29 June 2012.

By September 2011, the TDP was at the end of its term and needed an extension of funding to continue. The US National Science Foundation (NSF)) intended to hold a "Programmatic Review" to assess the technical progress of the project at the CDR level as well as the value of the DVA-1 program to US radio astronomy beyond the SKA. However, in the light of the ASTRO2010 decadal report (see Sect. 4.5.3), the NSF was reluctant to continue funding all aspects of the TDP program but was willing to consider the DVA-1 development separately from the SKA on the basis that an innovative dish program might be useful in a future project. Nevertheless, they did permit the TDP to use its remaining resources to support the DVA-1 program. However, differing goals among the partners led to tensions within the project.

A Preliminary Design Review (PDR) was held for DVA-1 in October 2011; the review panel recommended that the project proceed to final design and hold a Critical Design Review (CDR).[238] However, by early 2012 the TDP funds had dried up and the project had to consider a 'Plan B'. The Canadian NRC agreed to carry on, provided there was support from PrepSKA for the build phase, especially the pedestal and mount, which was close to production-ready in the US.

The DVA-1 project was now 'under one roof', in Canada, with one goal, to provide the SKA with a qualified dish, as described in (Lacy et al., 2012).

A CDR was held in July 2012 and construction began with a combination of NRC and PrepSKA funds.[239] This allowed the DVA-1 pedestal and mount to be built and sent to the DRAO site and provided support for key TDP personnel to continue.

The CDR review was carried out by five internationally recognised experts in the field. Their report[240] was very complimentary, while noting a few reservations on the maturity of some aspects of the design, understandable given the number of design innovations.[241] In particular, they noted: "The key aspects of the DVA-1 design include:

1. Use of a single-piece rim-supported carbon fibre reflecting dish that serves not only as the primary optical element but also as a major structural component,
2. Use of an unblocked offset optical design leading to a very clean antenna pattern,
3. Use of shaped (non-conic section) reflectors that are used to maximise the antenna gain while still minimising side-lobe response,
4. A secondary focus point optimised for today's leading wide-band feeds,
5. Clear access to both the secondary focus and primary focal region.

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[238] hba.skao.int/SKAHB-300 *DVA-1 Preliminary Design Review,* Brisken, W., et al., Review Panel Report, 21 October 2011.

[239] At the time, the top frequency specification was 10 GHz, later increased to 20 GHz.

[240] hba.skao.int/SKAHB-306 *DVA-1 Critical Design Review,* Brisken, W., et al., Review Panel Report, 07 July 2012.

[241] At that point the design became known as the "Single piece Rim supported Composite (SRC)".

While DVA-1 was not the first antenna to demonstrate these individual aspects, it was the first to apply all of them. Moreover, they were being applied to an impressively large 15-m by 18-m structure with surface tolerance requirements of 1 mm or better, while encountering a wide range of environmental conditions. Collectively these features offered promise of high antenna performance at low cost."

In addition to these innovations, the design team also demonstrated a reflectivity of the surface comparable to that of aluminium while maintaining a protective dielectric cover over the reflecting surface. The DVA-1 design also employed a semi-compliant diaphragm at the centre of the main reflector which reduced the need for a backup structure while maintaining sufficient stiffness against transverse wind loading. Moreover, the DVA-1 mount was also an innovative design. Its innovative features are neatly summarised in one of the DVA-1 CDR documents.[242] The key features of the design were later documented in more detail in an NRC report.[243] It is unfortunate that this group of features have yet to be found in a production antenna design.

Overall, this gave the SPDO reason to support this work in the expectation that a cost-effective, high-performance design would emerge.

Nevertheless, in the months leading up to the DVA-1 CDR, the SPDO was concerned about coverage of all the aspects of dish design for the SKA in reviews, eventually resulting in a tree-structured mind map.[244] The number of items beyond just an innovative and cost-effective structure indicated that it would be impossible to cover them all in a single review. This led to a persistent concern in the SPDO.

At this point the option for testing the DVA-1 antenna on the VLA site in interferometric mode disappeared. The level of funding required from Canada to build a facility there was more than was available. This highlighted one of the principal shortcomings of the composite design, the one-piece reflector required fabrication on site. The DRAO group carried out several studies on building portable fabrication facilities but was not able to follow through, and the alternative of fabricating multi-piece reflectors was thought to have significant cost and performance disadvantages.

At the same time DRAO found that they did not have the space to comfortably construct a 15 × 18-m reflector on the DRAO site and decided to build it in a nearby town which had a suitably large building. After working out weights, they realised that a large helicopter would be capable of lifting the main reflector and carrying it over the intervening mountain to the site. Moulds for the two reflectors were

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[242] hba.skao.int/SKAHB-304 *DVA1 Mount Design,* Fleming, M., DVA1 2012-06-28 CDR document, 23 June 2012.

[243] hba.skao.int/SKAHB-321 *Single-piece Rim-supported Elevation Assembly Mechanical Design,* Lacy, G., NRC document, 316-000000-004_DishStructures_SRC_Release, V2, 30 October 2015.

[244] hba.skao.int/SKAHB-301 *Dish Array Aspect Tree,* Dewdney, P., Rev. F, SPDO design note, 09 February 2012.

**Fig. 6.16** Top Left: The mould for the DVA-1 main reflector (16 × 18 m) under construction. Top Right: The DVA-1 mould for the sub-reflector (4 m diameter). Bottom left: The DVA-1 reflector unexpectedly becoming airborne and being abruptly halted by the rigging during helicopter transport. Credit: Gary Hovey. Bottom right: The reflector after being “popped back into place” and repaired. Credit: The National Research Council of Canada

assembled there and construction began (Fig. 6.16 top). Several improvements to the design were also incorporated.

In Oct. 2013, DRAO was ready to fly the reflector to the site. The dish was suspended under the helicopter by a long tether (Fig. 6.17). The first part of the journey went just as planned, but on the final approach the helicopter decelerated faster than the reflector causing the dish to swing ahead of the tether point. It then became airborne and when the reflector fell back down, the rigging halted its fall abruptly. The force from the deceleration caused the concave reflector to invert to a crumpled convex shape, apparently destroying a now inverted surface.

It seemed very unlikely that the reflector could be recovered. However, the head engineer suspected that industrial airbags used to right over-turned trucks could be used to ‘pop’ the surface back to its original shape. In an extraordinary effort, the team managed to successfully carry this out (Fig. 6.16 bottom). Although a few surface repairs were needed, the accuracy of the surface was retained to the original specification except for one small area. This was certainly a demonstration of the incredible resilience of the carbon fibre surface design.

While this was seen as a disaster at the time, it did demonstrate that a reflector suitable for the SKA could be transported from a central fabrication site to where it was to be installed. The fact that a helicopter can easily carry the weight illustrates an important advantage of CFRP construction. Of course, several more precautions would have been needed, such as providing some reinforcement of the surface during transport. Figure 6.18 shows the result after repair. Amazingly, the performance met design specifications, which at the time were for high efficiency at 10 GHz.

**Fig. 6.17** The DVA-1 15 × 18-m reflector being flown from the fabrication site near Penticton, B.C. to the DRAO site. Credit: The National Research Council of Canada

A significant design aspect was whether the feed should be located above the reflector ("feed high") or below ("feed low"). There were, and still are, pros and cons, and this was debated extensively. The structural issues were covered in a document presented at the DVA-1 CDR (June, 2012).[245] Structurally, the feed-high design presented advantages: the structure could be almost balanced on the pedestal and the support structure behind the reflector could be stiffer, leading to a compact design. The problem with the feed-low option was mechanical interference with the pedestal when pointing close to the horizon; in that case the elevation axis had to be cantilevered out from the top of the pedestal, or the back-up structure had to be split to avoid hitting the pedestal. In the analysis of a TDP Antenna Design Note,[246] this led to at least a 30% increase in capital cost. On the other hand, access to a high feed would require an elevated platform; the implications of this would certainly increase operations cost, but a thorough study of this was never carried out.

A third consideration was the impact on system noise originating from feed spill-over, radiation entering the feed from the ground (see Sects. 6.4.3.3 and 6.4.3.4). A thorough analysis[247] did indeed see this effect but concluded that only a modest increase in noise at low elevation angles would be incurred. In any case, radio astronomy observations attempt to avoid these angles because of increased

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[245] hba.skao.int/SKAHB-288 *Antenna Configuration Cost Comparison,* Fleming, M., TDP Antenna Design Note, 21 December 2010.

[246] hba.skao.int/SKAHB-288 *Antenna Configuration Cost Comparison,* Fleming, M., TDP Antenna Design Note, 21 December 2010.

[247] hba.skao.int/SKAHB-302 *DVA1 Optics Design and Analysis,* Cortés-Medellín, G., et al., DVA1 2011-10-04 PDR document, 17 June 2012.

**Fig. 6.18** The DVA-1 dish, after repairs and shortly after the sub-reflector was mounted. Credit: The National Research Council of Canada

atmospheric noise. However, this document did also note that for the feed-low option it was possible to shield the feed from the spill-over noise, but not possible for the feed-high option. The final call was feed high.

The feed-high/feed-low discussion became a controversy, and eventually came back to haunt the DVA-1 project, mainly because of the operations cost, but also because of the ability to shield spill-over noise. Ultimately, the feed-low option was chosen for the SKA. This forced the NRC/DRAO to re-design the antenna as they readied themselves to build a second prototype. The original DVA-1 antenna is still in use for observations at 20-cm wavelengths but has never been fully tested to SKA specifications.

Although slightly beyond the scope of this book, an SKA Dish Consortium (SKADC) had been formed with the responsibility for choosing a dish design for the SKA. By that time three other concepts were being proposed, including the Single-piece Rim-supported Composite (DVA-1/SRC). The SKA required a low-risk technology encompassing as little development as possible.[248] A dish

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[248] hba.skao.int/SKAHB-316 *Elevation Assembly Structure Technology Down Selection Report,* Chalmers, D., SKA-TEL-DSH-0000040, 16 February 2015.

with panels, rather than a single-piece reflector, supported by a traditional space-frame backup structure was selected. The overall cost of SKA-Mid led to a descoping of the project, including a reduction of the number of new antennas for SKA1-Mid while making up the difference by incorporating the new MeerKAT antennas for lower frequencies.

The DVA-1 saga came to an end, at least for the SKA. The planned DVA-2, designed to meet the 20-GHz specification, was eventually built. Nevertheless, development of technology continued at a low level, with designs proposed for the next-generation VLA (ngVLA) [249] antennas. As well, small-scale commercialisation of the technology occurred for satellite communications at high frequencies.

Looking back at this story, it is easy to see reasons why the original intentions for innovation were not finally realised:

- Many relatively new technologies had to be incorporated into the design.
- Traditional structural designers and fabricators could not take on board the use of carbon fibre composites, which require a completely different knowledge base.
- The National Research Council of Canada (NRC Canada) devoted significant resources over the years, but still not enough to 'put it over the top'. In this respect, it is like the hydroforming program in the United States, although the effort in Canada was many times larger.
- Apart from the fading US contribution, the SKA community, itself, was not entirely behind the DVA-1 project, making international collaboration difficult. Other countries were still promoting options to either replace dishes entirely with aperture arrays, or were interested in other aspects of dish design (e.g. PAFs - see Sects. 6.4.4.1 and 4.3.3.1).
- The commercial market for large antennas is small. A large market has been the key to the adoption of carbon composites to other large structures, such as for aircraft. NRC Canada would have been much more interested and helpful in partnering with commercial organisations if significant commercial opportunities had been available.
- A way to tunnel through capital and collaboration barriers was needed. Perhaps only huge companies not beholden to taxpayers can afford this kind of risk. And perhaps they are huge because enough technology bets have paid off.

It is impossible to tell whether a real opportunity has been lost, or whether this technology would never have been competitive anyway. However, more persistence, time and resources would have made a big difference. If the US had not dropped out of the SKA, it would have been much more likely that resources and improvements in the practicality of the design would be found to bring the DVA-1 technology to maturity (see point {C} in Chap. 6 introduction). Nevertheless, as noted in Sect.

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[249] hba.skao.int/SKAHB-318 *Next Generation Very Large Array, Memo No. 5 Science Working Groups, Project Overview,* Carilli, C., et al., National Radio Astronomy Observatory (NRAO), ngVLA Memo 5, 28 October 2015.

6.4.3.1, the CHORD project has selected technology developed for DVA-1 for simpler, smaller dishes. This may be a steppingstone to the future.

#### 6.4.5.2 Independent Dish Array Developments, Precursor Telescopes and Impasses Leading to the System Concept Design Review

As it turned out, the dish development process was not as clean or clear-cut as initially planned in the Guiding Principles document (see Program 4 (P4) in SKASUP6-1[250]) and lack of focus was also noticed at the System CoDR in 2010 (see Sect. 6.2.2.9). National priorities took over, although cross fertilisation continued and there were many cooperative meetings over the next few years, led by the SPDO with the larger project in view. CSIRO persisted in developing a sky-mount design (see Sect. 6.4.4.1), eventually leading to ASKAP. SKA South Africa, as it was then known, continued with their own design iterations, ending with a version of an offset reflector, that led to MeerKAT antennas. ASTRON funded the design of a small, prime focus antenna that would fit with their interest in mid-frequency Dense Aperture Arrays as part of the SKADS Benchmark Scenario (see Sect. 6.5.5.2). In India a design for a reflector based on tension structures was being designed and was later prototyped (see Sect. 6.4.4.3). The TDP initially pursued hydroforming technology for fabricating reflectors, as used for the ATA dishes (see Sect. 6.4.4.2.3), but later collaborated with NRC/DRAO in Canada to build a prototype offset reflector using carbon fibre fabrication technology.

### *6.4.6 Cost Estimates for Dishes*[251]

The sensitivity of the system design to dish costs and the number of dishes was well understood.[252] Attempts were made to estimate the costs of dishes throughout the period covered in this book as proponents of the different dish designs were searching for ways to optimise the SKA system, especially to model the scaling of dish diameters and frequency ranges with cost.[253] Historical information on the cost of dishes was used for the latter approach despite the pitfalls of doing so.[254]

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[250] hba.skao.int/SKASUP6-1—WP2 Description of Work as a Matrix of Tasks and Programs.

[251] An expanded version of this section can be found in hba.skao.int/SKASUP6-10.

[252] hba.skao.int/SKAHB-273 *Discussion on SKA system cost sensitivity to assumptions,* Dewdney, P. E., Colgate, T., Roddis, N., exchange of email messages, 07 September 2009.

[253] hba.skao.int/SKAHB-278 *Discussion on SKA system cost vs antenna diameter*, Kellermann, K. I., Schilizzi, R. T., Dewdney, P. E., exchange of email messages, 08 January 2010.

[254] hba.skao.int/SKASUP6-10—Detailed Version: Cost Estimates for Dishes.

An interesting attempt at SKA cost modelling was made in 2007 in SKA Memo 90,[255] in which John Bunton (Australia Telescope National Facility) derived scaling for cost vs frequency, using collected historical information. Although the analysis was thorough, Bunton concluded "The author does not have a great deal of confidence in this result and, to confirm it, significantly more data are needed."

While cost-modelling of dishes was unreliable, cost models of the entire SKA system were an essential tool for understanding system trade-space, although not with high precision. (For a more general discussion of system trade-space, see Sect. 6.2.2.7 and SKASUP6-4). The radio astronomy community had actual construction experience with other components of the system, such as receivers, correlators, beamformers, operations and software. These other components have a direct influence on the number of dishes, hence their diameter and cost. Apart from the aforementioned Benchmark Scenario cost, a competing cost package, SKAcost,[256,257,258] was set up to include PAF technology and WBSPFs,[259] but not aperture arrays. Neither tool was complete, and so they were later combined into one tool that could be used for either vision of the SKA.[260] It is unclear whether these cost tools had much influence in the final version of SKA1-Mid, but it probably had little influence on dish size, design, or cost. It would be three years before a System Concept Design Review[261] forced the SKA to consider a more realistic size for the project, leading to a revised two-phase vision,[262] SKA Phase 1 and SKA Phase 2, and a more detailed system description[263] of an SKA Phase 1 system. The options available in these tools, including the size and number of dishes, had already been nailed down and the tools at that point were no longer needed.

The 'rubber hit the road' in 2009. To keep the US in the project, the SKA needed to be represented and highly rated in the upcoming report from the ASTRO2010

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[255] hba.skao.int/SKAMEM-90 *Dish Cost Frequency Scaling,* Bunton, J., SKA Memo 90, 15 January 2007.

[256] hba.skao.int/SKAMEM-92 *SKAcost: a Tool for SKA Cost and Performance Estimation,* Chippendale, A., et al., SKA Memo 92, 12 June 2007.

[257] hba.skao.int/SKAHB-277 *The cost of science: Performance and cost modelling of the Square Kilometre Array,* Colgate, T., et al., Poster Paper, January 2010.

[258] SKAcost could calculate NPV costs. However, when NPV was used without the accompanying information on the discount rate and construction schedule, the meaning has been lost.

[259] Wide-band Single Pixel feeds (WBSPFs) are feeds that can cover more than the approximately 2:1 bandwidth ratio, available to the most efficient feed horns. The 2:1 ratio is that maximum ratio that maintains a single waveguide mode in the feed.

[260] hba.skao.int/SKAMEM-120 *The SKA Costing and Design Tool,* Ford, D., et al., SKA Memo 120, January 2010.

[261] hba.skao.int/SKAHB-184 *SKA System CoDR_Panel_Review_Report*, Wild, W., et al., SKA Document, System CoDR Review Report, 19 March 2010.

[262] hba.skao.int/SKAMEM-125 *A Concept Design for SKA Phase 1 (SKA1),* Garrett, M.A., et al., SKA Memo 125, August 2010.

[263] hba.skao.int/SKAMEM-130 *SKA Phase 1: Preliminary System Description,* Dewdney, P. E., et al., SKA Memo 130, 22 November 2010.

Decadal Survey of astronomy[264] (Blandford et al., 2011). Among other things, the SKA needed to put forward a costed design, even though the SKA project was not sufficiently mature to undergo such detailed scrutiny.

Despite the risks (see SKASUP6-10[265]), the TDP, supported by the SPDO,[266] directly used dish-cost estimates from the ASKAP project to underpin costs, as that was the best information available at the time. The 12-m ASKAP antennas were designed and fabricated by the CETC54 company in China and built on site in Western Australia. Their unit structural cost was expected to be €160 k in 2009 (€1400/m$^2$).[267,268] In hindsight, this basis of estimate was difficult to ascertain for a variety of reasons. This led to scepticism, especially in the US, that the total cost estimate of $1767 million for the full SKA was reliable (see discussion in Sect. 4.5.3), leading to the eventual withdrawal of the US from the project.

By mid-2010 the 15-m DVA-1 design had momentum (see Sect. 6.4.5.1). Funded by a combination of TDP, NRC (Canada) and SPDO funds, the construction of a prototype dish began. The reflectors were provided by NRC and a contract was let for the mount and drive system to Minex Engineering Corporation, a small company led by Matt Fleming, who was very active in the SKA and the TDP.

A detailed budget[269] was assembled for all aspects of the job: design, fabrication, feeds and low-noise amplifiers (LNA), receiver backend, outfitting and single dish tests (no management overhead). It came to a grand total of US$4.2 million. Of this, the fabrication cost was US$2.26 M, of which US$1.04 M was tooling and setup, leaving US$1.2 M for the dish structure, itself. This was 5.5 times the cost submitted to ASTRO2010, €160 k (US$212 k in 2010). Although a reduction in the DVA-1 cost in production quantities[270] would have been substantial, there was no possibility of matching the ASKAP dish costs. A further reduction might have been found by fabrication in a country with low labour costs, but it still would have been a stretch.

So why the huge increase? The conclusion is that it is naïve to give too much credence to cost estimates until there is access to every detail of the design and all the

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[264] Every 10 years, the astronomical communities in the US gather panels of experts to set community-wide priorities for the coming decade. These surveys are facilitated by the US National Academies and commissioned by US Federal agencies, the National Science Foundation and NASA. A very high rating in the report of the survey is essential for large projects to proceed.

[265] hba.skao.int/SKASUP6-10—Detailed Version: Cost Estimates for Dishes.

[266] hba.skao.int/SKAHB-258 *ASTRO2010 Cost-page Submission,* Kellermann, K. and Schilizzi, R. T., SPDO-TDP draft document, 09 March 2010.

[267] hba.skao.int/SKAHB-259 *The Square Kilometre Array, Response to Request for Information (RFI1),* Cordes, J. M., et al., Project Description for Astro2010 Response to Program Prioritization Panels, 01 April 2009.

[268] hba.skao.int/SKAHB-271 *The Square Kilometre Array, Response to 2nd Request for Information (RFI2)*, Cordes, J. M., et al., Astro 2010 RFI#2 Ground Response, 27 July 2009.

[269] hba.skao.int/SKAHB-289 *DVA1_Detailed_Cost_Estimate, Baker,* L. and Fleming, M., TDP-SPDO_document, 04 May 2011.

[270] hba.skao.int/SKAMEM-116 *Feasibility and Cost Study of Manufacturing Composite Parabolic Reflectors for the SKA,* Wood, G. M., SKA Memo 116, 04 September 2009.

assumptions. Even less credence should be given to scaling. The conundrum is that to obtain accurate costs, irrevocable design decisions must be made, cutting off options.

Cost estimates based on a naïve understanding of the motivations of suppliers leads to poor cost projections, knowledge that is almost impossible to obtain in most supplier situations. An advantage of SPDO paying for part of the work was to have a say in the detailed design and to have access to a detailed cost breakdown, including labour and tooling. This is rarely possible in industry, where cost breakdowns are considered private intellectual property.

### *6.4.7 Innovations in Sampling the Focal Plane and the Struggle for Phased Array Feeds*

The basic theory of Phased Array Feeds (PAFs) has been known for a long time and was described by Rick Fisher[271] in 1993, inspired by discussions at the URSI General Assembly in Kyoto, Japan that year. Describing the region around the geometrical focus as a "Fuzzy Focus",[272] he pointed out that by sampling the focal region of a dish, all the information needed to construct multiple beams would be available. At the time, however, the necessary signal processing power did not exist.

Sampling the focal plane fields can be done by two basic methods: Method 1) building an array or grid of feed horns, each of which feeds the dish in the way described in the Box in SKASUP6-7[273] or Method 2) sampling the electromagnetic fields directly using an array of small antennas fundamentally similar to an aperture array (see Sect. 6.5.1).

Figure 6.19 shows a PAF mounted in the focal plane of a parabolic reflector (dish). It illustrates a scheme that collects information not only from the axial (central) ray path, but also from all ray-paths displaced from the axial ray out to a radius that depends on the details of the design. Thus, the electromagnetic field pattern in the focal region (i.e., the Fuzzy Focus) emanates from a large angular region on the sky around the axial direction. The PAF consists of an array of small antennas (PAF elements, each about half a wavelength in size) that senses the off-axis fields. Their outputs can be combined to provide an image of a patch of sky several beams wide, rather than just one beam area. A more detailed explanation is provided in the Box in SKASUP6-11.[274]

PAF-equipped dishes also have the advantage that the field-of-view is approximately constant over its useful operating frequency range. This is in contrast to

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[271] hba.skao.int/SKAHB-211 *Very Large Aperture Radio Telescope: Possible Fundamental Changes in Design, Fisher, J. R., Research Note*, 27 October 1993.

[272] The distribution of electric field around the geometrical focal point of the reflector.

[273] hba.skao.int/SKASUP6-7—The Operating Principles of a Radio Telescope Antenna.

[274] hba.skao.int/SKASUP6-11—Detailed Version: Principles of Phased Array Feeds (PAFs).

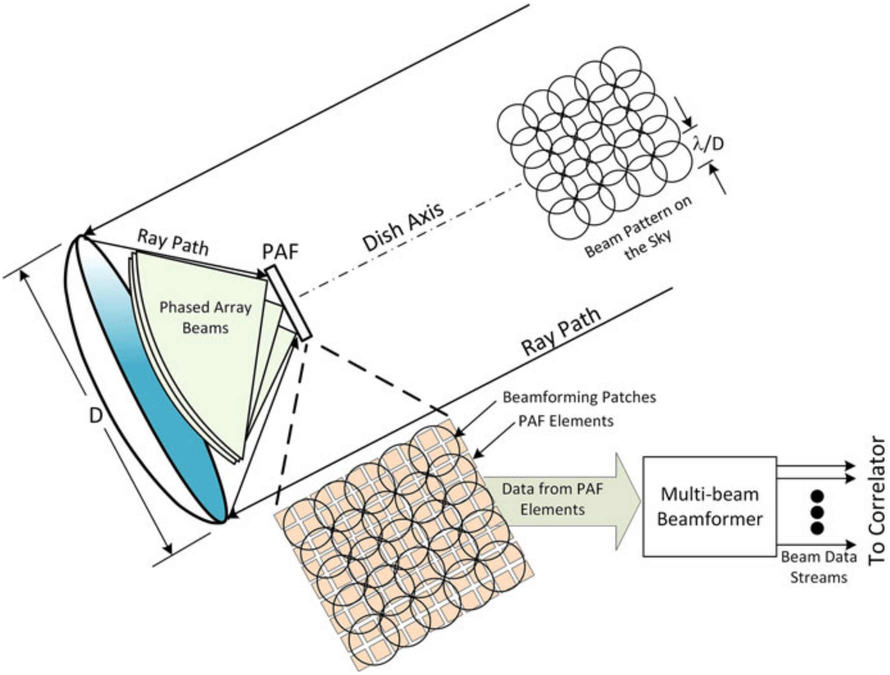

**Fig. 6.19** An illustration of the principles of PAFs

dishes with single-pixel feeds, whose areal field-of-view is inversely proportional to the square of frequency.

Although PAFs are an attractive concept, there are several issues that have made its widespread implementation in arrays difficult:

- Each of the antenna elements in the PAF requires an LNA. In a standard radio astronomy configuration, the LNAs are cryogenically cooled to reduce amplifier noise.[275] But for a PAF at the frequency of the hydrogen line (1420 MHz) whose diameter is more than one metre, this would require an impractically large, heavy cryostat. Hence, since the LNAs on large PAFs must operate at ambient temperature, the amplifier noise can be ten times that for cryo-cooled LNAs. In a comparison of PAF Survey Speed sensitivity[276] (see Sect. 6.4.1 and SKASUP6-7[277]) with the traditional system, a dish with a low-noise LNA, scanning the same area as the PAF sky-coverage, can image with higher sensitivity than a PAF in the same observing time.

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[275] A side-benefit of cryo-cooling is also temperature stability, which stabilises the amplifier gain.

[276] The Survey Speed sensitivity is inversely proportional to the square of system noise (Tsys$^2$).

[277] hba.skao.int/SKASUP6-7—The Operating Principles of a Radio Telescope Antenna.

- In any parabolic dish, the maximum focussed power is available on the principal axis. Off-axis power is lower and more spread out. This means that efficiency is lower for beams formed from PAF antenna elements in off-axis positions.[278] Moreover, the off-axis beam shapes vary slightly from one another, complicating calibration and beamforming. Efficiency loss lowers the signal-to-noise ratio of data from those beams. And finally, there are strong coupling effects between the PAF antenna elements, which must be considered in forming the beams. This means that more inputs from the elements must be summed than if the antenna elements were receiving independent information.
- Another area of concern is the cost of signal and data processing (see Fig. 6.19). This system component is not required in a traditional design where single 'analogue' feed horn does the same job for one beam.

In the long term, it may be possible to overcome or ameliorate these issues. For example, the cost of digital signal processing (DSP) continues to fall, and such processes now consume less power. Also, uncooled LNAs have been developed that are much less noisy than those from a few years ago, but LNA progress is much slower than observed for DSP. Research workshops continue to be held (see Sect. 6.4.7.4) to utilise these developments with the goal of making PAFs more competitive.

PAFs are easiest to implement on large single dishes where there is the space and weight-bearing capacity at the focus to mount cryogenically cooled PAFs (cryoPAFs) (e.g., (Jeffs et al., 2008; Cortés Medellín et al., 2015; Roshi et al., 2017)). This investment is much more worthwhile on these telescopes than on arrays of smaller antennas.

However, there is a corner of radio astronomy discovery space inhabited by uncooled PAF-equipped arrays of radio telescopes like ASKAP where there is more of a premium placed on sky coverage than sensitivity. With the large sky coverage, ASKAP and other telescopes in this category (e.g., CHIME (Amiri et al., 2018)) have discovered extraordinary tracers of far-away astrophysical events—powerful radio transients of extremely short duration—now known as Fast Radio Bursts (FRBs). Because they are strong and originate randomly in the sky, instantaneous sky coverage is more important than sensitivity (see Sect. 6.2.2.8).

### 6.4.7.1 PAF Developments in Individual Institutions

Over many years starting in 1998, significant research and prototyping effort was devoted to PAFs in Canada, Australia, the Netherlands and the USA which we briefly summarise in the following sections. A brief history of these developments from the Australian perspective has been written by Ron Ekers and John O'Sullivan that describes the transition from the successful development of multi-beam

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[278] This effect is worse for dual-reflector antennas and for shaped reflectors (see Sect. 6.4.5.1 and 6.4.7.1.2 for an explanation).

receivers on the Parkes radio telescope (method 1 in the previous section) to discussions at CSIRO in the late 1990s of PAF designs (method 2).[279] Some of this work continues at the time of writing. Each institution had different motivations, but all were intent on applying them to the SKA telescopes in some way.

#### 6.4.7.1.1 Dominion Radio Astronomy Observatory (DRAO, Canada)[280]

DRAO/National Research Council began planning the Large Adaptive Reflector (LAR)[281] in about 1996, which required a large PAF suspended by an aerostat to feed a huge prime focus reflector on the ground. This scheme could not operate efficiently without the 'programmable beam-shape' capability inherent in the PAF concept. Hence LAR success was completely dependent on the success of PAFs.

When the SKA Reference Design (see Sect. 6.2.1.3), including the choice of small diameter dishes was adopted in 2006, the LAR project was wound down, but interest in PAFs continued as a potential contribution to the SKA. The initial investigations had already begun to reveal some of the limitations of PAFs for radio astronomy (Veidt & Dewdney, 2005b). By that time, other groups were active in PAF research and DRAO's inclination was to collaborate but continue their own program. DRAO collaborated actively with NRAO and the Université Catholique de Louvain in Belgium to understand whether PAFs could play a role in upgrading the Very Large Array (VLA) in New Mexico.[282]

But it was obvious that such complicated radio frequency (RF) systems could not be understood by paper analysis and theory alone. In 2005, DRAO obtained funding to build a Phased Array Demonstrator,[283] known as PHAD[284] (Veidt & Dewdney, 2005a), collaborating with the University of Calgary.

The PHAD program was created to develop a fundamental understanding of the capabilities and limitations of phased-array feeds on reflector antennas, and to answer some key questions about the design of PAFs[285,286] (Veidt et al., 2011). It

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[279] hba.skao.int/SKAHB-327 *The Development of Focal Plane Arrays in Radio Astronomy,* Ekers, R. D. and O'Sullivan, J., presentation, 14 November 2022.

[280] The Dominion Radio Astrophysical Observatory (DRAO) at the time was part of the Herzberg Institute of Astrophysics in the National Research Council of Canada.

[281] See hba.skao.int/SKASUP6-28—The Large Adaptive Reflector (LAR).

[282] hba.skao.int/SKAHB-216 *Focal Plane Arrays for the VLA?,* Brisken, *W., presentation,* ASTRON, The Netherlands, 11 May 2004.

[283] hba.skao.int/SKAHB-222 *PHased-Array feed Demonstrator: Project Definition,* Veidt, B., NRC/DRAO document, 16 May 2006.

[284] hba.skao.int/SKAHB-220 *HIA Penticton—Phased-array Feed Development for Radio Astronomy,* Dewdney, P., NRC document, 12 May 2005.

[285] hba.skao.int/SKASUP6-12—Detailed Version: Development of PAFs at the Dominion Radio Astronomy Observatory (DRAO, Canada) and the University of Calgary.

[286] hba.skao.int/SKAMEM-115 Focal Plane Array Simulations with MeqTrees 1: Beamforming, Willis, A.G., et al., SKA Memo 115, August 2009.

was a modest-sized, engineering demonstrator consisting of a 200-element array of Vivaldi antenna elements.[287] The system was designed for flexibility and quick turn-around of results.[288] In a related program, the University of Calgary pursued an even more advanced version of focal plane sampling using 3D space-time plane-wave filtering techniques.[289,290] For further details see SKASUP6-12.[291]

DRAO continued an active role in collaborations with the other institutions until 2015, when the Herzberg Institute proposed to build a large cryogenically cooled PAF,[292] although this never came to fruition.

#### 6.4.7.1.2 CSIRO (Australia): Development of ASKAP

The CSIRO group in Australia recognised PAFs quite early as an emerging technology for radio astronomy, a compromise design approach between passive collecting area exhibited by reflectors and active collecting area exhibited by aperture arrays. PAFs could combine well understood technology for both. In contrast to the conservative investigations in Canada, the well-funded CSIRO group eventually 'bet the farm' on PAFs as the best approach to achieving the sensitivity (survey speed) goals of the SKA. In 2002 CSIRO and ASTRON collaborated on an experiment to use an aperture array tile as a feed for a Luneburg Lens.[293] In 2004/2005 PAFs became the underlying technology driver for the series of prototype array proposals. Prototyping began in 2005 with a series of test interferometers, the New Technology Demonstrator (NTD) (Hayman et al., 2008), followed by the xNTD.[294] But these were overtaken by events and not actually completed.

Not surprisingly, the test sites in the Sydney area were badly contaminated with RFI, which led to a decision to carry out the testing on the remote site proposed for the whole SKA in Western Australia. This also satisfied a quasi-political need to show that CSIRO could effectively use the site and led to the test project becoming an entity encompassing almost all of Australia's SKA ambitions. Progressing

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[287] hba.skao.int/SKANEWS-9 *SKA Newsletter Vol.* 9, January 2006.

[288] hba.skao.int/SKAHB-237 *Phased-Array Feeds for Centimetre-Wave Radio Telescopes,* Veidt, B., et al., presentation at the Joint URSI-APS meeting, Ottawa, Canada, 22 July 2007.

[289] hba.skao.int/SKAHB-242 *Real-time Systolic Three-dimensional Space-time Digital Filters for SKA Radio Astronomy,* Bruton, L. T. and Madanayake, A., University of Calgary Electrical Engineering document, 15 November 2007.

[290] hba.skao.int/SKAHB-243 *Beamforming of Temporally-Broadband-Bandpass Plane Waves using 2D FIR Trapezoidal Filters,* Gunaratne, T. and Bruton, L., presentation at the Dominion Radio Astrophysical Observatory (DRAO), 20 December 2007.

[291] hba.skao.int/SKASUP6-12—Detailed Version: Development of PAFs at the Dominion Radio Astronomy Observatory (DRAO, Canada) and the University of Calgary.

[292] hba.skao.int/SKAHB-324 *NRC cryoPAF4—a cryogenic phased array feed,* Locke, L., presentation, PAF Workshop, Penticton, Canada, 04 November 2015.

[293] See hba.skao.int/SKASUP6-30—Luneburg Lenses.

[294] hba.skao.int/SKANEWS-9 *SKA Newsletter Vol.* 9, January 2006.

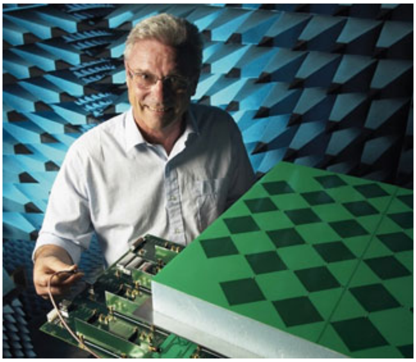

**Fig. 6.20** An early version of the ASKAP chequerboard array being tested in an anechoic chamber by John O'Sullivan, the designer. Credit: CSIRO Radio Astronomy Image Archive CRAIA-SKA009

through a variety of names,[295,296] by 2007 it had grown into a 36-antenna telescope proposal, now renamed the Australian SKA Pathfinder (ASKAP), and received $A95M in construction funding (see Sect. 4.3.3.1). At that point it had all the accoutrements of a formal project.[297]

Although the TDP in the US was not very interested in PAFs, they were charged with tracking the progress of dish technology, and ASKAP was reported upon and promoted in Antenna Working Group (AWG) meetings[298] on both technical and scientific fronts.

By this time there was a great deal of confidence at CSIRO in PAFs and how to build their supporting infrastructure, such as beamformers, for a reasonable cost. For example, with considerable foresight in 2004, it was clear that many thousands of RF signal chains would be required for the SKA, and so CSIRO embarked on plans for a Wideband Complementary Metal-Oxide-Semiconductor (CMOS) Integrated Receiver (Jackson, 2004), an integrated circuit that could greatly reduce the cost of these components.

While most competitors were focussed on Vivaldi antenna elements, the CSIRO group developed an array of patch antennas for the ASKAP PAFs, which they reported on in 2006[299,300] (O'Sullivan et al., 2008). These look like a chequer board printed circuit (Fig. 6.20), connected to amplifiers located below the circuit

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[295] Initially the project was called the Mileura International Radio Array (MIRA). That name was subsequently replaced by MIRA-NdA—large-N, small-d Array (MIRANdA). All these eventually developed into ASKAP.

[296] hba.skao.int/SKAHB-232 *The Milyura International Radio Array (MIRA) C.*

[297] hba.skao.int/SKAHB-231 *Australian SKA Pathfinder ASKAP Master Plan,* Australia Telescope National Facility, CSIRO, 03 January 2007.

[298] hba.skao.int/SKAHB-254 *Rationale for Re-Organizing PrepSKA WP2 Work Packages related to Dish Design and RF Systems,* Roddis, N. and Dewdney, P., SKA SPDO Memo, 26 October 2008.

[299] hba.skao.int/SKAHB-223 *Array impedance and receiver matching,* O'Sullivan, J., et al., 18 May 2006.

[300] hba.skao.int/SKAHB-224 *Beamforming for Focal Plane Arrays,* O'Sullivan, J., 18 May 2006.

board through perpendicular transmission lines at the corners of each patch. The development of sky-mount antennas (see Sect. 6.4.4.1) solved a major issue with PAFs, fixing the orientation of the array of beams on the sky while the Earth rotates. By 2009 the ASKAP proposal was transformed into a major astronomical facility (DeBoer, 2009).

A collaboration on ASKAP was initiated in 2006 between CSIRO and the Canadian institutes involved in this aspect of SKA design.[301] Canadian scientists were very interested in a Southern Hemisphere telescope at deci-metre wavelengths that promised observing in such a short timeframe. A science proposal with a Canadian flavour[302] was developed and discussed widely, and significant instrumental variations to improve ASKAP's capabilities were included.[303] However, at the same time, concerns were building[304] that such a major effort would deflect from the larger goal of SKA participation. Not being able to negotiate a solid contribution to ASKAP, the National Research Council in Canada eventually abandoned the collaboration in favour of putting as much effort as possible into the SKA itself.

An additional collaboration between CSIRO and SKA South Africa, called CONRAD (CONvergent Radio Astronomy Demonstrator[305]) was established in 2007 to address SKA computing challenges, particularly for the software required for very wide-field imaging. This turned out to be a fruitful exercise that continued for several years.

Adoption of PAFs for the SKA hit a major bump in the road around 2010; there was a building consensus in a series of meetings organised by the TDP that the optical design for the SKA dishes had to be an offset Gregorian (dual reflector) antenna.[306] Moreover, in the quest to maximise sensitivity, the SKA dishes were to be 'shaped' (see Sect. 6.4.5.1). This greatly increases the gain of the antennas at the expense of lower gain when the feed is displaced from the central ray (off-axis performance). This obviously affects the sensitivity of the off-axis elements of a PAF array. The energy is still present in the off-axis focal region, but it is more spread out and requires a larger PAF to capture it efficiently.

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[301] hba.skao.int/SKASUP6-14—CSIRO Collaboration with Canadian Institutes on ASKAP.

[302] hba.skao.int/SKAHB-235 *Science with MIRA—Discussion Document,* Bartel, N., et al., The Canadian SKA Science Advisory Committee, 08 March 2007.

[303] hba.skao.int/SKAHB-233 *Potential Variations on MIRA Performance with the addition of Canadian funding,* Dewdney, P. E., Herzberg Institute of Astrophysics Document, 22 February 2007.

[304] hba.skao.int/SKAHB-234 *MIRA Collaboration Concerns,* Wall, J., private communication, 01 March 2007.

[305] See hba.skao.int/SKASUP6-15—Computing Challenges: CSIRO collaboration with South Africa.

[306] hba.skao.int/SKAHB-282 *Summary of a Group Discussion after Main DVA1 Meeting: Design Choices,* Baker, L., 15 April 2010.

In comparison, the ASKAP dishes are relatively simple prime-focus, unshaped designs,[307] ideal for PAFs because off-axis performance in this design falls off relatively slowly. In the case of a PAF feed, shaping is not necessary because in principle the same effect can be created by the way that the sampled data from all the PAF elements is combined to synthesise a dish beam.[308]

In 2008, anticipating the trend towards offset Gregorian designs, the CSIRO began a series of investigations as to how well PAFs would work on these reflectors. This work continued for several years, primarily to preserve the option to construct a third SKA telescope in Australia—SKA Survey (see Sect. 6.4.7.5). SKA Survey was proposed in the 2013 Baseline Design[309] (see Sect. 6.4.7.5) as a much larger follow-on to ASKAP. However, designing specific dishes for SKA Survey would have been quite expensive; the cost would be much lower to simply adopt the SKA-Mid design and to equip them with PAFs for SKA Survey. This led in two directions, one to influence the SKA design to be as PAF-friendly as possible, and the other to address the performance and cost issues arising from equipping SKA dishes with PAFs. A PAF-friendly design would be unshaped, but the other SKA partners were not willing to accept the concomitant lower sensitivity.

A presentation at the Dish Conceptual Design Review in 2011 discussed the possibilities and concerns to be addressed.[310] One of the greatest concerns was field rotation for an offset Gregorian dish design; the option of a third axis was not possible because the dish is not rotationally symmetric.[311] In 2012 the design of the two telescopes (dubbed 'SKA SPF' and 'SKA Survey') were broadly compared.[312]

Further developments on PAFs for the SKA are summarised in SKASUP6-13.[313]

#### 6.4.7.1.3 ASTRON (The Netherlands)

Although the SKA-related focus in The Netherlands was mostly on dense Aperture Array (AA) technology (see Sect. 6.5.5), there was a significant interest and effort

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[307] The optical elements of an unshaped dish are exactly conic sections. In the case of the main reflector, this is a parabola.

[308] Whether this operates fully in practice is debatable because of the impact of noise and other factors.

[309] hba.skao.int/SKAHB-206 *SKA1 System Baseline Design,* Dewdney, P. E., et al., SKA Document SKA-TEL-SKO-DD-001, 12 March 2013.

[310] hba.skao.int/SKAHB-296 *WP2.2 CoDR PAF Concepts,* Hay, S. G. and Veidt, B., presentation, SKA Dish Array Concept Design Review, 13 July 2011.

[311] In principle, rotation can be achieved electronically as part of the beamforming process, but in practice the sampling of the electric fields with an affordable PAF is too coarse to provide good results. Another option was rotating the PAF, itself.

[312] hba.skao.int/SKAHB-303 *SKA Antenna Issues*, Hay, S. G., presentation, 10 July 2012.

[313] hba.skao.int/SKASUP6-13—Further developments on PAFs for the SKA after 2013.

devoted to PAFs, beginning in 2002 when ASTRON sent an AA tile to CSIRO for evaluation as a PAF.

Driving the development of PAFs in The Netherlands was extending the life of the Westerbork Synthesis Radio Telescope (WSRT). The WSRT had been a workhorse of radio astronomy for decades, but the development of newer radio astronomy initiatives in The Netherlands indicated that a change was needed. The combination of general expertise in phased array technology and a scientific interest in deeper wide-field observations of atomic hydrogen gas (HI) pointed almost directly at PAFs for the WSRT. Moreover, ASTRON experts in electromagnetics had been closely involved with PAF theory (e.g., (Ivashina et al., 2011)). They collaborated extensively with colleagues at CSIRO, Brigham-Young University (BYU) and the National Radio Astronomy Observatory (NRAO) in the USA, and DRAO in Canada.

Serious development began with a PAF prototype, DIGESTIF, a small array of Vivaldi antenna elements, mounted at the focus of one of the WSRT reflectors. Interferometric imaging was demonstrated in 2009[314] by using other antennas in the WSRT array to correlate with a beam formed from a PAF-equipped antenna. APERTIF (APERture Tile In Focus), the full system, deployed on 12 of the WSRT antennas, opened in September, 2018. An updated technical description is contained in (van Cappellen et al., 2022). A surprising and important technical result was a reduction in so-called standing waves,[315,316] multiple reflections of the radio waves between the focus box and the vertex of the reflector.[317] This effect had long been a bugbear for spectral line observers.

Although the uncooled APERTIF PAFs were a good fit for their purpose on the WSRT, they were not suitable for modern antenna arrays like those being built for the SKA, mainly because of system noise.

From the perspective of the SKA, the influence of PAF development in The Netherlands came mainly through research into electromagnetic fundamentals rather than direct involvement in their implementation on SKA antennas.

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[314] hba.skao.int/SKANEWS-16 *SKA Newsletter Vol.* 16, July 2009.

[315] hba.skao.int/SKAHB-285 *Eliminating Sensitivity Ripples in Prime Focus Reflectors with Low-scattering Phased Array Feeds,* van Cappellen, W. A., presentation, Brigham-Young University Phased Array Workshop, 22 May 2010.

[316] hba.skao.int/SKAHB-323 *PAF Commissioning and First Science: Feedback for Engineers,* Chippendale, A., et al., presentation, PAF Workshop, Penticton, Canada, 04 November 2015.

[317] This generates a wavy background to the observed spectrum, which impedes the detection and measurement of spectral lines.

#### 6.4.7.1.4 US National Radio Astronomy Observatory (NRAO) and Brigham-Young University (BYU)

Stemming from long-standing interest in PAFs,[318] NRAO and BYU carried out an energetic academic research program in phased array feeds. Funding for this work was mainly motivated by the ultra-challenging radio astronomy application, but phased array feeds have many other applications in remote sensing and radar as well. BYU provided early theoretical underpinning (e.g., (Warnick & Jeffs, 2008; Warnick et al., 2018)), especially the signal processing for PAFs. They also contributed practical experimental verification in collaboration with NRAO (Jeffs et al., 2008), building a PAF mounted on a 20-m antenna at Green Bank, West Virginia. They also carried out experiments to illustrate the capability to 'null out' incoming radio frequency interference (RFI) (e.g., (Nagel et al., 2007)).

These groups understood the need to reduce the noise from PAF receivers and were early developers of cryogenically cooled PAFs (e.g., (Warnick et al., 2011)).[319] While impractically large and expensive for arrays like the SKA, they are ideally suited for single large antennas such as Arecibo (Cortés Medellín et al., 2015), the Green Bank Telescope and the Parkes 64-m telescope.

### 6.4.7.2 US Technology Development Program (TDP)

Although the TDP had a mandate in 2007 to coordinate dish development through the Antenna Working Group (AWG) (see Sect. 6.4.5), it paid little attention to PAF developments. The TDP was aware of PAF developments through presentations at AWG meetings and major SKA meetings (e.g., a presentation in March 2008 at the AWG meeting in San Francisco[320]) as well as publications (DeBoer, 2009). This position was partly because of scepticism of PAFs as technically ready for the SKA, and partly because of the influence of the group from the Allen Telescope Array (ATA), which favoured cryo-cooled, wide-band single-pixel feeds (WBSPF). By 2009, this thinking was reinforced by the SPDO, which was anxious to pin down a practical SKA antenna design as soon as possible.

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[318] hba.skao.int/SKAHB-211 *Very Large Aperture Radio Telescope: Possible Fundamental Changes in Design, Fisher, J. R., Research Note*, 27 October 1993.

[319] hba.skao.int/SKAHB-263 *Phased Array Feeds: Astro2010 Technology Development White Paper,* Fisher, J. R., et al., April 2009.

[320] hba.skao.int/SKAHB-248 *The Australian SKA Pathfinder (ASKAP),* DeBoer, D., presentation, Antennas Working Group Meeting, San Francisco, 13 March 2008.

#### 6.4.7.3 Discussions on the Technical Readiness of PAFs, 2006–2015

The technical readiness levels of the wide-field technologies, PAFs (and Aperture Arrays), were the subject of almost continuous discussion in SKA engineering and steering committee meetings for a decade from 2005 (e.g., SKA meeting in Manchester in 2007[321,322]).

At a major SKA meeting in Paris in 2006, Peter Hall, the Project Engineer at the ISPO, summarised[323] the state of development: the newly agreed Reference Design, non-technical issues, the realities of a looming time scale and most importantly, "hard questions" facing the SKA. All together it was a sweeping summary of the state of the technology and the diverse interests of the 12 or so major players. Of course, this especially included the wide-field technologies, AAs and PAFs.

The decision trees contained in this presentation indicated the complexity of design choices facing the SKA; several trees running in parallel were displayed, indicating a major organisational challenge to satisfy the interests of the proponents while also making optimum technical choices. Remnants of this challenge are still present, even as the SKA is well into the build phase.

As described in Sect. 6.2.1.4, a 'Tiger Team' was established by the International SKA Steering Committee (ISSC) in March 2007 to revise the SKA specifications and propose a baseline implementation of the SKA, leading to SKA Memo 100. Although the specifications were quite clear, many technical options remained open in SKA Memo 100. For the mid-frequency range (500 MHz to 10 GHz), the options were dishes with single-pixel feeds (wide-band feeds), dishes with PAFs and Aperture Arrays. Sub-groups were assigned to assess the strengths and weaknesses of each option including technical challenges and cost drivers, trade-offs and science implications.

For PAFs, SKA Memo 100 noted that further work was needed[324] to optimise "complex tradeoffs between many parameters including: focal length-to-dish-diameter ratio (F/D), prime focus or dual reflector, dish diameter, distance of focal plane from the focus, focal plane array size, number of elements, element spacing, upper and lower frequencies and number of beams and beam former inputs." It was also clear that more experience with operational systems for PAFs was needed. The state of SKA technology development at that time was summarised in a compendium of white papers on potential SKA technology in September 2009,[325] providing a factual

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[321] hba.skao.int/SKAHB-239 *Analysis & Specification of the Aperture Array System,* Faulkner, A. J. and Alexander, P., presentation at the Manchester SKA2007 meeting, 28 September 2007.

[322] hba.skao.int/SKAHB-240 *SKA Specifications Tiger Team Dish with Focal Plane Array,* Ekers, R.D. and Dewdney, P. E., presentation at the Manchester SKA2007 meeting, 28 September 2007.

[323] hba.skao.int/SKAHB-227 *SKA—Engineering, Reference Design & Hard Questions,* Hall, P. J., presentation, SKA Engineering and Joint Working Group Meeting, Paris, 04 September 2006.

[324] hba.skao.int/SKAHB-238 *Challenges of PAFs,* Dewdney, P. E., Contribution to the SKA Specifications Tiger Team, 30 August 2007.

[325] hba.skao.int/SKAMEM-91 *An SKA Engineering Overview: White Papers by the Task Forces of the International Engineering Working Group,* Hall, P. J., ed., SKA Memo 91, 14 September 2007.

background for the Tiger Team discussions leading up to SKA Memo 100. Some months after publication of the Memo, in a compendium of comments made by members of the Tiger Team at a meeting in March 2008,[326] it was clear that proponents of AAs were defending their corner with the insistence that AAs would operate very well up to 1 GHz. PAF proponents were less subtle but clearly thought that PAFs were likely to win out. The SPDO emphasised that early choices between PAFs and AAs might be forced by time scale considerations, not allowing much time for deep development.

In the SKA Project Execution Plan) (PEP) of 2011[327] (see Chap. 4 and Sect. 6.2.2.14), PAFs were not part of the Baseline Technology but were included in the AIP along with dense AAs at mid-frequencies and Wide-band Single Pixel Feeds (WBSPF). In this vein "The PAF design and development work will be guided significantly from the results of the PAFSKA program, which encompasses the pathfinder systems APERTIF, ASKAP and PHAD. The aim is to design, fabricate and test a prototype feed system in preparation for procurement for SKA Phase 1.". This mirrored the approach outlined in November 2010 (SKA Phase 1: Preliminary System Description SKA Memo 130[328]), where there is more detail on the expectations required of the AIP for each of the three technologies.

From those early days and until about 2015, PAF sensitivity (survey speed) in practice was a concern at the SPDO. A theoretical approach in 2010, but considering practical realities, was contained in a conference paper outlining the achievable field-of-view of antennas equipped with PAFs (Bunton & Hay, 2010). In 2012 the first key measurements of early ASKAP PAF sensitivity were available[329] as measured on a 12-m antenna at Parkes. Referring also to the previous paper on the achievable field-of-view, the average survey speed performance of these telescopes, when off-axis aperture efficiency was included, was of great interest at the SPDO.[330] The reduction of sensitivity and additional complexity effects were likely to be exacerbated in SKA dish designs.

In early 2015 a note[331] was circulated disputing the survey-speed projections contained in the SKA Baseline Design and found that the survey speeds of SKA1 Survey and SKA1-Mid were similar.

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[326] hba.skao.int/SKAHB-250 *Compendium of Tiger Team comments on SSRC Report,* Schilizzi, R. T., et al., Tiger Team internal discussions on the SKA Specifications Review Committee (SSRC) report, 26 March 2008.

[327] hba.skao.int/SKAHB-192 *Project Execution Plan: Pre-Construction Phase for the Square Kilometre Array (SKA),* Schilizzi, R. T., et al., SKA Document MGT-001.005.005-MP-001, 17 January 2011.

[328] hba.skao.int/SKAMEM-130 *SKA Phase 1: Preliminary System Description,* Dewdney, P. E., et al., SKA Memo 130, 22 November 2010.

[329] hba.skao.int/SKAHB-307 *ASKAP Phased Array Feeds,* Gough, R. & Chippendale A., presentation, 11 October 2012.

[330] hba.skao.int/SKAHB-313 *CSIRO PAF Optics Analysis,* Hay, S. G. and Smith, S., presentation at the Dish CoDR in Sydney, Australia, 02 June 2014.

[331] hba.skao.int/SKAHB-206 *SKA1 System Baseline Design*, Dewdney, P. E., et al., SKA Document SKA-TEL-SKO-DD-001, 12 March 2013.

#### 6.4.7.3.1 Cost of PAFs

Early attempts to develop cost models for PAFs were made in 2006.[332,333] Concluding that the cost of PAFs could be almost as great as the cost of a 10-m antenna structure, the "Cost of PAFs" document[333] noted (edited for clarity): “Threshold of pain: If the cost per frequency channel were $1000 and the cost of a beam-former were $20, then the cost of a PAF would have been $95,000, about the cost of an antenna. We must do much better than this!”. In hindsight, both PAF and antenna costs were underpriced.

At the Dish Array CoDR in July 2011, now approaching the PEP phase of the SKA,[334] review documents from CSIRO on behalf of the PAFSKA group (see below) contained a cost estimate for PAFs in production[335] of between €200 k and €250 k. This was substantially more accurate, but because SKA1-Survey was never built, it is impossible to know for sure.

### 6.4.7.4 PAFSKA

PAFSKA was a formal collaboration established in July 2010[336] to obtain a consensus agreement on the SKA PAF design within 1–2 years. It kicked off at a PAF workshop hosted by BYU in Provo, Utah in May 2010. Partners were primarily CSIRO, ASTRON, DRAO and BYU/NRAO, with CSIRO as the PrepSKA Lead Institute and coordinator.

A work plan[337] was developed and circulated in July 2010, which contained several milestones from November 2010, ending with the delivery of a production-ready PAF in December 2012. At the Dish Array CoDR in July 2011, PAFSKA presented a series of documents including a concept description for the SKA PAF Sub-system.[338]

PAFSKA was instrumental in holding together a global collaboration of partners with varying institutional goals in the SKA. The individual investigators had a strong

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[332] hba.skao.int/SKAHB-225 *Cost Equation Derivation for PFPAs,* Dewdney, P. E., personal archives, DRAO document, 31 July 2006.

[333] hba.skao.int/SKAHB-226 *Cost of PFPAs,* Dewdney, P. E. and Veidt, B., personal archives, presentation, 31 July 2006.

[334] hba.skao.int/SKAHB-200 *Overview of the PEP phase of the SKA,* Dewdney, P., presentation to the Dish Array CoDR meeting, 13 July 2011.

[335] hba.skao.int/SKAHB-294 *Concept Description: PAF Sub-System Initial Cost Estimate,* Jackson, C., SPDO document WP2-025.030-TD-001-A, 27 June 2011.

[336] hba.skao.int/SKAHB-281 *Minutes of the 4th Meeting of the SSEC (SSEC4) SKA* Science and Engineering Committee, 26 March 2010.

[337] hba.skao.int/SKAHB-287 *PAFSKA Work Plan,* Jackson, C., PAFSKA Consortium Work Plan for PrepSKA work package WP2, July 2010.

[338] hba.skao.int/SKAHB-293 *Concept Description: PAF Sub-System,* Jackson, C., SPDO document WP2-025.030-TD-001-A, 16 June 2011.

interest in overcoming the challenges of this enticing technology. But, despite several workshops, fundamental questions remained (see the next section).

#### 6.4.7.5 Postscript: The SKA1 Survey Telescope[339]

Following the inclusion of an SKA1-Survey Telescope equipped with PAFs in the 2012 SKA site decision, along with a dish array (SKA1-Mid) in Southern Africa and a low-frequency dipole array in Australia (SKA1-Low) (see Sect. 8.6.3), it was included in the official Baseline Design of 2013[340] as a complete telescope sited in Australia. It was foreseen to be a mixed array of 36 12-m diameter dishes from the ASKAP array and 60 15-m SKA Phase 1 dishes, all equipped with PAFs like those for ASKAP. The PAFs covered the frequency range from 650 to 1670 MHz in a single dual-polarised PAF with a 500-MHz instantaneous bandwidth.

An important development occurred in 2014. A more detailed electromagnetic analysis of PAFs[341,342,343] in the optical configurations of the preliminary concept design (Preliminary CoDR) emerged, targeted to participate in the SKA dish downselect process.[344,345] This document was effectively a proposal for a telescope with three PAFs covering three frequency bands starting at 350 MHz.

Although this was a large body of work, it came late in the game, and despite several PAF workshops, reviews and papers in 2012 and subsequent years, fundamental questions remained even in 2015[346] although it was recognised that much progress had been made.[347] Time was running short for the SKA Organisation to make major decisions, and more work on the practical side would be needed to ensure the viability of SKA1-Survey. Three telescopes were looking expensive, and

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[339] An expanded version of this section can be found in hba.skao.int/SKASUP6-16.

[340] hba.skao.int/SKAHB-206 *SKA1 System Baseline Design*, Dewdney, P. E., et al., SKA Document SKA-TEL-SKO-DD-001, 12 March 2013.

[341] hba.skao.int/SKAHB-303 *SKA Antenna Issues*, Hay, S. G., presentation, 10 July 2012.

[342] hba.skao.int/SKAHB-313 *CSIRO PAF Optics Analysis,* Hay, S. G. and Smith, S., presentation at the Dish CoDR in Sydney, Australia, 02 June 2014.

[343] hba.skao.int/SKAHB-311 *PAF & Optics Electromagnetic Performance Analysis,* Hay, S. G. and Smith, S., SKA Document, SKA-TEL.DSH.SE-CSIRO-R-003, 06 August 2014.

[344] hba.skao.int/SKAHB-308 *SKA Dishes Options Downselect Process,* Küsel, T., SKA document SKA-TEL.DSH.SE-NRF-MP-003, 05 September 2013.

[345] hba.skao.int/SKAHB-309 (*Dishes) Concept Definition: Process Overview,* Küsel, T., presentation, 02 June 2013.

[346] hba.skao.int/SKAHB-322 *Objective Questions for PAF feeds,* Veidt, B., presentation, PAF Workshop, Penticton, Canada, 04 November 2015.

[347] hba.skao.int/SKAHB-323 *PAF Commissioning and First Science: Feedback for Engineers,* Chippendale, A., et al., presentation, PAF Workshop, Penticton, Canada, 04 November 2015.

SKA1-Survey was finally dropped from the SKA Baseline Design in a ‘rebaselining exercise’[348] in 2015.

In summary, only in Australia did PAFs remain the focus of continued development and implementation as an entire SKA precursor array (ASKAP), including a continuing scientific program. ASKAP was completed in 2019 and has already contributed new scientific results. Australia continues to lead research and development of PAFs, and there is still hope that a breakthrough (or more likely, a series of incremental improvements) will inspire another generation of PAF-equipped radio telescopes arrays.

PAF workshops continued throughout the pre-construction phase, and PAFs remained in the AIP and, post-2021, are included in the SKA Observatory Development Program.

## 6.5 Aperture Arrays for the SKA

Aperture Arrays (AAs) have a long history in radio astronomy. The earliest radio telescopes were often arrays of simple antennas such as dipoles or Yagi antennas. The first radio telescope, the famous Jansky antenna (Jansky, 1932), operated in a similar way; the principles have been known for a long time. The AA terminology is more recent and refers to a much more sophisticated use of the same basic idea.

As described in Sects. 3.2 and 3.3, in the period beginning in 1993 with the formation of the Large Telescope Working Group (LTWG) and the later signing of the Memoranda of Agreement in 1996 for collaboration on technology studies[349] and in 2000 to form the International SKA Steering Committee (ISSC), all the countries involved were motivated to explore innovative technologies, particularly for ‘receptors’ or ‘concentrators’, that could enable the realisation of the SKA.

AA technology seems seductively simple, in principle, but is actually sophisticated and complex. The big push in the early part of this century was to develop dense AAs (see Sects. 6.5.5.3 and 3.2.6.1). Dense AAs promised in principle to revolutionise radio astronomy around the all-important wavelength of the neutral hydrogen line, 21 cm (see Sect. 5.10).

AAs were and are being used in other radio science and engineering disciplines such as radar, but these applications are typically much less demanding than those for radio astronomy (van Ardenne et al., 2009).

To understand the long history of AA development in the SKA and why individuals and whole institutions took heartfelt (sometimes entrenched) positions on the

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[348] hba.skao.int/SKAHB-325 *SKA1 System Baseline v2 Description,* Dewdney, P. E., SKA Document SKA-TEL-SKO-0000308, 04 November 2015.

[349] hba.skao.int/SKAHB-142 Memorandum *of an Agreement to Cooperate in a Technology Study Program Leading to a Future Very Large Radio Telescope,* Directors of eight global astronomy institutes, 1996.

design, it is important to understand some of the basic technology. This is described briefly in the next section.

### 6.5.1 Basic Technology of Aperture Arrays at Low- and Mid-Frequencies[350]

AAs tailored for the SKA have taken the form of large, horizontal arrays consisting of 100 s to many 1000s of simple antennas, referred to as array elements. Each array, known as a station, forms one or more beams, each of which are equivalent to a lighthouse beam working in reverse, receiving radiation rather than transmitting radiation. The outputs of these beams are delivered to a centralised facility where they are correlated. In this sense each station acts like a dish, except that in principle, AAs can produce multiple beams in arbitrary directions. An array of AA stations can be seen as equivalent to re-using the collecting area of the telescope for making multiple observations at once.

In theory, AAs offer great flexibility. Multiple beams can be formed, which in principle can cover most of a hemisphere simultaneously. In addition, the shape of beams can be adjusted to form nulls[351] in the directions of strong sources of radio frequency interference. There are no moving parts, in contrast to reflector antennas.

Figure 6.21 is a simplified view of an AA station for the SKA that applies for both low- and mid-frequencies. The depiction in this case is more like that used for SKA-low than that proposed for SKA-Mid but shares most of principles described here. Each of the red and blue antenna elements is represented here as a kind of dipole with triangular arms, somewhat less than a wavelength in size. Each element has two dipoles orthogonal to each other so that they can receive both polarisations of the incoming radio waves. These antennas are sensitive to almost any direction in the sky. Their outputs are amplified (not shown) and delivered to a device that can introduce programmable amounts of delay into each signal. A wavefront is shown in the figure as radio waves emanating from a direction which is chosen by programming the delays to compensate for the geometrical delay between each element and a reference point, normally the centre of the array. An example of the geometrical delay for one antenna is shown in the figure. After the delays have been introduced, the signals are all aligned for the desired direction. When they are arithmetically summed in the next step to form one output signal, the peak occurs for signals in the desired direction. This can be done to form a beam anywhere above the horizon.

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[350] An expanded version of this section can be found in hba.skao.int/SKASUP6-17.

[351] Beams from radio telescopes have a 'main lobe' which is the area of sky of greatest sensitivity. Outside that area are 'side lobes', which are areas of sky with some sensitivity but are suppressed by the beam-forming network as much as possible. In between the main lobe and the side lobes (also between multiple side lobes), the response of the telescope is zero, resulting from cancellation of all the components of the signal. These points are called 'nulls'.

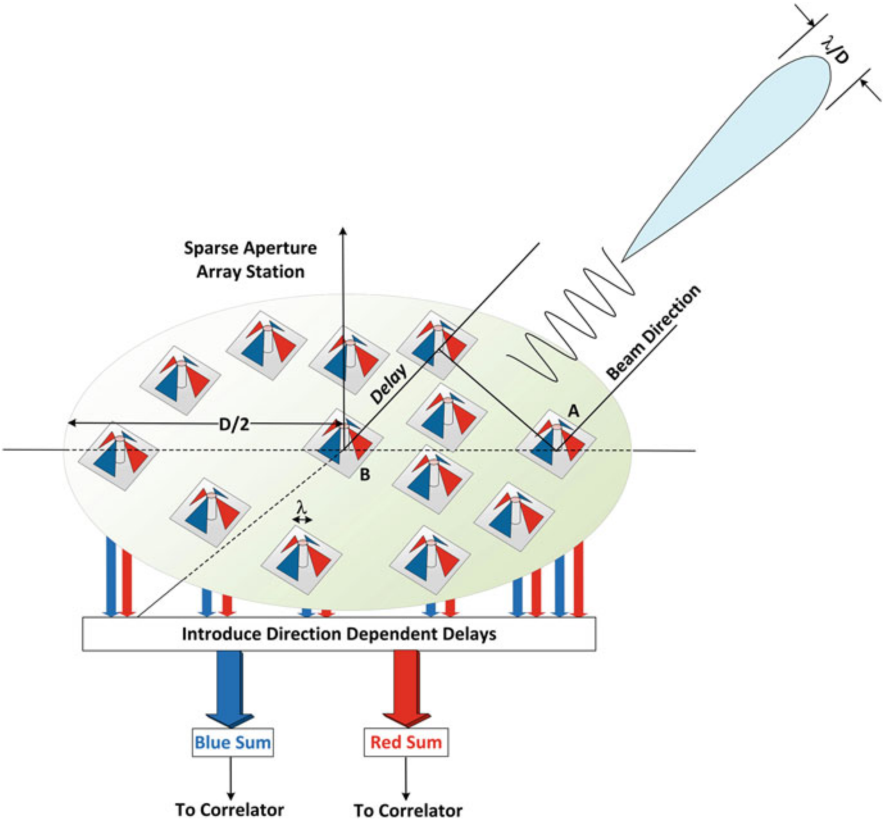

**Fig. 6.21** A simplified view of an aperture array station for the SKA. The array elements are red and blue, used to denote the two antennas oriented to receive orthogonal polarisations

Beyond this simple concept are a variety of effects that are much more complex and require significant performance trade-offs.

The ability to form multiple beams means that the instantaneous field-of-view can be increased just by forming more beams from the same collecting area. Survey speed (see also Sect. 6.4.3.1 and SKASUP6-7[352]), a fundamental metric of telescope sensitivity, is used to capture the time taken to survey an area of sky to a given sensitivity level. The metric is $(A_e/T_{sys})^2 \cdot \Omega$, where $\Omega$ is the area of sky covered by the beams and $A_e/T_{sys}$ is the sensitivity of the collecting area. Reuse of the collecting area is a powerful concept, and if beamforming could be formed at negligible cost, then AAs could easily achieve very high survey speed. However, beamforming cost is not negligible, and one must evaluate survey speed based on the full system cost.

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[352] hba.skao.int/SKASUP6-7—The Operating Principles of a Radio Telescope Antenna.

Dense AAs (see Sect. 6.5.5) contain closely packed elements in a rectangular or hexagonal array so that the elements are approximately a half-wavelength ($\lambda/2$) apart (Fig. 6.24). This means that all possible spatial scales are sampled by the array, up to the limit set by the size of the array. AAs whose elements are farther apart than $\lambda/2$ are so-called sparse (sparsely sampled).

The sensitivities of sparse and dense AAs differ: In a sparse array, the elements are far enough apart to act independently, and the collecting area of the individual elements is proportional to the square of the wavelength ($\lambda^2$). Thus, the collecting area of the array is proportional to $N\lambda^2$, where N is the number of elements in the array. On the other hand, because the elements of dense AAs are strongly coupled, the collecting area is proportional only to the area of the array, regardless of the number of antenna elements. Over a wide frequency range, it is possible that a single array may be dense at long wavelengths but sparse at shorter ones. Setting the transition frequency, which occurs approximately when the elements are a half wavelength apart, involves a complex trade space containing the design of the elements, the frequency coverage desired and the sensitivity.

Another design choice for the SKA is the size of AA stations. For a fixed total collecting area, for example as specified in SKA Memo 100, larger stations will require fewer of them. If the stations are too large, then there may not be enough of them to support accurate, high dynamic range imaging. If they are too small, the system cost will rise. The station beam area is proportional to $(\lambda/D)^2$, where $\lambda$ is the wavelength and D is the station diameter. If there is a requirement to observe a fixed area on the sky (field-of-view) or to maximise it, then it may require several beams to cover the required area on the sky. Each beam requires a beam-forming apparatus, whose cost is also proportional to the number of antenna elements in the station.

The station size affects cost in other ways as well: each antenna element requires at least a Low Noise Amplifier, which consumes power. Transmission of their output signals also consumes power. In general, the power consumed by a station is proportional to its area.[353]

Finally, as with all radio telescopes, system noise[354] is crucial. Figure 6.22 shows a dramatic natural phenomenon. The sky is exceedingly bright at long wavelengths (low frequencies) but almost completely dark at frequencies greater than about 500 MHz.[355] The other typical source of noise is from Low Noise Amplifiers (LNAs). LNAs that operate at ambient temperatures contribute about 40 K of noise, which is insignificant at 50 MHz but much higher than sky noise at 1000 MHz. The sensitivity of telescopes is proportional to $(A/T_{sys})$, where A is the total collecting area and $T_{sys}$ is the system temperature. At low frequencies it pays to

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[353] Note that this is a contrast with dishes, whose collecting area is passive (i.e., power is consumed but it does not scale with area).

[354] System noise is the sum of all sources of noise (i.e., from the sky, itself, as well as the telescope). Noise units are usually in Kelvins, the equivalent temperature of a resistor that produces the same noise. In terms of a radio signal, noise comprises random fluctuations of voltage, current or power.

[355] Note that the vertical scale is a log scale.

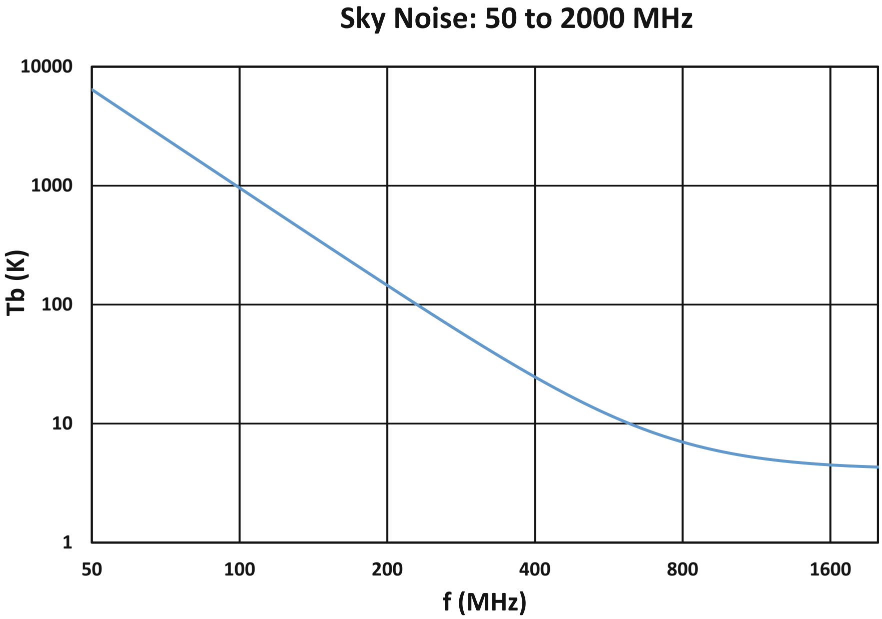

**Fig. 6.22** The average radio brightness of the sky at SKA's AA frequencies. Note that the vertical scale is logarithmic and the horizontal scale intervals are in factors of 2

maximise collecting area but at high frequencies it pays to minimise LNA noise. This is a key reason why it is difficult to imagine one telescope covering the entire SKA frequency range. It is also the reason why AAs are more suitable for wavelengths longer than about a metre (300 MHz) than for shorter wavelengths, although AAs at higher than 300 MHz are certainly possible.

SKASUP6-17[356] contains a summary of the AA challenges, both fundamental and cost-related. In terms of the SKA specifications as they were known in the 2004–2007 timeframe, the decision space looked like the following:

- Frequency range? (How many AAs?)
- Station size?
- Reconfigurability and flexibility?
- Antenna element?
- Sparse or dense; if sparse, what transition frequency, if any?
- Field-of-View? (How many beams?)

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[356] See hba.skao.int/SKASUP6-17—Basic Technology of Aperture Arrays at Low- and Mid-frequencies.

- Cost per square metre of collecting area?
- Cost per square degree on the sky?
- Operating cost?
- Sensitivity and instrument noise?

Optimising this enormous trade space was the task at hand, but the results would not appear for years.

### 6.5.2 AA-Focussed System Architecture

In the period from before the SKADS program (see Sects. 6.2.1.6 and 6.5.5.2) began in 2005 (see Sects. 3.3.3.4.3 and 6.2.2.1) until the SKA System CoDR in early 2010, when dense AAs were included in the AIP but not in the system baseline (see Sects. 4.6.2 and 6.2.2.9), there was an underlying assumption that there would be an integrated approach to AAs at the system level (i.e., one beamforming 'engine' would handle inputs from both sparse AAs at low frequencies as well as dense AAs at high frequencies). It would also provide a central correlator system for AA beams and for dishes. This approach is clearly efficient since the basic beamforming process is the same for both. In principle, it could also provide the flexibility to process more or fewer beams from either of the AA arrays.

Arnold van Ardenne included a version of this architecture (Fig. 6.23) in a presentation of the Aperture Array Verification Program (AAVP)[357] to the SKA International Engineering Advisory Committee (IEAC) in April 2009 in which he declared that "AA's are essential for SKA Science", meaning that this architecture and structure would meet SKA Memo 100 specifications (see Sect. 6.2.1.4).

Because of the shared processing for both dense and sparse AAs, it was difficult to see how to map this architecture into a footprint on the ground—the array configuration. For example, the distribution of both sparse and dense AAs, as well as dishes, were supposed to be highly concentrated at a single centre. It would have been difficult to find room for everything, exemplified by leaving AA-Low arrays out of publicity pictures. This led later to a multi-core approach (see Figs. 6.6 and 6.7), which if this integrated architecture were to be retained, would mean long-distance data transmission networks. Moreover, the subsequent dual-site decision in 2012 completely changed all the underlying architecture assumptions.

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[357] hba.skao.int/SKAHB-340 The *Aperture Array Verification Program,* van Ardenne, A., presentation to the International Engineering Advisory Committee (IEAC) on behalf of the European SKA Consortium, 14 April 2009.

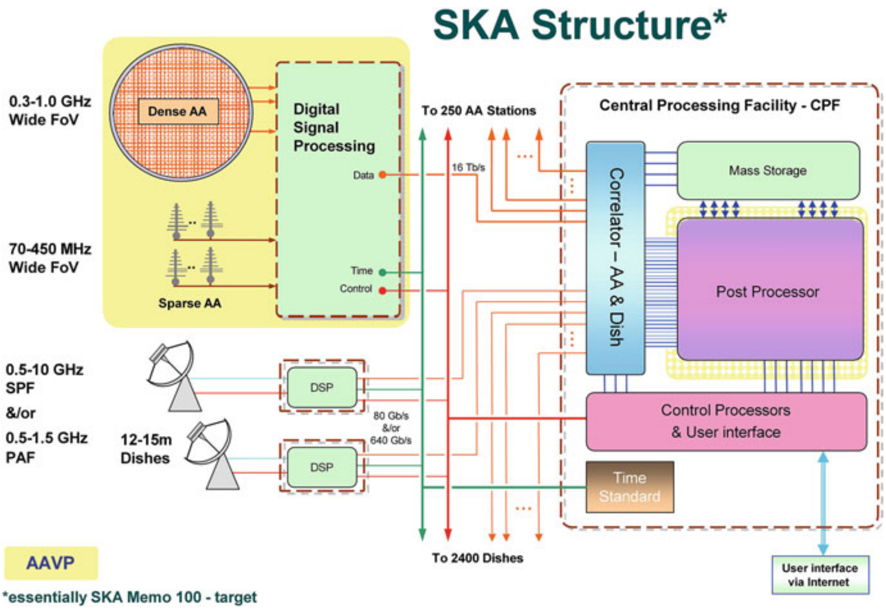

**Fig. 6.23** AAVP system design. Credit: Andrew Faulkner and the AAVP Program

### *6.5.3 Design of SKA Low Frequency Aperture Arrays: Compromise and Convergence*

Aperture Arrays go back to the earliest days of radio astronomy. After his much earlier observations with dishes, the pioneer radio astronomer, Grote Reber, built an array in Tasmania at the extraordinarily long wavelength of 144-m (frequency of about 2 MHz) in the 1950s and 1960s.[358] Other pioneering array-type telescopes for shorter radio wavelengths were built at several observatories (e.g., (Caswell, 1976; Erickson & Kuiper, 1973; Braude et al., 1978; Roger et al., 1999)). Because their antenna elements were tightly coupled, they were dense AAs, although the term was not used then.

Interest in detecting neutral hydrogen at cosmological distances using a telescope with about a square kilometre of collecting area was sparked by Swarup, Braun et al. and Wilkinson in the late-1980s (see Sect. 2.4.1). This idea and science discussions in the late-1990s roughly set the scene for the low-frequency limit for SKA-low, which began at 100 MHz, and changed downwards to 70 MHz in 2005 and is now

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[358] hba.skao.int/SKAHB-328 Grote *Reber: Yesterday and Today,* Feldman, P., Sky and Telescope, July 1988.

50 MHz.[359,360] The high frequency limit, which depended on defining a cross-over point between SKA-Mid and SKA-Low, was initially about 350 MHz but remained fluid for a long time afterwards.

The prospect of discovering highly redshifted hydrogen was one of the ideas that also propelled LOFAR as a potential mega-project at low frequencies (see (van Haarlem et al., 2013) for a sketch of its early history), which emerged as a named project in 2000 (Bregman, 2000). However, for a variety of reasons the original consortium dramatically trifurcated in 2004 into the modern LOFAR telescope in Europe, the international Murchison Widefield Array (MWA) in Australia and the Long Wavelength Array (LWA) in the US (see Sect. 3.2.6.1). The builders of LOFAR and MWA (Lonsdale et al., 2000) have also been major contributors to the design and construction of SKA-Low. They are pathfinder and precursor telescopes, respectively, to the SKA. One of the originating institutions of LOFAR, MIT/Haystack,[361] was responsible for much of the initial design work, especially the antenna arrays.

Earnest paring down of the SKA design began in 2006 with the SKA Reference Design (see Sect. 6.2.1.3). In the 'sausage-making' discussions[362] in the Tiger-Team leading up to the Reference Design, the so-called 'Epoch of Re-ionisation Array' (EoR Array) was given short shrift and most of the emphasis was given to dense AAs at higher frequencies. Although there was acknowledgement that an array spanning $<$100 to 300 MHz was needed, there was very little discussion of the science potential in the upper end of that frequency range. The EoR Array was not even included in the publicity image of the Reference Design. It is ironic that of all the technologies being discussed at the time (2005), only the EoR Array and dishes were included in the final design of SKA1. Nevertheless, these were optimistic, exciting times when huge technical strides in the designs of radio telescopes were thought to be possible.

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[359] It is interesting to note that Reber's first reaction on hearing of the initial plans for the SKA was not positive (hba.skao.int/SKAHB-425), Note to the editors of Physics Today, 28 December 2000, Papers of Grote Reber, NRAO/AUI Archives). In a several-paragraph note for proposed publication, he said "It sounds good, but I have the impression the promoters don't know what they are doing. .... Those fellows in the October issue of Physics Today are working at wrong end of spectrum. They should change from millimeter to hectometer waves." There is a polite letter from the editor turning the note down. Perhaps, were Reber alive today, he would approve of SKA-Low being built in Western Australia with plans to operate at decametre wavelengths. We thank Ellen Bouton, NRAO Archivist, for bringing this note to our attention.

[360] hba.skao.int/SKAHB-425 *Grote Reber's letter to Physics Today and Reply*, Reber, G., personal letter and reply from Physics Today editor, 28 December 2000.

[361] hba.skao.int/SKAHB-332 Haystack *Observatory Visiting Committee Report,* Ulvestad, J., et al., document commissioned by Massachusetts Institute of Technology, Haystack Observatory, 14 October 2004.

[362] hba.skao.int/SKAHB-333 SKA *Reference Design Tiger-Team Discussion,* Schilizzi, et al., Email Message Exchanges, 24 November 2005.

In the Reference Design document, the EoR Array was not included in SKA Phase 1[363] because "10% SKA has the same collecting area as LOFAR at 0.1 GHz, and therefore is not expected to add substantially to EoR knowledge unless the EoR signal is primarily to be found in the Frequency Modulation (FM) bands which LOFAR cannot observe."[364] (Note that at that time, SKA Phase 1 was considered as just a milestone on the way to constructing the full SKA).

In SKA Memo 100 (see Sect. 6.2.1.4), the assumed implementation of AAs included two sparse AAs, one covering from 70 to 250 MHz and the other one up to 450 MHz. These two AAs would have used two ranks of dipole-like antennas to cover the range. There was also an acknowledgement that perhaps Vivaldi antenna elements could cover the entire range with one array. But neither array was eventually chosen for SKA Phase 1.

Performance requirements were extraordinarily ambitious. For example, in 2008 Joe Lazio, the SKA Project Scientist, presented AA-Low specifications to the SSRC,[365] which included sensitivity of at least 4000 $m^2$/K for zenith angles up to 45°, polarisation purity of $-30$ dB (1 part in 1000) over a wide field-of-view, and frequency resolution of 500 Hz up to a frequency of 250 MHz. These were widely accepted at the time and did not 'raise any eyebrows', even in the SKA engineering community. The polarisation requirement was especially difficult because dipole-like antennas inherently change polarisation in off-axis directions.

Detection and imaging of neutral hydrogen in the eras of Reionisation and Cosmic Dawn remained the science drivers for SKA-low[366] (see Sect. 5.5.19) and formed the basis for the SKA1-Low part of the Baseline Design[367] in 2012/13.

In the AAVP program as defined in 2009, INAF and ICRAR[368] were assigned the development of low-frequency specific AA components (Fig. 6.32), but it was expected most development would entail adapting designs from LOFAR.[369] However, other approaches were still being considered throughout the AAVP period, and there was some frustration at the slow pace of convergence on a design. At the

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[363] At the time, SKA Phase 1 was defined in Memo 69 as 10% of the full SKA and in Memo 100 as "representing the stage in construction when the SKA has reached approximately 15–20% of its full capability".

[364] The site ultimately chosen for SKA1-Low in remote Western Australia is far more isolated than LOFAR from FM radio transmissions.

[365] hba.skao.int/SKAHB-336 SKA *Specifications Requirement Review,* Lazio, J., presentation to the SKA Specifications Review Committee (SSRC), 29 January 2008.

[366] hba.skao.int/SKAHB-366 Reionization *and the Cosmic Dawn with the Square Kilometre Array,* Mellema, G. and Koopmans, L., et al., The European SKA EoR Science Working Group White Paper, 13 September 2012.

[367] hba.skao.int/SKAHB-206 *SKA1 System Baseline Design*, Dewdney, P. E., et al., SKA Document SKA-TEL-SKO-DD-001, 12 March 2013.

[368] The Instituto Nazionale di Astrofisica (INAF) and the International Centre for Radio Astronomy Research (ICRAR), respectively.

[369] hba.skao.int/SKAHB-358 From the LOFAR design to the SKA1-Low System, Gunst, A. W., presentation at the AAVP Workshop in Cambridge, UK, 08 December 2010.

AAVP meeting Perth in 2011,[370] Andre Gunst, who at the time was working at the SPDO, frustrated at the pace, pointed out that SKA system requirements and an SKA high-level design were in place already and LOFAR could just be scaled to build AA-Low, without further design iterations.

Nevertheless, the AAVP project engineer, Andy Faulkner showed in a presentation at the AAVP meeting in Medicina[371] that many key choices were open,[372] even in 2012. But by that time, dense AAs were no longer part of the Baseline Design, and all the options were tailored for SKA1-Low.

As noted in the example above, a characteristic of this period was to avoid making design choices that would constrain the potential flexibility of AAs. However, the pressure of the imminent end of the PrepSKA program and the beginning of pre-construction, meant that choices did have to be made. These choices were embodied in the Baseline Design document of 2013, which set the project on a course to follow, and which remained broadly stable up to SKA construction start in 2021.

#### 6.5.3.1 SKA-Low Array Elements[373]

A great deal of effort was put into studies of the design of antenna elements for SKA-low.[374] Although other alternatives were studied, the choices most intensively studied were: (1) Simple dipoles and their derivatives (the default), (2) Vivaldi antennas,[375] (3) Log-periodic dipole antennas,[376] and (4) Conical antennas. Further detail on these antennas is given in SKASUP6-18.[377]

Another question discussed early in the pre-construction phase (October 2012), was whether to have two arrays of 'simple' dipole arrays or one array of log-periodic or Vivaldi antennas covering the whole SKA1-Low frequency range from

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[370] hba.skao.int/SKAHB-362 SKA-Low *System Design: Process and Requirements,* Gunst, A. W., presentation at the AAVP Meeting in Perth, 07 September 2011.

[371] hba.skao.int/SKAHB-367 AAVP *Agenda: AA-low Technical Progress MeetingMedicina,* Italy, 22 October 2012.

[372] hba.skao.int/SKAHB-368 SKA-Low—*AA System Configuration Options,* Faulkner, A. J., presentation at the AAVP Meeting in Medicina, 22 October 2012.

[373] An expanded version of this section can be found in hba.skao.int/SKASUP6-18.

[374] hba.skao.int/SKAHB-360 SKA-Low *RF Systems Overview,* Bakker, L., and Bij de Vaate, J.-G., presentation at the AAVP Meeting in Perth, 07 September 2011.

[375] hba.skao.int/SKAHB-372 Measurements *of Vivaldi v2 Antennas for AAVS0,* Virone, G., et al., presentation at the AAVP Meeting in Medicina, 22 October 2012.

[376] hba.skao.int/SKAHB-359 SKALA*: SKA Log-periodic Antenna: A candidate for the SKA AA-low,* de Lera Acedo, E., presentation at the AAVP Meeting in Perth, 07 September 2011.

[377] See hba.skao.int/SKASUP6-18—Detailed Version: SKA-low Array Elements.

50 to 350 MHz.[378,379] Log-periodic elements were ultimately selected for SKA1-Low in the Baseline Design in early 2013 because they could cover the frequency range from 50 MHz to 350 MHz, obviating a dual array approach.[380] At the upper frequency, this choice was made easier by the choice of 15-m dishes for SKA-Mid which could provide acceptable performance down to 350 MHz. However, the choice of log-periodic dipole antennas remained controversial for years (see SKASUP6-18).

### *6.5.4 SKA-Low Stations and Array Configurations*[381]

Because the flexibility of the AA concept provides an enormous number of design options, both the configurations of the antennas within stations and the configurations of the array of stations generated considerable discussion. The issue of flexibility was not fully settled until 2016.[382]

In the 2010/11 period, discussions in the AAVP, which was leading the SKA-low design, led to an array design containing 50 very large (180-m diameter) stations containing about 10,000 antenna elements each. This diameter was carried forward to the AA CoDR in April, 2011.[383] This approach was partly based on being able to calibrate quickly in the face of variable ionospheric distortions, particularly when travelling ionospheric disturbances (TIDs) occurred (Wijnholds et al., 2011). This diameter was carried forward to the AA CoDR in April 2011 together with equivalent information for the dense AAs. However, it was made clear in the CoDR panel's report[384] that treating dense AAs, which were not in the 2010 version of the baseline design (SKA Memo 130), together with sparse AAs for low frequencies in the same Architecture Design Description (ADD) was not optimum for either one.

The clock was running down to the end of PrepSKA, with the expected delivery of a system design, but the debate over the SKA1-Low station size did not end there. Following considerable discussion, especially regarding flexibility, (see SKASUP6-

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[378] hba.skao.int/SKAMEM-140 Cost-effective *aperture arrays for SKA Phase 1: single or dual-band?,* Colegate, T., et al., SKA Memo 140, 27 February 2012.

[379] hba.skao.int/SKAHB-369 SKA-Low*: One Band or Two,* Hall, P. J., presentation at the AAVP Meeting in Medicina, 22 October 2012.

[380] The lower frequency had been 70 MHz. But theoreticians were beginning to think that the EoR/CD signal might lower than 70 MHz and would prefer to see the lower frequency moved to 50 MHz, about half an octave lower.

[381] An expanded version of this section can be found in hba.skao.int/SKASUP6-19.

[382] hba.skao.int/SKAHB-376 SKA1-Low *Configuration—Constraints & Performance Analysis,* Dewdney, P. E., et al., SKA document, SKA-TEL-SKO-0000557, 31 May 2016.

[383] hba.skao.int/SKAHB-354 AA *Concept Descriptions,* Bij de Vaate, J. G., et al., SPDO Document, WP-2-010.020.010-TD-001, 12 April 2011.

[384] hba.skao.int/SKAHB-357 Panel *Report: SKA Aperture Array Concept Design Review (CoDR), Dewdney*, P. E., et al., SKA Project Office Report, 20 April 2011.

19[385]) the 2013 Baseline Design chosen was an array of 911 35-m diameter stations, 75% of which were within 1000 m of the centre. The rest were in spiral arms arranged so that the maximum baseline was 100 km. Each station contained 289 log-periodic dipole (LPDA) elements. Further consolidation of collecting area was done in the three spiral arms (see Sect. 6.2.2.10) by arranging clusters of five such stations along each arm (beyond a radius of 2500 m). This configuration is not as good as separating the stations to form more independent samples of spatial frequencies but entails much less expensive provision of power and communication infrastructure.

The design of the configuration of antenna elements within a station became a major research effort in the AAVP. There are several highly coupled design aspects that require multi-way design trades. The technical issues are complex (see SKASUP6-19). They were intensively explored,[386] particularly in the UK (El-Makadema et al., 2014), and tested in small prototype arrays.[387] A sophisticated array simulator, OSKAR[388] (Oxford SKA Radio Telescope Simulator) was developed for radio telescopes containing AAs and is still used for these investigations.

### 6.5.5 Pursuit of the Ultimate SKA Telescope Design: Dense Aperture Arrays

While sparse AAs had been used for many years, the real prize was dense AAs, scaled to shorter wavelengths or SKA1-Mid-frequencies, as short as 15 cm. Dense Aperture Arrays (AAs) promised to revolutionise radio astronomy.

Figure 6.24 illustrates the variant pursued in The Netherlands, joined later by all of Europe.[389] The incoming radio wave induces currents on the Vivaldi antenna elements, shown as colour concentrated around the slot. Low noise amplifiers (LNAs) are connected to each slot. Their outputs are collected in a layer that can deliver all the signals to each beam former. The beams are formed by adding the electrical signals from the elements in a processing network so that delays are equalised for signals arriving from the desired direction (see Figs. 6.21 and 6.24). As with any aperture, the width of the beam is inversely proportional to the size of the aperture, D, in wavelengths, λ (i.e., λ/D) projected on the beam direction. By

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[385] See hba.skao.int/SKASUP6-19—Detailed Version: SKA-low Station and Array Configurations.

[386] hba.skao.int/SKAHB-361 SKA *Low Frequency Aperture Array Configurations and Optimisations,* Razavi-Ghods, N., presentation at the AAVP Meeting in Perth, 07 September 2011.

[387] hba.skao.int/SKAHB-371 AAVS0 *& AAVS0.5: System Design and Test Plan,* Razavi-Ghods, N., presentation at the AAVP Meeting in Medicina, 22 October 2012.

[388] hba.skao.int/SKAHB-365 The *OSKAR Simulator (Version 2!),* Dulwich, F., et al., presentation at the AAVP Workshop, Dwingeloo, The Netherlands, 15 December 2011.

[389] hba.skao.int/SKAMEM-19 *The European Concept for the SKA—Aperture Array Tles,* European SKA Consortium, SKA Memo 19, July 2002.

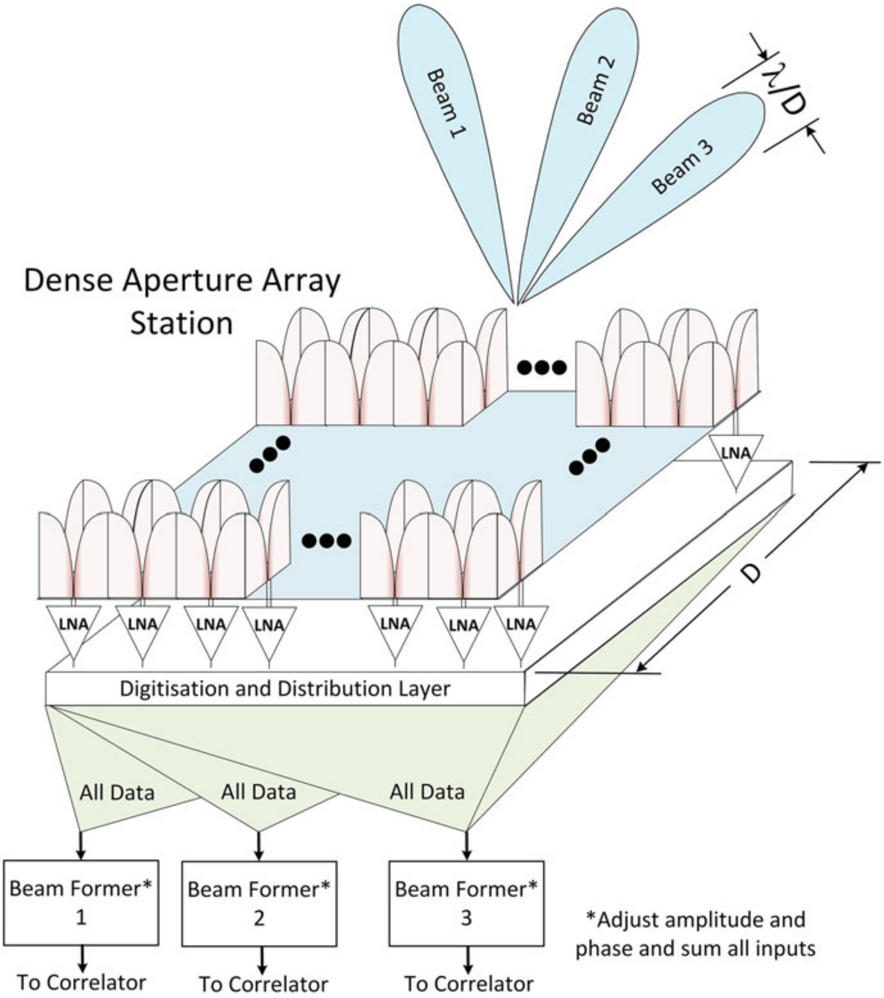

**Fig. 6.24** An illustration of a Dense Aperture Array Station using Vivaldi antennas

adjusting the delays, the beam can be pointed over an entire hemisphere. Because the AA station lies in a horizontal plane, beams directed away from the zenith become progressively wider as they approach the horizon. Therefore, practical observations with AAs are confined to angles less than about 50 degrees from the zenith.

However, there are several practical challenges associated with dense AAs. This are outlined in Box 2 of SKASUP6-17.[390]

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[390] See hba.skao.int/SKASUP6-17—Basic Technology of Aperture Arrays at Low- and Mid-frequencies.

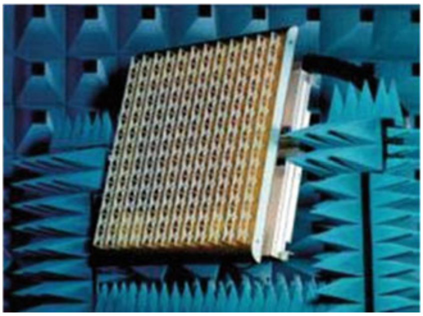

**Fig. 6.25** OSMA in an anechoic chamber at The Netherlands Foundation for Radio Astronomy (later ASTRON). Credit: ASTRON

#### 6.5.5.1 Mid-Frequency Aperture Array Development Before SKADS

Real interest in AA technology for large-aperture telescopes began in The Netherlands, led by Arnold van Ardenne in about 1993, shortly after ASTRON began investigating innovative technologies for the next large radio telescope. This was followed in 1995 by a significant grant from the Dutch government to bolster the effort (see Sect. 3.2.6.1). Note that slightly later, in the late 1990s, similar technology was being developed in The Netherlands, Australia, and Canada for use at the focus of reflector antennas (focal plane arrays). This aspect is covered in Sect. 6.4.7.

In 1997, ASTRON began designing a series of prototype aperture arrays for the SKA. A major research effort was made, including ascertaining the properties of many different antenna elements, dielectric losses, low-noise amplifier designs, beamforming and developing test apparatus that would be suitable for measuring arrays in an anechoic chamber. The first effort, the Adaptive Array Demonstrator (AAD), was only an 8-element array.[391] Of considerable interest was adaptive beamforming whereby weights used in summing the signals from the individual elements could be adjusted in real time to form beam nulls in directions from which radio interference was arriving (see Sect. 6.5.1). This concept was pursued vigorously throughout a series of prototypes.

This prototype was followed by the One Square Metre Array (OSMA) Fig. 6.25, which was much more elaborate. It contained 64 active antennas surrounded by two rows of passive antennas (144 in total) and was designed for the 1.5–3 GHz frequency range. A photo of OSMA on the front cover and a complete summary appeared in the ASTRON 1998 Annual Report,[392] as well as in the first SKA Newsletter,[393] indicating the importance of this work.

OSMA was followed in 1999 by the Thousand Element Array (THEA) (Hampson & bei de Vaate, 2001) (Fig. 6.26). This was designed to operate in the 600–1700 MHz range outdoors and to detect radio sources even in the presence of

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[391] hba.skao.int/SKAHB-329 The Adaptive Array Demonstrator, Hampson, G., et al., conference poster paper, 06 August 1998.

[392] hba.skao.int/SKAHB-330 ASTRON/*NFRA Annual Report, 1998 published by* the Netherlands Foundation for Research in Astronomy, P.O. Box 2, 7990 AA Dwingeloo, The Netherlands.

[393] hba.skao.int/SKANEWS-1 SKA *Newsletter Vol. 1,* February 2000.

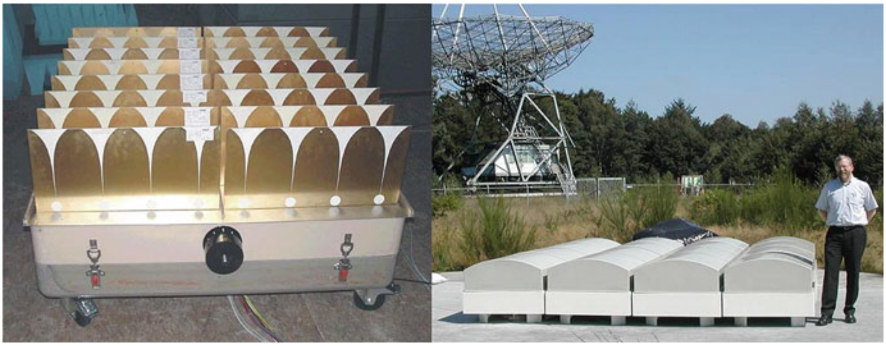

**Fig. 6.26** Left: The THEA Tile with the radome removed Credit: ASTRON. Right: An array of 16 THEA tiles, four active tiles surrounded by 12 passive tiles on the Dwingeloo site, flanked by Harvey Butcher, ASTRON Director at the time. Credit: ASTRON

radio interference. THEA was constructed using Vivaldi antenna-elements arranged in 64-element ‘tiles’, which showed considerable promise for very wide bandwidth. Sixteen of these were built and deployed on the Dwingeloo telescope site. Its analogue beamforming network was elaborate: 32 beams that could be directed to any point in the sky, a scheme for adaptive nulling and full computer control (van Ardenne et al., 2000; Smolders & Kant, 2000; Kant et al., 2000). In 2002, observations with THEA detected Galactic HI[394] (Wijnholds et al., 2004) and could track GPS satellites in orbit. This was described in detail, in Dong Xiao's thesis from the Eindhoven University of Technology (TU/e).[395]

Effort began to develop innovative beamforming techniques using photonic devices (e.g., as proposed in a poster paper by Peter Maat[396]). This continued into the SKADS era (see next chapter).

In general, an extraordinary effort was devoted to dense AAs at ASTRON and associated universities in The Netherlands, in the period up to the funding of the SKADS program in 2005. At that point work continued at the European level but led in The Netherlands. Apart from the developments described above, a highlight of the activity was work on developing adaptive beamforming for radio telescopes utilising AAs. This is summarised in Dong Xiao's thesis and in some of the publications referenced above.

#### 6.5.5.2 SKADS: Mid-Frequency AAs

Section 6.2.1.6 describes the inception of the SKA Design Study (SKADS)) program, funded by the European Commission’s Sixth Framework Program (FP6).

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[394] hba.skao.int/SKANEWS-4 *SKA Newsletter* Vol. 4, November 2002.

[395] hba.skao.int/SKAHB-331 Wide *Band Adaptive Beamforming in Phased Array Based Radio Telescope, Xiao*, D., Thesis, Eindhoven University of Technology (TUE), November 2002.

[396] hba.skao.int/SKAHB-334 Photonic *Phased Array Signal Processing, Maat*, D. H. P., poster paper, 19 September 2006.

The technical focus of SKADS was the continued development of mid-frequency AAs for the SKA, but its overall goals went beyond this remit: make the case for AA technology including readiness for production, produce science requirements, develop a full-blown architecture and project plan, estimate a cost and organise industrial participation. Although these goals were only partly achieved, SKADS left a large technical legacy. The technical component was led by ASTRON but continued with significant collaborators from the UK and France, and connected projects in Australia and Canada, where some of the results of this work fed into the development of phased array feeds (PAFs) for dishes (see Sect. 6.4.7).

At mid-frequencies, the AA-inspired design promoted a very wide-ranging vision of a telescope with key properties delivered concurrently: wide field-of-view, high resolution, wide frequency range, wide bandwidth, high sensitivity, dual-polarisation capable, wide time-domain capabilities, and the flexibility to observe multiple targets concurrently at will, all at modest cost. In general information theory terms, the amount of information available is proportional to the product of all these terms except ‘flexibility’. An efficient, error-free telescope would deliver an unprecedented amount of data to be processed and understood, and such a telescope would satisfy almost any science requirements. The question is whether a practical implementation of the AA-inspired telescope could come close to this ideal.

AAs have one advantage that is often overlooked: electronic beamforming can be very rapid. This allows beams to be steered quickly to respond to transients detected on other telescopes or detectors (multi-messenger astronomy). It is also well suited to carry out transient surveys, sampling a variety of astrophysical timescales. This was an emerging aspect of astronomy, the SKA prospects for which are described by Jim Cordes in SKA Memo 97[397] and in other places (see Sect. 6.2.2.8).

The program was assembled into a four-year Description of Work (DoW),[398] encompassing almost every aspect of radio telescope design and operation. The DoW was organised according to institutions assigned to carry out the work. The University of Manchester was assigned the SKA System Design. The primary AA technology investigations were assigned to ASTRON (Technical Foundations and Enabling Technology) and the University of Cambridge (Networks and Data). The program culminated in the construction of three major prototypes and a beamforming test program.[399] Two prototypes, using the AA technology previously developed in the THEA phase, were sited at the Westerbork and the Nançay observatory sites in The Netherlands and France, respectively. The third prototype,

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[397] hba.skao.int/SKAMEM-97 The *Square Kilometer Array as a Radio Synoptic Survey Telescope: Widefield Surveys for Transients, Pulsars and ETI, Cordes*, J., SKA Memo 97, 21 September 2007.

[398] hba.skao.int/SKAHB-335 Description *of Work, Square Kilometre Array Design Studies (SKADS) Sixth Framework* Program of the European Research Area—Research Infrastructures, 01 July 2005.

[399] Demonstrators were assigned to ASTRON (EMBRACE, Westerbork station), Paris Observatory (EMBRACE, Nançay station), and The University of Manchester (2PAD). An additional program, BEST, involved the testing of devices and beamforming algorithms on the Northern Cross at Medicina.

2-Polarisation All Digital (2-PAD), was constructed at Jodrell Bank site in the UK (see Sect. 6.5.5.2.2.).

Of particular interest is Fig. 2 of the DoW, which lists the "Critical Technology Areas". These illustrate the SKADS overall approach to meeting the challenges outlined in SKASUP6-17.[400] The topics were:

1. Science requirement studies including Configurations, Array calibration, Dynamic range etc.
2. Wideband Antenna and Integrated low cost, Front-end technology,
3. (Adaptive) (multi) beamforming,
4. (Sparse) Array System Design and Engineering,
5. High speed processing and Massive Data Handling,
6. Array Infrastructure and Network technologies,
7. RFI system-level and Mitigation technologies,
8. Low-cost Design and Manufacturing,
9. Siting and related issues,
10. Costing and Specifications, System Design and SKA Plan.

SKASUP6-20[401] contains a cross-reference table between the list above from the DoW and the challenges described in Box 2 of SKASUP6-17. While not quite a one-to-one correspondence, this indicates that the proposers were generally aware of the challenges and had outlined an organised approach to investigating them.

By mid-2007, the SKADS had put together a proposal for a system vision for the entire SKA frequency range (100 MHz–20 GHz), which they called the "SKADS Benchmark Scenario",[402] but which focussed principally on the mid-frequency aperture array, but also included a low-frequency aperture array, modelled on LOFAR or the MWA, and an array of 6-m dishes modelled after the ATA dishes with Wide-band Single Pixel Feeds (WBSPFs) (DeBoer et al., 2004). More detail on this scenario was provided in October 2008,[403] following the publication of SKA Memo 100[404] (see Sect. 6.2.1.4), which provided a broad consensus on the specifications for the SKA.

The underlying architecture of the Benchmark Scenario (see Sect. 6.5.2) was generally followed until the end of the SKADS program, except for changes in the frequency boundaries between technologies deployed (e.g., the boundary between dishes and dense AAs shifted from 1 GHz to 1.4 GHz (see Table 6.4)).

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[400] See hba.skao.int/SKASUP6-17—Basic Technology of Aperture Arrays at Low- and Mid-frequencies.

[401] See hba.skao.int/SKASUP6-20—Cross-reference of AA 'challenges' and the Description of Work (DoW) Investigations.

[402] hba.skao.int/SKAMEM-93 *SKADS Benchmark Scenario Design and Costing,* Alexander, P., SKA Memo 93, June 2007.

[403] hba.skao.int/SKAMEM-111 *SKADS Benchmark Scenario Design and Costing—2 (The SKA Phase 2 AA Scenario),* Bolton, R., SKA Memo 111, September 2007.

[404] In Memo 100, the assumption was that dense AAs would cover from 450 MHz to 1 GHz, becoming sparse at 750 MHz.

**Table 6.4** Proposed SKADS-SKA implementation from the SKADS White Paper

| Freq. range | Collector | Sensitivity | Number/ size | Distribution |
|---|---|---|---|---|
| 70–450 MHz | Aperture array (AA-lo) (sparse) | 4000 $m^2/K$ at 100 MHz | 250 arrays (stations), diameter 180 m | 66% within core 5 km diameter, rest along 5 spiral arms out to 180 km radius |
| 400 MHz—1.4 GHz | Aperture array (AA-hi) (dense) | 10,000 $m^2/K$ at 800 MHz | 250 arrays (stations), diameter 56 m | |
| 1.2 GHz—10 GHz | Dishes with wide-band single pixel feed (SD-WBSPF) | 5000 $m^2/K$ at 1.4 GHz | 1200 dishes diameter 15 m | 50% within core 5 km diameter, 25% between the core and 180 km, 25% between 180 km and 3000 km radius |

#### 6.5.5.2.1 SKADS Results (2009)

The SKADS program culminated with a major conference in Belgium in November 2009. The detailed summary of achievements was published electronically in a 410-page volume in the Proceedings of Science.[405] However, this was not the end of development of AAs for the SKA, which continued in the AIP program even after dense AAs were not selected for SKA Phase 1 (SKA1) in 2010[406] (see Sect. 6.2.2.9).

The SKADS remit was to present a system design for the SKA, focussing on AAs as the primary collectors for Mid and Low frequencies. At Low frequencies, this was not controversial as it had a long history in radio astronomy and indeed this is the technology under construction for SKA1-Low. Also, from a noise perspective, natural noise sources (i.e., sky noise) are the dominant component of total system noise, even for uncooled LNAs, at frequencies below about 250 MHz (1.2 m wavelength).

However, within the four-year program, SKADS could not have been expected to discover or invent new technologies but to create a system that takes advantage of existing and projected technologies to realise the ‘obvious’ advantages of AAs for radio telescopes. An overview of this system was presented in summary form at the SKADS meeting noted above in 2009 by Faulkner, et al.[407] and later in more

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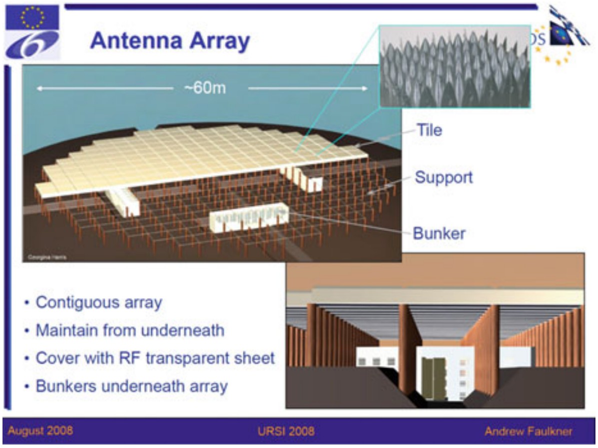
[405] hba.skao.int/SKAHB-341 Wide *Field Astronomy & Technology for the Square Kilometre Array, Torchinsky*, S. A., et al. (eds.), Proceedings of Science (https://pos.sissa.it/132/), SKADS Conf. Wide Field Science and Technology for the Square Kilometre Array, Château de Limelette, Belgium, 04 November 2009.

[406] hba.skao.int/SKAMEM-125 *A Concept Design for SKA Phase 1 (SKA1),* Garrett, M.A., et al., SKA Memo 125, 2010-08.

[407] hba.skao.int/SKAHB-345 SKADS *White Paper, Faulkner*, A. J., Proceedings of Science (https://pos.sissa.it/132/), SKADS Conf. Wide Field Science and Technology for the Square Kilometre Array (eds. Torchinsky, S. A., et al.), Château de Limelette, Belgium, 04 November 2009.



Antenna Array

~60m

Tile

Support

Bunker

- Contiguous array
- Maintain from underneath
- Cover with RF transparent sheet
- Bunkers underneath array

August 2008 URSI 2008 Andrew Faulkner

**Fig. 6.27** A slide from the presentation by A. J. Faulkner at the 2008 URSI General Assembly (hba.skao.int/SKAHB-337 Design *of an Aperture Phased Array System for the Square Kilometre Array, Faulkner*, A. J., et al., presentation at the URSI General Assembly, Chicago, USA, 2008–08) showing the size and extent of an AA station for the SKA. Credit: Andrew Faulkner and the AAVP Program

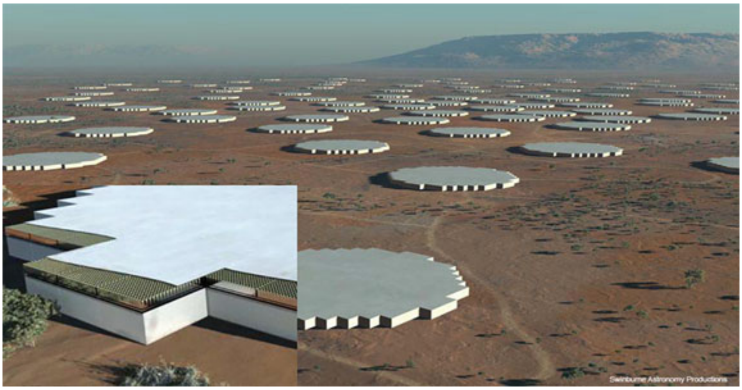


**Fig. 6.28** A grand view of an SKA telescope comprising AA stations. The lower left panel is a view of the arrays of antenna elements in each station. In this rendition each station is about 60 m in diameter. Credit: Swinburne University of Technology, Melbourne, Australia

complete form in an SKA Memo.[408] Both documents are entitled “SKADS White Paper”. This was delivered thoroughly, presenting the SKA array design shown in Table 6.4, supported by an optical network for gathering data from the stations and dishes, large hierarchical digital beamforming[409] subsystems, and large correlation and post-processing subsystems. Note the emphasis on very large stations (diameter 56 m) (Fig. 6.27). As illustrated in Fig. 6.28, the AAs were plunging into new technical territory on a large scale.

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[408] hba.skao.int/SKAMEM-122 The *Aperture Arrays for the SKA: the SKADS White Paper, Faulkner*, A., et al., SKA Memo 122, April 2010.

[409] Hierarchical beamforming forms wide ‘envelope beams’ from sub-sections of the aperture, which are then combined to form much narrower beams from the full aperture. This method is efficient but incurs significant errors and coherence loss. A full beamformer requires much more data distribution and processing.

**Fig. 6.29** Participants at the final SKADS conference in 2009 at Chateau de Limelette, Belgium. Credit: S. A. Torchinsky

To examine the results of SKADS in detail is well beyond the scope of this volume. SKASUP6-21[410] contains a compressed approach to explaining how successful SKADS was in meeting the challenges outlined in SKASUP6-17.[411]

The notes in SKASUP6-21 indicate that although SKADS carried out a thoroughgoing investigation of design alternatives, many of the technical challenges inherent in dense AAs remained below the level of maturity needed to build a telescope. The SKADS program was certainly one of the highlights of the development of the SKA project up to 2009. Although many of the technical challenges remained in 2009, the huge level of effort provided its own momentum. It was perfectly clear to funding agencies around the world, not just in Europe, that scientists and engineers in large numbers were determined to build a next generation radio telescope and were willing to devote major parts of their careers to do the hard work needed to investigate designs using new technologies. Figure 6.29 is a group picture that illustrates the

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[410] See hba.skao.int/SKASUP6-21—Approximate cross-reference of AA ‘challenges’ and the SKADS results.

[411] See hba.skao.int/SKASUP6-17—Basic Technology of Aperture Arrays at Low- and Mid-frequencies.

**Fig. 6.30** Left: The EMBRACE station under a large, curved radome. Right: Inside the radome. Shown are the aluminium Vivaldi radiators in a dual polarisation configuration of about a quarter of the array. Credit: ASTRON

breadth of interest and the impressive size of the pool of talent working on AA technology.

#### 6.5.5.2.2 Prototype AAs: EMBRACE, 2-PAD and BEST

Although a detailed description of these prototypes is beyond the scope of this volume, a brief outline is included in SKASUP6-22.[412] These prototypes[413] demonstrated that paper investigations could be realised in real hardware. The EMBRACE prototypes[414] (Torchinsky, 2016) (Fig. 6.30) were capable of astronomical observations (Benthem & Kant, 2012). The 2-PAD[415] (Fig. 6.31) and BEST[416] prototypes provided valuable data on the overall performance of SKADS technology and system designs.

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[412] See hba.skao.int/SKASUP6-22—An Outline of the Development of AA Prototypes.

[413] EMBRACE: Electronic MultiBeam Radio Astronomy *ConcEpt.* 2-PAD: 2-Polarisation All Digital. BEST: Basic Element for SKA Training.

[414] hba.skao.int/SKAHB-346 EMBRACE *System Design and Realisation, Kant*, G. W., et al., Proceedings of Science (https://pos.sissa.it/132/), SKADS Conf. Wide Field Science and Technology for the Square Kilometre Array (eds. Torchinsky, S. A., et al.), Château de Limelette, Belgium, 04 November 2009.

[415] hba.skao.int/SKAHB-349 Integrated *Aperture Array Antenna Design for Radio Astronomy, Zhang*, Y., and Brown, A. K., Proceedings of Science (https://pos.sissa.it/132/), SKADS Conf. Wide Field Science and Technology for the Square Kilometre Array (eds. Torchinsky, S. A., et al.), Château de Limelette, Belgium, 04 November 2009.

[416] hba.skao.int/SKAHB-347 BEST*: Basic Element for SKA Training, Montebugnoli*, et al., Proceedings of Science (https://pos.sissa.it/132/), SKADS Conf. Wide Field Science and Technology for the Square Kilometre Array (eds. Torchinsky, S. A., et al.), Château de Limelette, Belgium, 04 November 2009.

**Fig. 6.31** 2-PAD installed at Jodrell Bank Observatory. Credit: Peter Wilkinson

#### 6.5.5.3 Dense AAs in the Aperture Array Verification Program (AAVP)

Section 6.2.1.6 describes the transition from the SKADS program to the Aperture Array Verification Program (AAVP), in which work on Dense AAs continued under a new program.

In most respects, the AAVP program continued the structure of the SKADS work packages: AA system design studies (AA-SDS), AA technology development (AA-Tech), build and test AAs on the sky with EMBRACE (A3IV), build and test an all-digital AA (DAAVS), low-frequency component development (AA-lo), and power/infrastructure studies (AA-SEM). Figure 6.32 from van Ardenne's 2009 IEAC presentation[417] illustrates the way that assignments and allocations were given to participating organisations. In a prelude to the Aperture Array Verification Program (AAVP) in 2008, Faulkner presented a similar outline.

Because frequencies up to 1.5 GHz (or somewhat higher) were to be covered using dense AAs, there was little need in this architecture for large dishes to cover these 'mid-band' frequencies. Initially, ATA-style 6.5 m dishes were proposed.

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[417] hba.skao.int/SKAHB-340 The *Aperture Array Verification Program,* van Ardenne, A., presentation to the International Engineering Advisory Committee (IEAC) on behalf of the European SKA Consortium, 14 April 2009.

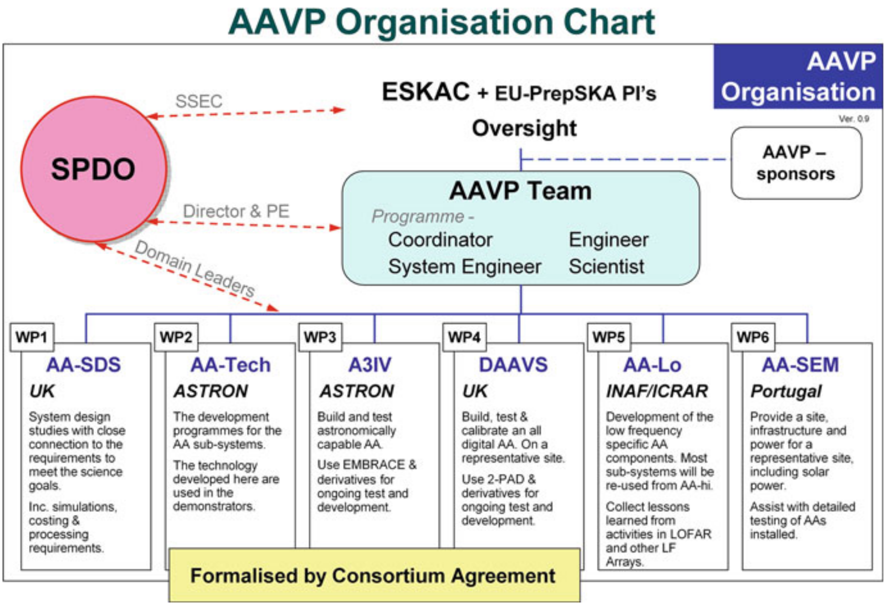

**Fig. 6.32** The AAVP institutional organisation chart as developed in October 2008. Credit: van Ardenne and the AAVP Program

Later, somewhat larger 'simple' axi-symmetric dishes were proposed.[418] Later still, 15-m dishes were incorporated, but it became clear that this was not consistent with the AAVP architecture.

As importantly, the integrated nature of architecture and organisational structure was brittle. Everything depended on the assumption that the underpinning technology was successful. When the technology and cost prospects turned out to be more involved than expected, the higher-level structure came under scrutiny. After the SKA System CoDR in February 2010 and the subsequent re-definition of SKA Phase 1, dense AAs were no longer part of the SKA Phase 1 technical concept, and the integrated approach no longer looked appropriate. This did not prevent two large AAVP workshops from being held in late 2010 at Cambridge (UK)[419] and late-2011 at Dwingeloo.[420]

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[418] hba.skao.int/SKAHB-356 *Thermoplastic* axi-symmetric dish, *Pragt,* J. and van den Brink, R., presentation at the Dish CoDR, Penticton, 13 July 2011.

[419] hba.skao.int/SKAHB-352 AAVP *Workshop AgendaCambridge, United* Kingdom, 06 December 2010.

[420] hba.skao.int/SKAHB-364 AAVP *Workshop AgendaDwingeloo, The* Netherlands, 12 December 2011.

#### 6.5.5.4 Postscript

Following the System CoDR held in February 2010 and the subsequent decision at the SSEC meeting in March 2010 to down-select technologies for SKA Phase 1 (see Sect. 4.5.2), dense AAs were not included in the baseline SKA Phase 1 technical concept.[421] Recognising the large investment in AA innovations, they became part of the SKA Advanced Instrumentation Program (AIP), along with PAFs and Wideband Single Pixel Feeds.[422]

The formal AA Conceptual Design Review (CoDR) and a delta-CoDR on the mid-frequency aspects were held in April and November 2011, respectively. The review reports[423,424] continued to outline issues with technical maturity of the mid-frequency (dense) AAs.

Despite a very large effort and significant innovation, the practical implementation of AAs at short wavelengths for radio astronomy has yet to be achieved. SKASUP6-23[425] speculates on whether AAs might have become 'mainstream' if the equivalent effort were to have begun at the time of writing.

## 6.6 Critical Supporting Technologies

Although antenna development has been emphasised in much of the foregoing, aperture synthesis telescopes require much more apparatus to function, the most important of which are discussed in this section.

Arguably the most important devices are the Low Noise Amplifiers (LNAs), which are connected directly to telescope antennas. LNA development had in some cases reached close to the quantum limit (Bryerton et al., 2013), below which no further improvement in noise is possible. Much work was also carried out to produce efficient feeds for dish antennas (see Sect. 6.6.1).

Before 2008 especially, the SKA telescopes were described as Information and Communications Technology (ICT)[426] devices, to emphasise the use of digital

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[421] hba.skao.int/SKAMEM-125 *A Concept Design for SKA Phase 1 (SKA1),* Garrett, M.A., et al., SKA Memo 125, August 2010.

[422] hba.skao.int/SKAMEM-130 *SKA Phase 1: Preliminary System Description,* Dewdney, P. E., et al., SKA Memo 130, 22 November 2010.

[423] hba.skao.int/SKAHB-357 Panel *Report: SKA Aperture Array Concept Design Review (CoDR), Dewdney*, P. E., et al., SKA Project Office Report, 20 April 2011.

[424] hba.skao.int/SKAHB-363 Report *of the Review Panel: AA delta-Concept Design Review, SKA AA-mid Aperture Arrays, Dewdney*, P., SKA Project Office Report, 23 November 2011.

[425] See hba.skao.int/SKASUP6-23—Dense AAs for Radio Astronomy using today Technology of 2022—What would change?

[426] This is an industry term which is generally accepted to mean all devices, networking components, applications and software systems that allow businesses and organisations to interact in the digital world.

technologies in their design. Compared with early radio telescope technologies, which relied more on analogue devices, this represented a great potential improvement in both the performance and cost of the SKA. Peter Hall, then SKA Project Engineer, used the term "ICT engine", "viewed as a large data transport and processing system" to describe the SKA in general.[427] The emphasis on ICT aspects of the SKA project also attracted talented people from the field, such as John Bunton who was working initially for the CSIRO ICT Centre in Australia.

For broad appeal, the catch phrase "sensor network" was used to describe the LOFAR telescope as a "generic Wide Area Sensor Network for astronomy, geophysics and precision agriculture".[428] This term was picked up in other documents as well, particularly regarding industrial liaisons.[429]

These improvements permitted the analogue 'signal chains', which start at the antenna and end with digitisation of the signals, to be very short. This confers the advantage of stability and predictability of the all-digital parts of the telescope. Moreover, rapid advances in these technologies provided a route to larger arrays of telescopes than previously thought possible (see points {G} {H} in Chap. 6 introduction). By 2011, cloud computing had also entered the ICT and SKA lexicons.[430]

All these technologies are impacted by RFI and are key components of mitigation strategies in the design of radio telescopes (see Sect. 6.2.2.12).

### *6.6.1 Feeds, Low Noise Amplifiers (LNAs) and Cryogenics*

Because astrophysical radio signals are so weak, designs of radio telescopes go to great lengths to maximise sensitivity. For a given size of telescope (i.e., collecting area), sensitivity is determined by sources of noise, the lower the better (see Sect. 6.4.1). For many years, the most cost-effective approach to improving radio telescope performance was to improve the noise contributed by the LNA, the first amplifier on the antenna, exemplified in a summary from the pre-SKA era by Marian Pospieszalski (Pospieszalski, 1990). These were always cryo-cooled. This strategy was used by the National Radio Astronomy Observatory (NRAO) for many years to maintain its leading role in radio astronomy.

In the early PrepSKA period, it was assumed that cryo-cooling of LNAs on dishes would be too expensive, especially to maintain on the very large number of dishes

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[427] hba.skao.int/SKAMEM-91 *An SKA Engineering Overview: White Papers by the Task Forces of the International Engineering Working Group,* Hall, P. J., ed., SKA Memo 91, 14 September 2007.

[428] hba.skao.int/SKAHB-383 Status of Pathfinder Telescopes and Design Studies, Greenwood (ed.), C., International SKA Project Office Document, 10 December 2007.

[429] hba.skao.int/SKAMEM-80 *The International SKA Project: Industry Liaison Models and Policies,* Hall, P. J. and Kahn, S., SKA Memo 80, 28 July 2006.

[430] hba.skao.int/SKAMEM-134 Cloud Computing and the Square Kilometre Array, Newman, R. and Tseng, J., SKA Memo 134, May 2011.

proposed for the SKA. (It was realised much later that this assumption was too simplistic (see Sect. 6.4.3.3)). Also, during early PrepSPA, PAFs were a hot topic in Australia, The Netherlands and Canada, (see Sect. 6.4.7.1) and PAFs were too large to be contained in a cryostat. Therefore, there was a strong push, which continues at the time of writing, to reduce the noise of LNAs without cryo-cooling. There was also interest in cooling to an intermediate temperature, 80 K instead of 20 K. LNAs for a "Next Generation Very Large Microwave Array"[431] was already being considered by Sandy Weinreb at the US National Radio Astronomy Observatory (NRAO) in 1998, and continued at the Jet Propulsion Laboratory during PrepSKA[432] and beyond.

Beginning with a need to develop LNAs for the Large Adaptive Reflector (LAR),[433] Leonid Belostotski at the University of Calgary developed a series of LNAs for PAFs in general and many other radio telescopes (e.g., (Belostotski & Haslett, 2006)).

At radio frequencies less than about 500 MHz, the situation is quite different because noise from the sky, itself, is a major contributor to overall system noise for the telescope. In this situation, uncooled LNAs are competitive. For SKA1-Low, which is designed with thousands of elemental antennas (see Sect. 6.5.3), LNAs can be made small enough to be directly attached to each antenna.

#### 6.6.1.1 Wide Band Single Pixel Feeds (WBSPFs)

WBSPFs were included in the 2013 design baseline[434] for only two bands, Band 1 (350–1050 MHz) and Band 5 (4.6 13.8 GHz) (Tan et al., 2016). Band 5 was later converted to two octave bands for reasons outlined below.

WBSPFs were a featured area of SKA innovation and research long before the PrepSKA era. They are feed antennas used at the foci of dishes to receive concentrated emission from the dish optics and are considered 'wide-band' if the ratio of the upper to lower frequencies is greater than two (an octave). This is in contrast with traditional octave band feeds (Granet et al., 2008), for which this ratio is about two. The design goal is to produce a beam that has a constant diameter over the entire frequency range, whereas the natural tendency of antennas is that the beamwidth scales with wavelength.

The ATA pioneered the use of a novel cooled WBSPF (0.5–11 GHz), consisting of a log-periodic dipole antenna encased in a glass cryostat so that the entire feed and

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[431] hba.skao.int/SKAMEM-47 Noise Temperature Estimates for a Next Generation Very Large Microwave Array, Weinreb, S., SKA Memo 47, 07 June 1998.

[432] hba.skao.int/SKAMEM-137 Very Low Noise Ambient-Temperature Amplifiers for the 0.6–1.6 GHz Range, Weinreb, S., SKA Memo 137, December 2011.

[433] See hba.skao.int/SKASUP6-28—The Large Adaptive Reflector (LAR).

[434] hba.skao.int/SKAHB-206 *SKA1 System Baseline Design,* Dewdney, P. E., et al., SKA Document SKA-TEL-SKO-DD-001, 12 March 2013.

Low Noise Amplifier was cooled to about 80 K[435] (see Sect. 6.4.2). They were considered an important innovation in SKA Memo 100 (see Sect. 6.2.1.4), the first comprehensive set of SKA specifications. Germán Cortés-Medellín summarised the performance of eight different WBSPF designs being put forward for the SKA at the DVA-1 CoDR meeting in Socorro[436] in 2011.

The appeal of WBSPFs was obvious. Only one or two feeds are required instead of several, the cost is potentially much lower, and it was possible that only one set of RF electronics (the signal chain) would be needed. However, difficulties arise because the beam is usually only quasi-constant with frequency. This affects the efficiency, imaging dynamic range and the spillover noise (from the feed beam spilling over the edge of the dish and intersecting the 'hot' ground) (see Sect. 6.4.3.3). The pros and cons of WBSPFs were summarised in a presentation[437] at the PrepSKA WP2 meeting in Manchester in 2011.

The panel report from the System CoDR review[438] in 2010 suggested that the SPDO "Plan a roadmap of the introduction of innovative technologies which will become available in later phases (e.g., WBSPF)". WBSPFs later became part of the AIP (see Sect. 6.2.2.9). Post-2012 developments in WBSPFs can be found in SKASUP6-24.[439]

### 6.6.2 Signal Transport

An important example of enabling technology diffusion for the SKA is the rapid development of data transport by optical fibre (see point {H} in Chap. 6 introduction), a core part of the ICT 'revolution'. By 1995, when the SKA concept was already circulating in the radio astronomy community, a frequent measure of performance, capacity-distance per fibre had doubled every 12 months since 1975 (Agrawa et al., 2016), faster than Moore's Law (see point {G} in Chap. 6 introduction). A high rate of capacity growth has continued to the time of writing. Except for cost, in 1995 this would have made feasible data-rates of about 300 Gigabits per second (Gpbs) transmitted from antenna stations at 3000 km, more than enough for the SKA. By 2006 in Europe, VLBI stations were routinely connected by optical

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[435] hba.skao.int/SKAHB-144 *Evaluating the TRW and ATA Feeds*, deBoer, D. R., ATA Memo 49, 05 April 2002.

[436] hba.skao.int/SKAHB-396 Modeled Performance of Wideband Feeds, Cortes, G., presentation at the DVA1 CoDR at Socorro, N.M., 03 February 2011.

[437] hba.skao.int/SKAHB-411 Dishes with Wide Band Single Pixel Feeds, Dewdney, P. E., presentation at the SKA WP2 meeting, Manchester, 18 October 2011.

[438] hba.skao.int/SKAHB-181 *SKA System CoDR Panel Initial Feedback,* Wild, W., et al., presentation at the System CoDR Review, 26 February 2010.

[439] See hba.skao.int/SKASUP6-24—Post-2012 developments in WBSPFs.

fibre[440] and the use of optical fibre in radio telescopes had become widespread (McCool et al., 2006).

However, cost is still a dominant factor for the SKA. But rather than the fibres themselves, the cost of trenching was the largest factor. This led to a major mathematical study of the most efficient network of trenches in a dense array of antennas (see Fig. 6.7).[441] Signal transport costs over long distances led South Africa to propose in their site bid of 2011 to co-locate the SKA correlator-beamformer and the processing super-computer to an "Astronomy Complex" near the site of the telescope, itself.[442]

Although the fibre optic cable is not a major part of the cost, the circuitry at the endpoints, including the cost of digitising the RF signals from the antenna, is expensive and requires considerable power. Although for dishes with PAFs or WBSPFs, the total bandwidth is higher than for typical single-pixel feeds, it is still well within reach of commercially available optical fibre systems. However, for the original configuration of the SKA-Low telescope discussed in Sect. 6.5.4, there would have been as many as 10,000 antennas in a station. This was later reduced to 256 antennas in more stations. In either case, the cost and practicality of digitising the signals from each individual antenna would have been prohibitive.

A much less expensive approach was to send RF signals directly over optical fibre, so called RF-over-fibre (RFoF). In its simplest form this technique uses an amplified version of the electrical RF signal from an antenna to modulate the amplitude of a laser whose output is connected to a fibre. At a central receiving end, a photodetector is used to recover the electrical RF signal, which is then digitised before being transmitted to a correlator or beamformer. Apart from being less expensive, the advantages are that devices are smaller, and less power is required. RFoF data-transport was studied extensively[443] and evaluated in SKA-related prototypes: the Northern Cross Telescope,[444] the Karoo Array Tele-

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[440] Coordinated by the Joint Institute for VLBI (JIVE), the EXPReS project assembled an optical fibre network for connecting VLBI antennas in real time (see https://cordis.europa.eu/project/id/026642). This was seen as a significant advance for the SKA (see https://www.astron.nl/expres-hailed-as-extraordinarily-successful-to-ska-design/).

[441] hba.skao.int/SKAMEM-121 Cost-Effective Infrastructure in a Multiantenna Telescope Layout, Grigorescu, G., et al., SKA Memo 121, September 2010.

[442] hba.skao.int/SKAHB-410 South African Response to the SSG Request for Information—Data Transport, South African government, South African Response to the SSG Request for Information, 15 September 2011.

[443] hba.skao.int/SKAHB-403 RF over Fibre Solutions for the SKA, Maat, P., presentation at the Signal Transport and Networks CoDR, 26 June 2011.

[444] hba.skao.int/SKAHB-404 RF over fibre solutions for the SKA II Antenna Network For AA-Lo: Concept Description, Perini, F., presentation at the Signal Transport and Networks CoDR, 26 June 2011.

scope (KAT),[445] and ASKAP.[446] Although the many pros and cons of this approach are beyond the scope of this discussion, RFoF is now part of the design of SKA1-Low, under construction at the time of writing.

Signal Transport provides the connective tissue for a geographically diverse project like the SKA. Because the system architecture was still quite immature at the time of the Signal Transport and Networks Concept Design Review (CoDR) in 2011, it was clearly difficult to provide a mature Signal Transport architecture. Scaling studies[447] were used to partly overcome these issues, but nevertheless the risks of using RFoF continued to be highlighted in the panel report.[448]

### 6.6.3 Astrophysical Transients, Pulsar Searches and Timing[449]

Pulsar astronomy became a veritable industry after their discovery in 1968. A series of subsequent discoveries have clearly illustrated their importance to astronomy and to fundamental physics (see Chap. 5). Most observations and searches have been carried out with large single dishes, notably the Parkes radio telescope in Australia, the Lovell radio telescope at Jodrell Bank in the UK, the Effelsberg radio telescope in Germany, and the Green Bank and Arecibo Telescopes in the USA. The Handbook of Pulsar Astronomy (Lorimer & Kramer, 2004) contains a synopsis of pulsar astronomy as of 2004 and a very useful overview of basic instrumentation for pulsar observations.

Translating the science goals of pulsar research (see Chap. 5) into a set of potential SKA observational programs provides a way of ascertaining design requirements: (1) Assemble a complete census of Galactic pulsars. (2) Use a sub-set of very stable pulsars (a pulsar timing array), to detect and characterise nano-Hz gravitational waves. (3) Use a sub-set of pulsars in binary systems, especially with black-hole companions, as tests of General Relativity in extreme environments. Additionally, search for a pulsar orbiting the supermassive black hole at the centre of the Galaxy. (4) Use pulsars as probes of the Galactic Interstellar Medium, the plasma that permeates the Milky Way. More generally keep discovery

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[445] hba.skao.int/SKAHB-405 Lessons from the Pathfinder: KAT-7 to MeerKAT to SKA, Venkatasubramani, T. L., presentation at the Signal Transport and Networks CoDR, 26 June 2011.

[446] hba.skao.int/SKAHB-406 PAF Signal Transport Australian SKA Pathfinder STaN CoDR, Beresford, R., presentation at the Signal Transport and Networks CoDR, 26 June 2011.

[447] hba.skao.int/SKAHB-387 Data Transmission Cost Scaling for Long Baselines in the SKA, McCool, R., SPDO Document, 01 July 2009.

[448] hba.skao.int/SKAHB-408 SKA CoDR Signal Transport and Networks - Feedback, Durand, S., presentation of the review panel report for the Signal Transport and Networks CoDR, 30 June 2011.

[449] An expanded version of this section can be found in hba.skao.int/SKASUP6-25.

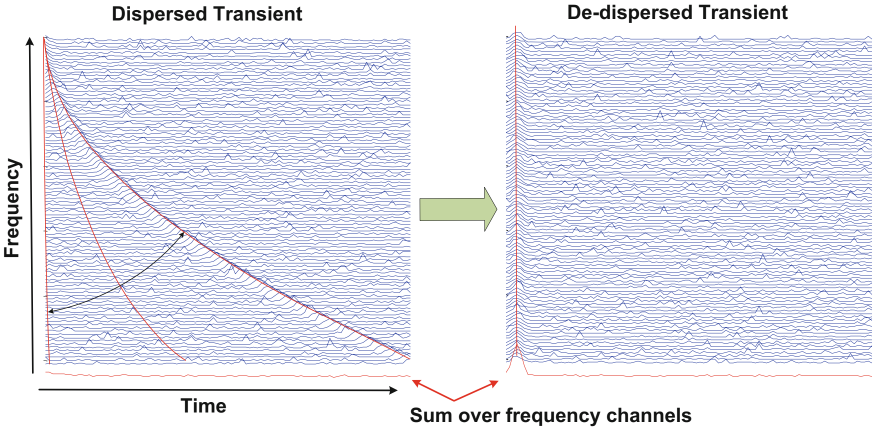

**Fig. 6.33** Left: The time-frequency (dynamic spectrum) signature of a dispersed pulsar pulse or an astronomical transient. The red solid curve suggests trials of unsuccessful lower dispersion-measures until the correct value has been reached. Right: Time-alignment after a matched de-dispersion operation has been applied. Bottom: The red plot shows the increase in signal-to-noise of the pulse after the de-dispersion operation and a summation over frequency has been applied

space in the time domain as wide-open as possible for discovery of unknown phenomena.

Array telescopes before the SKA were not normally designed to observe fast time-domain phenomena.[450] The need to detect and observe astrophysical transients was foreseen in a memo from the early 2000s,[451] in which detailed science and important instrumental requirements were described. In SKA Memo 86[452] and SKA Memo 97,[453] Jim Cordes developed modified definitions of survey speed and survey completeness to consider the nature of transient sources, pointing out that the time domain is a relatively unexplored "axis of discovery".

As shown in Fig. 6.33, when a transient signal of astrophysical origin traverses the path through the ionised medium from the source to the telescope, it undergoes dispersion, which means that the signal is 'stretched' over frequency so that the high frequency component arrives sooner than the low frequency component. This causes

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[450] Except the pulsar discovery telescope, the Interplanetary Scintillation Array, which was optimised for short-duration fluctuations due to interplanetary scintillation.

[451] hba.skao.int/SKAMEM-6 Radio Transients, Stellar End Products, and SETI Working Group Report, Lazio, J., et al., SKA Memo 6, 22 March 2002.

[452] hba.skao.int/SKAMEM-85 *Discovery and Understanding with the SKA,* Cordes, J., SKA Memo 85, October 2006.

[453] hba.skao.int/SKAMEM-97 The *Square Kilometer Array as a Radio Synoptic Survey Telescope: Widefield Surveys for Transients, Pulsars and ETI, Cordes*, J., SKA Memo 97, 21 September 2007.

an intrinsically narrow emitted pulse, which because of its narrowness covers a wide band of frequencies, to follow a parabolic curve downward towards lower frequencies with time. If the receiver band is divided into narrow frequency channels, a display of frequency versus time, the dynamic spectrum, will show the parabolic track.

If the transient is a one-off event, it must be strong enough that it can be detected in a narrow frequency band. If the transients are pulses from a pulsar, then the train of pulses can be detected even if the pulses are weaker than the telescope noise because of their precise repetition. Hence, when searching the sky for weak unknown pulsars, the telescope must be capable of searching a space consisting of the unknown repetition rate and the unknown dispersion. This is equivalent to searching for all possible tracks in the large space shown in Fig. 6.33, large because pulsar repetition periods cover a range from about 1 ms to 10 s, and measures of dispersion cover a similarly large range.

There are two aspects of telescope architecture that are directly related to time-domain observations, especially searching for pulsars. The first is a beamforming capability which is implemented in the correlator-beamformer (CBF) as described in Sect. 6.6.4. The figure in SKASUP6-26[454] shows the CBF outputting streams of data for each beam to be processed. For example, in the final design for SKA1-Mid, there are about 1500 beams, resulting a huge data rate, all to be searched in parallel. This is carried out by a pulsar search engine, a specialised computing device, designed to search the period-dispersion space described above (see the figure in SKASUP6-26). This device produces a small number of pulsar candidates that are further analysed in off-line software.[455]

The second is the array configuration. The ideal arrangement for time-domain observations is for all the collecting area to be concentrated at the centre of the array, the core. This is essentially equivalent to a large single dish, which provides the maximum sensitivity and the largest array beam (i.e., search area on the sky). The many competing goals for the design of the array configuration are discussed in Sect. 6.2.2.10 and depicted in Fig. 6.8. The compromise configuration, shown in the Box in SKASUP6-6,[456] contains a dense core, partly to satisfy pulsar search requirements. With this configuration there is an optimum area around the core to use for pulsar searching. For example, the Baseline Design document[457] provided an estimate of approximately the inner half of the SKA1-Mid antennas to be used for pulsar searching.

Pulsars have an emission spectrum that is stronger at low frequencies than high ones. But dispersion is also stronger at low frequencies. In general, the tension

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[454] See hba.skao.int/SKASUP6-26—Radio Telescope Correlators and Beamformers.

[455] hba.skao.int/SKAHB-416 Software and Computing CoDR: Processing for Pulsars and Transients, Stappers, B., SKA document WP2–050.020.010-SR-002, 27 January 2012.

[456] hba.skao.int/SKASUP6-6—The Influence of Array Configuration on Telescope Performance

[457] hba.skao.int/SKAHB-206 *SKA1 System Baseline Design,* Dewdney, P. E., et al., SKA Document SKA-TEL-SKO-DD-001, 12 March 2013.

between these two effects leads to a broad optimum frequency range for pulsar searching, around 1 GHz. This means that the telescope capabilities at this frequency are very important for pulsar astronomy, particularly because some of this frequency range is badly contaminated with RFI.

Capturing rare transients spawns additional design requirements. If a strong dispersed signal is detected in one of the pulsar engines, it can be captured in the pulsar engine's data store, but this will not provide much information on its direction. However, if output data from each antenna is stored for a short period of time in a data buffer before the event, then an image can be formed from these data to try to determine the position of the source on the sky. The contents of this 'ring buffer' is captured upon the detection of a transient and saved for subsequent analysis.

Discovering new pulsars is just a step towards the 'real science', which is enabled by follow-up observations to precisely track their Times-of-Arrival (ToAs). Strong-field tests of gravity and the detection of long-period gravitational waves require follow-up of a pulsar sub-set with both the capability to detect acceleration of pulsars orbiting compact objects and a long-term timing program. Only a sub-set of very stable pulsars or those that indicate accelerations will be covered in a long-term timing program. In instrumental terms, this means that measuring ToAs of pulses must be 'time-tagged' with a precision of a about 10 nanoseconds, traceable over a period of about 10 years, a ratio of about $10^{16}$. Such precision timing will reduce instrumental effects to the point where ToA scatter will be dominated by intrinsic scatter in the pulsar signals, themselves. Timing is carried out by a pulsar timing engine (see the figure in SKASUP6-26[458]) in conjunction with an Observatory 'clock'[459] that maintains accurate timing.

The foregoing illustrates the design complexity required to enable exploration of the radio-astronomy time-domain. As described above for the array configuration, compromises with other design goals and with cost inevitably had to be made. Based on the system architecture described in SKA Memo 130[460] and modelling the results of an earlier survey using the Parkes telescope, estimates of computational requirements and processing options[461] were made. One driving aspect stood out: finding highly accelerated pulsars in a tight orbit around a massive object requires about 100 times the processing power than that required for isolated pulsars. This work led to a more complete high-level description[462] of pulsar search processing written for the Central Signal Processing (CSP) CoDR in April 2011.

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[458] See hba.skao.int/SKASUP6-26—Radio Telescope Correlators and Beamformers.

[459] hba.skao.int/SKAHB-407 Timing and Synchronisation Concept Description, Garrington, S., presentation at the CoDR for Signal Transport and Networks, 28 June 2011.

[460] hba.skao.int/SKAMEM-130 *SKA Phase 1: Preliminary System Description,* Dewdney, P. E., et al., SKA Memo 130, 22 November 2010.

[461] hba.skao.int/SKAHB-401 Pulsar Survey with SKA phase 1, Smits, R., SKA document WP2-040.030.010-TD-003, 31 March 2011.

[462] hba.skao.int/SKAHB-398 High-Level SKA Signal Processing Description, Turner, W., SKA document WP2-040.030.010-TD-001, 29 March 2011.

Another aspect of this work was optimising a survey of the entire visible sky from the two SKA telescope sites. While frequencies covered by SKA1-Mid are best for regions near the Galactic disc where the interstellar medium (ISM) is most dense (i.e., high dispersion), a suitably equipped SKA1-Low could be used to survey the rest of the sky, where the ISM density falls off (low dispersion). For this and other reasons, both telescopes contain similar array beamformers and pulsar engines.

Over the years, pulsar astronomers had already developed sophisticated processors, similar in many respects to those needed for the SKA. By 2004 (Lorimer & Kramer, 2004), most of the fundamental algorithms had been developed. Further progress could only be made by developing optimised architectures for implementing them in the available hardware of the day. From 2003 to 2007, the field moved away from recording the signal from the telescope and processing off-line to processing the signal in real time at the telescope site. By 2010, many implementations of real-time processors were being used, and versatile computer code (van Straten & Bailes, 2010) was widely distributed.

In principle, just replicating these devices would suffice for the SKA, since it is just a matter of one device per beam. As with the correlator-beamformer case (see Sect. 6.6.4.1), there was a tendency to jump directly to design solutions based on bespoke hardware.[463] But the field took another direction when Graphics Processing Units (GPUs) became widely available. They can very efficiently execute Fourier transforms and other basic functions, the key bottleneck in pulsar processing (e.g., see (Barsdell et al., 2012)). Unlike other components of the SKA system, it does not make sense to build too early due to the continuing rapid development of electronic technology (see point {G} in Chap. 6 introduction). Hence, continuing to build and develop pulsar processors (search and timing) using the latest technology on various available telescopes (e.g., (Bailes et al., 2016)) will benefit the SKA until finally it becomes necessary to build specifically for the SKA telescopes (Stappers et al., 2018). Further developments in this story are beyond the scope of this book.

### 6.6.4 Correlators and Beamformers

The correlator, often called the ‘processing heart’ of a radio telescope, is a central system that receives signals from antennas and processes them to produce viable scientific data. Modern correlators are based on the so-called FX architecture.[464] SKASUP6-26[465] explains how correlators and beamformers function in the SKA

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[463] hba.skao.int/SKAHB-399 Pulsar Signal Processing on Uniboard, AhmedSaid, A., SKA document WP2-WP2-040.170.010-TD-001, 01 April 2011.

[464] Although there have historically been other correlator architectures, most modern correlator designs carry out the division into frequency channels before multiplication. This is the so-called FX architecture, first proposed by Chikada et al. (1987). Sometimes this is preceded by an additional ‘F’, in which two stages of frequency division are used.

[465] See hba.skao.int/SKASUP6-26—Radio Telescope Correlators and Beamformers.

architecture. Combined to make the correlator-beamformer (CBF), they are specialised super-computers designed to carry out simple processing steps on vast quantities of data. The output data produced by the correlator represents points in the *u-v* plane for each channel (see Sect. 6.2.2.10 and the Box in SKASUP6-6[466]). From the data in the *u-v* planes, it is possible to create detailed radio images over the field-of-view, using the methods outlined in Sect. 6.6.5. Beamformers produce data streams by combining the data from the individual antennas in such a way that the output resembles that from a single large antenna with a narrow beam on the sky.

The Signal Processing CoDR in April 2011 was an opportunity for institutes to present their wares and to illustrate their capabilities. In a high-level description,[467] which was virtually a case study in a system-engineering approach to an early design review, the scene was set by Wallace Turner, SPDO's domain specialist in signal processing. It covered the system-engineering gamut: motivations, requirements, known algorithms, risk, costs, technology roadmap, and strategy to proceed to the next phase.

Ten architecture options for correlators from seven institutes, three beamformer options, and five options for pulsar processing were presented at the Signal Processing CoDR.[468] This became known as the Battle of the Boards (see next section). As highlighted in the report of the review committee,[469] the issues were how to compare the various options on the same basis: how to narrow them down without carrying forward too many and eliminating some too early, and how to make choices in the light of technology advances. The backdrop was the rapid changes in technology epitomised by Moore's Law (see point {H} in the Chap. 6 introduction). This was anticipated in a technology roadmap[470] produced at the time but turned out to be difficult to maintain in the ensuing years.

These issues were only resolved during the pre-construction period after 2012, when the Frequency Slice Processor was introduced.[471] By that time, many of the competing institutes had lost interest or moved on to other projects. It is interesting to note that resolution of the options dilemma was not achieved through attempting to choose options strictly on a technical or system-engineering basis, but rather through an allocation process among participating countries. While the process was messy (see point {E} in the Chap. 6 introduction), it had the overall effect of choosing the institutes with the strongest motivation, resources, and best track-records in the field.

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[466] hba.skao.int/SKASUP6-6—The Influence of Array Configuration on Telescope Performance.

[467] hba.skao.int/SKAHB-398 High-Level SKA Signal Processing Description, Turner, W., SKA document WP2-040.030.010-TD-001, 29 March 2011.

[468] hba.skao.int/SKAHB-400 Context of The SKA Signal Processing Concept Design Review, Turner, W., SKA document WP2-040.010.040-MR-001, 04 April 2011.

[469] hba.skao.int/SKAHB-402 SKA Signal Processing Concept Design Review—Report of the Review Panel, Sharpe, R., SKA document, 14 April 2011.

[470] hba.skao.int/SKAHB-397 Technology Roadmap Document For SKA Signal Processing, Turner, W., SKA document WP2-040.030.011-TD-001, 27 February 2011.

[471] hba.skao.int/SKAHB-420 SKA1 CSP Mid Correlator and Beamformer Sub-element Detailed Design Document, Pleasance, M., et al., SKA Document 311-000000-003, 18 December 2017.

While this did not completely avoid competition and challenges, it provided a simpler basis for moving forward.

#### 6.6.4.1 Battle of the Boards

Throughout the PrepSKA era, bespoke digital hardware was the favoured solution. This was because software correlators, based on commercially available computers, even supercomputers, could not handle the data volume. Each major radio-astronomy institute wanted to develop its own solution to this problem, mainly for telescopes for which they had already developed equipment, including the SKA pathfinder and precursor telescopes (e.g., (Szomoru, 2011; Hampson et al., 2014)). An overview of these options was presented by Brent Carlson at the 2010 PrepSKA WP2 meeting in Manchester.[472] In most cases, the processing hardware was based on Field-Programmable Gate Arrays (FPGAs), which are commercially available integrated circuits that can be configured to efficiently process data at high speed. Like other electronic devices, FPGAs have rapidly improved and provide a good route to building data-processing systems on a small to medium scale, rather than the very expensive development of ‘hard silicon’.

During the PrepSKA period, many institutes proclaimed the utility of their boards for all manner of uses, including for the SKA, itself. The most successful of these in this sense was the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER), headquartered at the University of California at Berkley (Werthimer, 2011). CASPER set out to produce designs of reconfigurable boards that could satisfy the needs of many institutions for a variety of purposes: correlators, beamformers, pulsar search and timing machines, etc. The project received a big boost when the MeerKAT project decided to join the collaboration and on behalf of the collaboration, designed what became known as the ROACH board, which was then used for the MeerKAT digital backend.[473] This board found uses in many different telescopes. The CASPER hardware was not necessarily better than the other boards, but the collaboration was specifically formed to pool resources (especially shared software/firmware) and was promoted heavily in the US.

At low frequencies, for which bandwidths are smaller, software correlators are viable instead of customised hardware. The LOFAR project did build a large software correlator in 2010, based on an IBM Blue Gene/P computer (Romein et al., 2010). This was replaced in 2018 by a GPU-based[474] correlator (Broekema et al., 2018), which uses commercially available hardware (see above {G} in Chap. 6

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[472] hba.skao.int/SKAHB-393 WP2.5.1—Correlator and Central Beamfomer, Carlson, B., presentation at the WP2 meeting in Oxford UK, 27 October 2010.

[473] hba.skao.int/SKAHB-409 The MeerKAT Digital BackEnd (DBE), Kapp, F., et al., presentation at the MeerKAT PDR, 18 July 2011.

[474] Graphic Processing Units (GPUs) were developed for the video gaming industry to accelerate graphics processing, but the architecture has turned out to be useful for more general-purpose computing as well.

introduction). Although the software correlator for LOFAR was only marginally successful, software correlators have been successful for processing VLBI observations (e.g., (Deller et al., 2011)).

The subsequent evolution of SKA correlator architectures post-2012 is discussed briefly in SKASUP6-27.[475]

### *6.6.5 Radio Images: SKA's Ambitious Software Requirements*

Information processing has always been a constraint on the theoretical performance of radio telescopes. Intuitively, the information available to a radio telescope is proportional to the number of radio-imaging pixels in the field-of-view of the telescope times the number of frequency channels to be acquired, often referred to as a 3-D image cube. However, the signals that convey this information are very weak and usually masked by noise. Moreover, a practical telescope does not capture the signals perfectly and contains errors. Finally, RFI signals (see Sect. 6.2.2.12) have the effect of making some frequency channels unusable. The software component of radio telescopes has the task of forming the image cubes from the correlator output data, applying calibrations to reduce the effects of errors, and ameliorating the effects of RFI and noise.

Calibration is a measurement or procedure that reverses the effects of errors in the telescope. There are many types of calibrations, but many require software-intensive processes. Although errors do not necessarily arise from the software itself, residual errors remaining after the data has been calibrated limit the performance of telescopes in general. An important additional effect occurs at frequencies covered by SKA-Low. The ionosphere inserts a time-varying distorting screen in front of the radio sky that, in its simplest form, moves the apparent position of radio sources on both short and long timescales. This effect must also be removed in software.

For example, a key science objective of the SKA was to be able to observe the very weakest radio sources, mainly those expected to be from the earliest galaxies in the 21-cm wavelength window. This capability, high dynamic range imaging, requires the detection of sources that are about 10 million times weaker than nearby strong radio sources in the sky (see Sect. 6.4.3.2). Even the smallest of errors will affect this goal.

Many software packages devoted to imaging and calibration have been developed over the decades of radio interferometry. A mathematical formalism for radio interferometry telescopes, the measurement equation, was formulated by Johan Hamaker and his collaborators in 1996 (Hamaker et al., 1996), although the principles were known long before. Ever since then, important practical advances in

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[475] See hba.skao.int/SKASUP6-27—Post-2012 Evolution of SKA Correlator Architectures.

algorithm development at various institutions (e.g., (Rau et al., 2009)) have been made, many of which have been relevant for developing the SKA software.

Historically, telescope operators have intentionally throttled the dataflow from the correlators to the downstream computers (ingest rate) so that they can keep up with the calculations or data storage. This has not been a major problem in the observer community because many are interested only in narrow objectives in field-size or frequency channels. Also, observers frequently carry out data reduction using their own compute facilities, and don't wish to be burdened with too much data. Nevertheless, these practices are discarding discovery space (see also Sect. 6.2.2.8). Because of scientific interest in re-examining archival data, it is important not to discard any data in the future. This was recognised as important in the PrepSKA era but not given high priority at that time.

The SKA planned to carry out full-field imaging continuously, and even to support very wide-field imaging by stitching adjacent images together or by scanning across large areas of sky. Storing the raw interferometer data was recognised as being very difficult because of limited data-storage capabilities, forcing imaging and other data reduction to be carried out in quasi-real time. Hence the observing schedule, data buffers, and data-processing computers must be jointly managed so that computing can keep up with the pace of observations. More importantly, raw correlator data will be eventually discarded, and observers cannot go back, for example, to reapply some calibrations. This is a break from tradition for major array telescopes for which observers have access to original data.

Computing capability has improved in the intervening years, but at the time of writing, the SKA will still not be capable of storing the raw data.

Of the many design aspects to fill in after the formulation of the Reference Design in 2006 (Sect. 6.2.1.3), one was the software capabilities required. In an early SKA memo on dish diameter,[476] for example, Tim Cornwell argued that the computing costs of wide-field imaging scaled as $d^{-8}$, where d is the dish diameter[477] (see Sect. 6.4.3.1). Nevertheless, in 2005 he advocated taking the Large-Number—Small-Dish (LNSD) design to an extreme with 1.5–3-m diameter dishes.[478] But to achieve this, a separate beam-forming stage would have been required to narrow the beam to a manageable field-size. In the end, issues other than software were more influential in determining dish size (see Sect. 6.4.3.1), recognising that the SKA could 'grow into' more capable software with time, but dish size would be immutable. Similar discussions were held around the size of Aperture Array stations.

As noted in Sect. 6.2.1.3, one of the PrepSKA responsibilities taken on by the US Technology Development Program (TDP)[479] was to carry out investigations of and

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[476] hba.skao.int/SKAMEM-49 *SKA and EVLA computing costs for wide field imaging (Revised),* Cornwell, T. J., SKA Memo 49, June 2004.

[477] Note that the field-of-view is inversely proportional to the dish diameter.

[478] hba.skao.int/SKAMEM-61 *LNSD reconsidered—the Big Gulp option,* Cornwell, T. J., SKA Memo 61, July 2005.

[479] hba.skao.int/SKAHB-230 *The U.S. Technology Development Project for the SKA: Revised Work Plan,* Cordes, J. M., et al., Submission to the National Science Foundation for The U.S. SKA Consortium, 30 January 2007.

to act as a clearing house for areas of high risk associated with SKA-Mid: dish designs, and calibration and processing software. A Calibration and Software Group (CPG) was formed, chaired by Athol Kemball, and consisted of about 12 members brought together key persons interested in this aspect of the SKA.[480] They produced a series of documents which directly addressed some of the issues described above: high dynamic range imaging,[481] peta-scale computing,[482] implications for antenna and feed design for wide-field imaging,[483] and the computation implications of realistic antenna arrays.[484]

During the PrepSKA period and continuing afterwards, the Calibration and Imaging CALIM[485] meetings were important fora for specialists in imaging with radio interferometers to discuss approaches to solving problems for the SKA and other telescopes. Staging the meetings across the globe[486] increased the visibility and importance of these meetings. The CALIM meetings were widely attended and provided the spark for many advances in the development of algorithms for radio telescope imaging. Sponsors were ASTRON, NRAO, SARAO, CSIRO and UWA.

Three significant programs were started in the PrepSKA period to develop software tools to improve the efficacy of calibration:

- MeqTrees (Noordam & Smirnov, 2010), a simulation tool that implements the measurement equation. This tool is particularly useful in simulation and calibration of so-called direction-dependent effects, manifestations of the complex behaviour of real antenna beams rather than idealised ones. It has played a major role in improving the imaging dynamic range of radio telescopes.[487]
- OSKAR (Mort et al., 2010), a software simulator which was designed to simulate beamforming for aperture array telescopes, specifically SKA-low and at an earlier stage, dense aperture arrays (see Sect. 6.5.5). A version is still in use at the time of writing.[488]

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[480] hba.skao.int/SKAHB-385 TDP calibration and processing group (CPG): Activities and Status, Kemball, A., presentation at the US SKA Meeting at Madison, 18 December 2008.

[481] hba.skao.int/SKAHB-390 Current State of Practice In Wide-Field, Low-Frequency, High Dynamic Range Imaging with Contemporary Radio Interferometers, Chakraborty, N. and Kemball, A. TDP Calibration & Processing Group CPG Memo 5, 15 December 2009.

[482] hba.skao.int/SKAHB-384 Petascale Computing Challenges for the SKA, Kemball, A., TDP Calibration & Processing Group CPG Memo 1, 01 May 2008.

[483] hba.skao.int/SKAHB-388 Calibration and Processing Constraints on Antenna and Feed Designs for the SKA, Kemball, A., et al., TDP Calibration & Processing Group CPG Memo 4, August 2009.

[484] hba.skao.int/SKAHB-389 Computational Costs of Radio Imaging Algorithms Dealing With the Non-Coplanar Baselines Effect, Yashar, M. and Kemball, A., TDP Calibration & Processing Group CPG Memo 3, 06 November 2009.

[485] CALIM: Calibration and Imaging.

[486] CALIM meeting venues: Dwingeloo, 2005. Cape Town, 2006. Perth, 2008. Sororro, 2009. Dwingeloo, 2010. Manchester, 2011. Cape Town, 2012. Kiama, 2014. Socorro, 2016.

[487] hba.skao.int/SKAHB-386 MeqTrees at 1,000,000:1 and Other Tales, Smirnov, O., presentation at the CALIM Meeting in Socorro, 31 March 2009.

[488] hba.skao.int/SKAHB-421 SKA-Low System Simulations with OSKAR, Dulwich, F., presentation at the AAVS2.0 meeting, Perth, 23 June 2022.

- CyberSKA.[489] This was a distributed computing infrastructure funded by Canada's National Research and Education Network (NREN) as a precursor to an SKA Regional Centre (SRC) in Canada. It was used to aggregate and process large datasets to which Canadian astronomers already had access. In subsequent years, the SRC concept has expanded to a global network of regional computer centres, through which observers will access and sometimes process SKA data products. CyberSKA was a very early experiment, especially since SRCs in the PrepSKA period were not much more than notional.

#### 6.6.5.1 Computer Engineering

Computer engineering is the implementation side of radio astronomy imaging. As noted above, the problem requires super-computing scale and unique software. Comments in 2003 by Marco de Vos, representing Software Engineering in the IEMT in a report to the ISSC,[490] bluntly outlined the challenges.

These challenges were the impetus for the Convergent Radio Astronomy Demonstrator CONRAD collaboration[491,492] between the ASKAP and MeerKAT groups in Australia and South Africa, respectively.[493]

Technically, the computer processing algorithms needed for the SKA are highly 'parallelisable'. This means that the computer architecture can provide the means to direct data to processors that independently carry out a slice of the processing. While it is beyond the scope of this book to explain this in detail, this fact greatly improves the prospects for computational feasibility for the SKA.

Software development was recognised as one of the greatest challenges in the period up to 2012 and remains so at the time of writing. Estimates in 2004 were that 1000–2000 person years of effort would be needed.[494] An heuristic scaling analysis concluded that the scientific and operational requirements must be scaled back, and at least 20% of the budget should be allocated to software development.[495] This

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[489] hba.skao.int/SKAHB-416 Case Study: CyberSKA—A Cyberinfrastructure Platform for Data-Intensive Radio Astronomy, Kiddle, C., SKA document WP2-050.020.010-SR-003, 27 January 2012.

[490] hba.skao.int/SKAMEM-41 *Report to the International SKA Steering Committee by The International Engineering and Management Team (IEMT),* Hall, P. J., SKA Memo 41, 03 October 2003.

[491] hba.skao.int/SKAHB-236 *CONRAD Architecture,* Cornwell, T. J., et al., CONRAD-SW-0011, CSIRO and Karoo Array Telescope Joint document, 02 June 2007.

[492] hba.skao.int/SKAHB-241 *CONRAD Status,* Cornwell, T. and Horrell, J., presentation at the Manchester SKA2007 meeting, 27 September 2007.

[493] See hba.skao.int/SKASUP6-15—Computing Challenges: CSIRO collaboration with South Africa.

[494] hba.skao.int/SKAMEM-50 Software development for the Square Kilometre Array, Cornwell, T. and Glendenning, B.E., SKA Memo 50, June 2004.

[495] hba.skao.int/SKAMEM-51 A simple model of software costs for the Square Kilometre Array, Kemball, A. J. and Cornwell, T., SKA Memo 51, June 2004.

document pointed out that the level of software effort scales with size of the project raised to a power greater than one (i.e., the so-called diseconomy of scale).

The computing cost scaling was re-estimated in 2005, where the scaling was closely related to the size of the field-of-view.[496] Again, a recommendation to limit the size of wide-field images resulted. By 2010, it appeared that peta-scale computers would not be sufficient for the SKA, that exa-scale computers would be needed, and that scaling of existing algorithms and code would not work.[497] These issues remain as the SKA is under construction, but there is a much better understanding of how to tackle them. One advantage of software and computing development is that the telescope can begin observations long before the 'ultimate' software package is available.

The Software and Computing (S&C) Concept Design Review (CoDR) was organised in February 2012,[498] by Duncan Hall, the S&C domain specialist. It was the last of the sub-system CoDRs and covered software for monitor and control, time-domain processing (see Sect. 6.6.3) and imaging (visibility processing). An analysis of the science requirements[499,500]and of the visibility processing[501] revealed that the SKA's ambitious science goals would indeed push software and computing to the limits of (then current) technology, especially because of the quasi-real time processing requirement described above. The software engineering analysis[502] outlined the new challenges presented by the SKA: novel scale, very large data flow and processing, management across the globe, small number of experienced people, novel front ends (if adopted, e.g., PAFs, dense AAs, WBSPFs) and substantial algorithm development.

The S&C panel report[503] noted a maturity lag in the S&C development compared with other parts of the SKA design and compared, for example, with the Large Synoptic Survey Telescope (now the Rubin Observatory) at a similar stage. The answers to all the standard CoDR questions were sceptical. They recommended

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[496] hba.skao.int/SKAMEM-64 SKA Computing Costs for a Generic Telescope Model, Cornwell, T., SKA Memo 64, September 2005.

[497] hba.skao.int/SKAMEM-128 SKA Exascale Software Challenges, Cornwell, T. and Humphreys, B., SKA Memo 128, October 2010.

[498] hba.skao.int/SKAHB-412 Software and Computing CODR - Context of the CODR, Hall, D., SKA document WP2-050.020.010-PLA-002, 27 January 2012.

[499] hba.skao.int/SKAHB-175 *The Square Kilometre Array Design Reference Mission (DRM): SKA-Mid and SKA-lo,* Lazio, J., et al., SKA Document V1.0, 02 February 2010.

[500] hba.skao.int/SKAHB-413 Software and Computing CODR - Analysis of Requirements Derived from the DRM, Alexander, P., SKA document WP2-050.020.010-RR-001, 27 January 2012.

[501] hba.skao.int/SKAHB-414 Software and Computing CODR - Visibility Processing, Cornwell, T. J., SKA document WP2-050.020.010-SR-001, 27 January 2012.

[502] hba.skao.int/SKAHB-415 Software and Computing CODR - Software Engineering and Development, Cornwell, T. J., SKA document WP2-050.020.010-MP-001, 27 January 2012.

[503] hba.skao.int/SKAHB-418 Software and Computing CODR—Report of the Review Panel, Glendenning, B., et al., SKA review document, 06 March 2012.

strong centralised management and recruitment of a full complement of software staff to offset the risk.

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# Chapter 7
# Site Selection Story, 2002–2006: Shortlist

## 7.1 Introduction

Site selection is often one of the most contentious decisions a project will face as hosting a large international scientific facility is a major prize for any country. It has the potential for severe disruption of the project, and often requires considerable negotiation and compromise to reach an acceptable solution. Decisions need to be driven primarily by considerations of where the best science can be done but political aspects and the obligations involved almost always come into play. In SKA's case, the site selection process was meticulously prepared with the participation of all contenders but, even so, in the final stages, a compromise was required taking political demands into account to ensure the project survived.

SKA site selection went through five distinct stages: (1) separate national initiatives in China and Australia to identify potential sites (1994–2002), (2) centrally coordinated activity to identify and characterise these and other potential sites (2000–2005), (3) the short-listing process and decision (2004–2006), (4) further characterisation of the two short-listed sites, and politicisation of the site competition (2007–2011), and (5) the final site selection process and decision (2009–2012).

Key characteristics of an acceptable site from the science perspective at the start of the formal process in 2002 were: a wide sky coverage and substantial overlap with other major astronomical facilities, radio quietness in view of the high sensitivity of the SKA, ability to site remote stations at distances up to 3000 km from the core of the array to provide the wide range of angular resolution required by the science case, and ionospheric and tropospheric stability to optimise image quality at low and high frequencies respectively.

This chapter describes and analyses the first three stages of site selection from the early national initiatives to the creation of a shortlist of two potential hosts, Australia and Southern Africa.

R. T. Schilizzi et al., *The Square Kilometre Array*, Historical & Cultural Astronomy,
https://doi.org/10.1007/978-3-031-51374-9_7

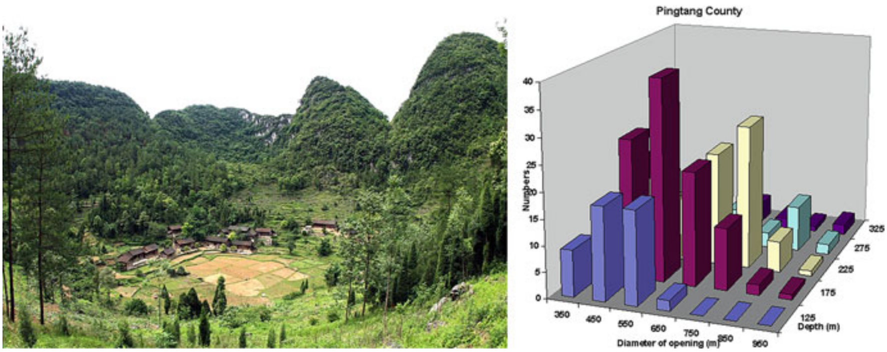

**Fig. 7.1** Left: The Dawodang karst depression in Guizhou Province before construction of the FAST telescope began. (Credit: National Astronomical Observatories of China). Right: Results of site surveying in Guizhou Province, China. Vertical axis is number of depressions vs diameter and depth in metres. (Credit: National Astronomical Observatories of China)

## 7.2 Early (National) Site Investigations

### *7.2.1 China (1994–2002)*

Initial studies in early 1994 of possible sites for a large radio telescope in China focussed on mid-latitude locations with large areas of relatively flat land that were isolated but accessible.[1] However, the best of these possible locations, in Sichuan Province, was not regarded as competitive with other countries and attention began to turn to the unique karst depression region of Guizhou province where multiple Arecibo-like spherical reflectors could be accommodated (see Fig. 7.1 left) in an array called KARST (Kilometre-square Area Radio Synthesis Telescope)). The first SKA Radio Frequency Interference (RFI) measurements in the world were made at eight potential sites in Puding and Pingtang counties in Guizhou by Bo Peng, Yaoping Nie (all from the National Astronomical Observatories of China) and Richard Strom (ASTRON, The Netherlands) in late 1994 (Peng et al., 1995), and resulted in a decision in mid-1995 to focus on this area as a potential site for the SKA in China.

In late-2002, following several years of project development and engineering effort on the telescope design for a KARST prototype called FAST (Five hundred metre Aperture Spherical radio Telescope), a site survey group in the Guizhou University of Technology extended the search to cover the entire province of Guizhou. Some 90 candidate depressions were located, each of 500 m or more in

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[1] hba.skao.int/SKAHB-426 *Advantage and disadvantage of mid-latitude geography in China for NGRT*, Nan, R, Cai, Z, Tian, W., paper presented at the first meeting of the Large Telescope WG, March 1994.

diameter, even up to about 1000 m in a small number of cases (see Fig. 7.1 right). Eventually, in 2005, the Dawodang depression was selected for FAST[2] in the final stages of the SKA site short-listing process (see Sect. 7.3.7.1).

### *7.2.2 Australia (1996–2002)*

As we have seen in Sect. 3.2.6.3, a proposal for Australian participation in the SKA was included in the decadal plan by the National Committee for Astronomy (an Australian Academy of Science sub-committee) in 1995. It was felt that Australia could provide design expertise and a 'superior site free from interference if sited in the western areas of the continent'. This was taken up by the State Government in Western Australia in 1997, following an interview given by ATNF Director, Ron Ekers, to the local press the previous year. Government support was offered in a letter from the State Premier to Ekers in February 1998.[3]

Bruce Thomas, an engineer in the CSIRO Radiophysics Division, spear-headed investigations on the suitability of potential sites for the central area of the SKA[4] (see Fig. 7.2). The main factors affecting the choice were the provision of protection against radio interference, minimising the impact on land users including the indigenous communities, pastoralists, and the mining industry, and how easy would it be for SKA operations staff to travel to the central site and to be accommodated there.

The first area of interest was near Carnarvon (830 km north of Perth), with a focus on properties which were no longer economic to operate as pastoral enterprises. In these cases, the State determined it could purchase the leases for conservation purposes. More interesting opportunities came up further south in the Murchison area north-east of Geraldton, and in 1999–2000 detailed studies[5] (see Fig. 7.3) were made by Thomas and colleagues of the possible impact of radio communication links and other services in the area. The Mileura Station (~100 km west of Meekatharra) was the main location[6] and a testing program was carried out in

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[2] hba.skao.int/SKAHB-427 *Summary of the origin of the FAST project,* B. Peng, 2016.

[3] hba.skao.int/SKAHB-428 Letter from Richard Court, Premier of Western Australia, to Ekers,17 February, 1998.

[4] hba.skao.int/SKAHB-429 *Background to the search for appropriate sites for a radio-quiet reserve including the SKA radio telescope, 1996–2002*, Thomas, B. M**.,** 2002, CSIRO Australia Telescope National Facility internal report (AT 43.16.1/026).

[5] hba.skao.int/SKAHB-430 *Radio-quietness measurements at Mileura Station, 100 km West of Meekatharra, Western Australia, 27 March to 17 April 2001. Report Number 4: A Summary Report covering the Frequency range 30–1800 MHz*, B. M. Thomas, 2001.

[6] hba.skao.int/SKAHB-429 *Background to the search for appropriate sites for a radio-quiet reserve including the SKA radio telescope, 1996–2002*, Thomas, B. M., 2002, CSIRO Australia Telescope National Facility internal report (AT 43.16.1/026).

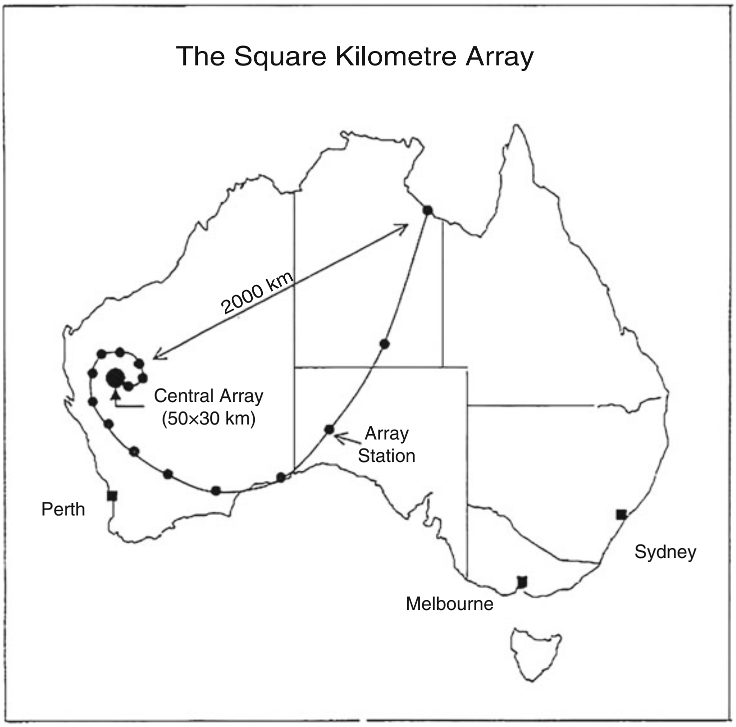

**Fig. 7.2** Map of Australia showing the central array at Mileura in Western Australia with remote stations out to 2000 km (Credit: Bruce Thomas, CSIRO Radio Astronomy Image Archive CRAIA-SKA005)

**Fig. 7.3** left and right: Two of the antennas used to monitor RFI in the Murchison area of Western Australia in 2001 (Credit: Bruce Thomas, CSIRO Radio Astronomy Image Archive CRAIA-SKA003 (left) and CRAIA-SKA004 (right))

March–April 2001 once the sheep muster[7] was over! The results showed that the levels of radio communication activity were extremely low. Subsequently, two adjacent areas in the Murchison (one including the Mileura Station) were gazetted under the WA Mining Act for exemption from mineral exploration. More elaborate studies continued in Western Australia to monitor RFI in 2002 and 2003.

Other Australian states were also interested in exploring opportunities to be involved and, by late 2001, South Australia, NSW and Queensland had also expressed interest in hosting the SKA. The Federal Government became involved in discussions that eventually led to WA being given priority in 2004.

By mid-2000, efforts were already underway to define a legal framework for RFI protection for the SKA if it were to be sited in Australia, and a workshop on interference mitigation was held in Sydney in December that year. This was motivated by the US Government's legal protection for the National Radio Astronomy Observatory's site at Green Bank, West Virginia which provided a precedent for Australian legislators. The interference environment became a major selection criterion for the SKA site as the process developed and, as we will see later in this chapter and the next, RFI measurement campaigns were carried out for both major stages of the selection.

## 7.3 Site Short-Listing

### *7.3.1 Identification of Potential SKA Sites (2000–2004)*

The International SKA Steering Committee (ISSC) began to take central control of the site selection process in 2000. The clear understanding was that the site choice would be made by the scientists involved based on where the science goals could be best accomplished. A recent example in people's minds was ALMA where the high-altitude Atacama Desert in northern Chile was the unanimous choice and was made by the scientific community.

At an ISSC meeting in Aug 2000, following a recommendation from the Five-year Management Plan and Technical Oversight Working Group chaired by Bob Preston, (Jet Propulsion Laboratory, USA) the ISSC decided to bring the site selection activities together under a common umbrella and formed the Site Evaluation and Selection Committee (SESC) chaired by Bruce Thomas (see Box 7.1). The same meeting decided to call for Expressions of Interest (EoI) to host the SKA, initially via the OECD Task Force on Radio Astronomy (see Sect. 3.2.5.2), but this was not pursued. Instead, direct invitations to URSI Commission J (Radio

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[7] A "muster" is the name given in Australia and New Zealand to the process of gathering livestock in one place. This can be for the purpose of routine livestock health checks, sale, feeding and transport etc. (Wikipedia).

Astronomy) national representatives from around the world were issued by the ISSC Executive Secretary, Russ Taylor, (University of Calgary, Canada) in late-2001.

The Call for EoIs had the desired effect, prompting the US to start examining the possibility of siting the SKA in the Southwestern United States in relation to the Expanded VLA project,[8] while in South Africa a proposal was submitted to the National Research Foundation in mid-2002 for SKA funding including €200 thousand for a site survey.[9] In the end, institutes in seven countries—Argentina, Australia, Brazil, China, Ireland, South Africa, and USA—responded to the Call. Ireland withdrew their response after discussion with European consortium leaders since Europe's position was that the SKA would be best sited in the southern hemisphere.[10]

**Box 7.1 Site Evaluation and Selection Committee (SESC)**

Bruce Thomas (CSIRO Australia) was the first chair. Other members of the initial SESC were Subramaniam Ananthakrishnan (TiFR, India), Willem Baan (ASTRON, Netherlands), Justin Jonas (Rhodes University, South Africa) and Shengyin Wu (NAOC, China). On Thomas' retirement in 2002, Yervant Terzian (Cornell University, USA) took over as SESC chair and Wim Brouw (CSIRO) replaced Thomas as Australian representative. In 2004, the management structure of the SKA evolved to reflect the growing coordination role of the International SKA Project Office (ISPO) and, as part of this change, the SESC became part of the ISPO with a new name—the Site Evaluation Working Group. Terzian remained as an enthusiastic and effective chair until 2008 when, as part of the PrepSKA re-organisation, the SESC was replaced by the Site Characterisation WG chaired by Rob Millenaar (ASTRON, The Netherlands) as Site Engineer in the SKA Program Development Office.

One of the high priority tasks for the SESC was to generate site selection guidelines to accompany the letters of invitation in 2002. Other tasks were to standardise RFI measurement sets and define the requirements for Radio Quiet Zones in which to site the SKA.

In November 2002, the ISSC invited 20-page initial site analyses from the six remaining candidate countries with the intent of narrowing down the field. Specific topics to be addressed by the candidate countries are shown in Box 7.2. In its preparatory discussion, the ISSC approved a suggestion from Justin Jonas (South Africa) that it would level the playing field for emerging radio astronomy countries if interim site "white papers" could be submitted for non-prejudicial assessment and feedback from the ISSC. Although the South Africans never availed

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[8] hba.skao.int/SKAHB-431 *Minutes of the 7th ISSC meeting*, January 2002.

[9] hba.skao.int/SKAHB-432 *Minutes of the 8th ISSC meeting*, August 2002.

[10] hba.skao.int/SKAHB-432 *Minutes of the 8th ISSC meeting*, August 2002.

themselves of this opportunity, the results of the site short-listing 4 years later proved they were fast learners!

**Box 7.2 Initial Site Analyses: Issues to be Addressed**

- general location and impact on science including sky observation range
- general attributes of the proposed Central Site, including the surrounding area out to a distance of about 300 km for access to services and radio-quietness and compatible land use;
- specific site attributes of importance for engineering design issues, impact on the operation and construction of the SKA facility, and service provision;
- radio-quietness determination and frequency band-occupancy measurements;
- willingness to host the SKA including an in-principle agreement with national and local authorities relating to legislation and/or regulation for protection of radio-quietness and land-use, as well as an indication of interest in providing the Central Site as an internationally-recognised Radio-quiet Reserve for compatible scientific facilities and research (in addition to the SKA), and for supporting its acceptance (prior to proclamation) at both national and international forums.

By the deadline of May 2003, the ISSC had received proposals from Australia, China, South Africa and the U.S.[11] The proposal from Australia noted three possible central sites and the array distributed throughout Australia. South Africa also suggested three possible central locations and with long baseline stations located in several countries to the North. China proposed two possible sites, one in the karst depressions region in Guizhou for Arecibo-type antennas, and the other, a region in Western China for an array of fully steerable smaller diameter dishes. The U.-S. proposed a location near the VLA site in New Mexico with array stations across the U.S., Canada and Mexico.

Argentina, Brazil, and Europe did not submit proposals—lack of resources was the problem in Argentina and Brazil, and Europe's opinion was that the site should be in the southern hemisphere. However, they reserved the right to submit a northern hemisphere proposal if no suitable site were to be found south of the equator. The ISSC extended the deadline for Argentina and Brazil to the end of March 2004 and separate proposals were submitted by the new date. Argentina identified three possible locations for the core including a high site at 2550 m and the distant array stations in Brazil. Brazil itself also proposed three possible locations for the core of the SKA, all in the eastern part of Brazil, a few hundred kilometres from Brasilia.

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[11] hba.skao.int/SKAHB-89 *Minutes of the 10th ISSC meeting*, August 2003.

Evaluation of the telescope site locations by the SESC was based on three global criteria[12]: (1) the ability to do the optimal science with the instrument, (2) the construction cost at the proposed site, and (3) the operational costs for the telescope at the proposed site. In July 2004, they duly recommended that the four original preliminary proposals from Australia, China, South Africa and the USA be accepted for a full site proposal. The Brazilian proposal was not accepted since its central sites were too close to the magnetic equator and at too low an altitude (900 m). Proximity to the magnetic equator carried the risk that observations would be subject to severe ionospheric disruption at the lower frequencies while low altitude, wet conditions carried the risk that tropospheric phase irregularities would cause problems at high frequencies. The SESC recommended that Argentina and Brazil cooperate in one new proposal, and this is what transpired. Five potential sites were in the competition.

## *7.3.2 Initial Characterisation of Potential Sites: Radio Frequency Interference (RFI) Monitoring, Radio Quiet Zones, 2002–2005*

### 7.3.2.1 RFI Monitoring

In 2002, the ISSC approved the establishment of a working group on RFI measurements[13] with Steve Ellingson (Ohio State University, USA) as chair. A report on RFI measurement was produced within a year,[14] and based on this report, the SESC recommended that RFI tests of all sites should be done with the same equipment and the same team. Standardisation of calibration and measurement was critical for a good quality comparison of the RFI situation at the sites, both in a relative and in an absolute sense.

In 2004,[15] the ISSC decided that ASTRON would supply the RFI monitoring equipment and the measurement procedure.[16] Four-week periods of testing were planned at the nominated candidate central sites by an ASTRON team under an MoU with the ISPO. Although providing the set of uniform measurements recommended by the SESC, the 4-week visits to each site by the ASTRON team were recognised as insufficient for full knowledge of the RFI environment and its variability, so each potential site was required to carry out a program of RFI monitoring using the same

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[12] hba.skao.int/SKAHB-433 *Minutes of the 12th ISSC meeting*, July 2004.

[13] hba.skao.int/SKAHB-432 *Minutes of the 8th ISSC Meeting*, August 2002.

[14] hba.skao.int/SKAHB-89 *Minutes of the 10th ISSC meeting,* August 2003.

[15] hba.skao.int/SKAHB-433 *Minutes of the 12th ISSC meeting*, July 2004.

[16] hba.skao.int/SKAMEM-37 RFI Measurement Protocol for Candidate SKA Sites, SKA Memo 37, WG on RFI Measurements, May 2003.

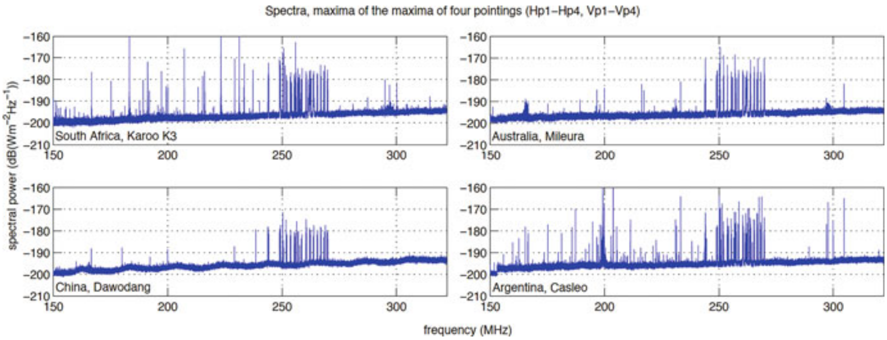

**Fig. 7.4** Samples of RFI measurements carried out at the four candidate sites by ASTRON on behalf of the International SKA Project Office in 2005. The cluster of frequency responses around 260 MHz is from the UFO (Ultra high frequency Follow On) geostationary satellites used by the US Navy. The other responses in the spectrum are mainly due to distant TV transmitters and other communications systems, see the plots for South Africa and Argentina (hba.skao.int/SKAHB-434 SKA Site Spectrum Monitoring (SSSM) Miscellaneous Notes—Sites: South Africa, China, Australia, Argentina-Measurement period: 2005/2006, A. J. Boonstra and R. P. Millenaar, ASTRON Report to ISPO, 19 March 2006. This figure is a re-worked version by Rob Millenaar of figure 4 in Boonstra and Millenaar, 2006. Information on the sources of interference in this figure from Rob Millenaar, email to R. Schilizzi, 12 May 2022) (Credit: A. J. Boonstra and R. P. Millenaar, ASTRON)

measurement protocol for 12 months. This was to include overlap with the centrally coordinated measurements, for cross-calibration purposes.

The ISPO (Peter Hall, International SKA Project Engineer) coordinated the international campaign with logistical assistance from a committee comprising members from each site. Measurements by ASTRON engineer, Rob Millenaar, took place at four of the five sites in 2005 over a range of frequencies from 70 MHz to 26.5 GHz. By this time, the US had withdrawn from the competition (see Sect. 7.3.5.1). The required local monitoring campaigns were also carried out in all four countries/regions for about 1 year (see Figs. 7.4 and 7.5).

#### 7.3.2.2 Radio Quiet Zones

Building on experience with the designated Radio Quiet Zones (RQZ) surrounding the NRAO Green Bank site, it was a requirement from the early days of the SKA that the core should be located in such a designated zone. In 2004, the OECD Global Science Forum Task Force on Radio Astronomy and the Radio Spectrum noted that, for optimum performance, the SKA should have local protection for all frequencies and global protection for specific bands allocated to radio astronomy.[17] A Resolution was passed at the URSI General Assembly in 2002 calling for an investigation of the

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[17] hba.skao.int/SKAHB-33 *Minutes of the 13th ISSC meeting*, March 2005.

**Fig. 7.5** Left: Rob Millenaar (foreground) and Bou Schipper (background, seated), ASTRON engineers in charge of the RFI measurement campaign together with Chinese colleagues, on site in July 2005. (Credit: NAOC). Right: The ASTRON RFI monitoring equipment in the foreground on site in China in 2005 (credit: R.P. Millenaar, ASTRON)

desirability of, and issues involved in, establishing International Radio Quiet Reserves for future radio astronomy. The OECD Task Force also recommended the establishment of a small number of "…zones on the ground where future radio observatories could be located and within which satellite emissions could be controlled.".[18] A proposal to establish such internationally protected zones was not approved by the ITU.

Since the establishment of RQZs required governments to pass appropriate laws or regulations, it was essential for the national communities to raise the priority of the SKA project among senior government figures. Discussions on RQZs began in earnest in Australia in 2004, when Ron Ekers made a presentation on the case for Australia to host the SKA to the Prime Minister's Science Engineering and Innovation Council.[19],[20] The Prime Minister supported this concept in principle and it was then given high priority in discussions by Government officials. In South Africa, Justin Jonas, Bernie Fanaroff (SKA South Africa) and colleagues raised the possibility with government officials in 2003 but in connection with a radio quiet area in the country that could be used for SKA technology testing.[21] Chinese discussions began somewhat later, in 2006, following approval of the FAST project by the Chinese Academy of Sciences.[22] In Argentina, the proposed location for the central site for the SKA was in a National Park in the Andes in San Juan Province which had the status of a Protected Astronomical Reserve. There, the Complejo Astronomico El

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[18] hba.skao.int/SKAHB-435 *Report of the OECD Global Science Forum Task Force on Radio Astronomy and the Radio Spectrum*, January 2004.

[19] hba.skao.int/SKAHB-433 *Minutes of the 12th ISSC meeting*, July 2004.

[20] hba.skao.int/SKAHB-33 Minutes of the 13th ISSC meeting, March 2005.

[21] hba.skao.int/SKAHB-31 Minutes of the 9th ISSC meeting, January 2003.

[22] hba.skao.int/SKAHB-47 *Minutes of the 15th ISSC meeting,* March 2006.

Leoncito (CASLEO) operated two optical telescopes and one solar radio telescope. A provincial law from 1987 protected the site from electro-magnetic interference, lights etc. within an area 15 km across. An extension to the law specifically for the SKA was under consideration in late-2005 at the time of the site proposal submission that would include a Coordination Zone for all transmitters operating between 100 MHz and 25 GHz located in the same area.

### *7.3.3 Timeline to Site Selection*

Bob Preston, as Chair of the Five-year Management Plan and Technical Oversight Working Group, led an ISSC discussion in January 2003[23] in which site selection by the ISSC in late-2005 and Facility Definition (technology, governance) in late-2007 was proposed. This led to questions about whether a simultaneous choice of site and technology might not be a better strategy (see Sect. 7.3.7), but the goal of site selection in late-2005 remained.

### *7.3.4 Request for Full Proposals, 2004–5*

A formal Request for Proposals (RfP)) for siting the SKA[24] was issued in September 2004 by the ISSC to the five countries that had submitted acceptable Site Analyses in the earlier round, with a deadline of the end of 2005, and decision on the SKA site in August 2006. It set out the defining characteristics of the SKA for both the LNSD and SNLD concepts, and the criteria by which the site proposals were to be evaluated (see Box 7.3). Each potential site was also required to carry out a 12-month program of RFI monitoring in addition to the month-long international measurement campaign at each individual site (see Sect. 7.3.2.1) and include the results in their response to the RfP. The clear aim of the ISSC was to select one site for the SKA Telescope by September 2006.

The RfP also set out the evaluation process. Proposals would be reviewed by the ISSC separately and an independent, external International SKA Site Advisory Committee (ISSAC), who would report their findings to the ISSC. Expert analysis of the data provided by the proposers would be made by the Site Evaluation Working Group (SEWG) and the Simulations Working Group (SimWG). The ISPO served as the clearing house for all queries from individual site proponents and distributed answers to all candidate sites to maintain an open and transparent process.

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[23] hba.skao.int/SKAHB-31 *Minutes of the 9th ISSC meeting*, January 2003.

[24] hba.skao.int/SKAHB-436 *Request for Proposals for Siting the SKA*, Supporting Paper for the 13th ISSC meeting, March 2005.

The final stage was expected to be a discussion between the ISSC and highly ranked proposers in order to come to the final decision. The ISSC declared itself as the final authority in all aspects of the decision process but, as we will see, the funding agencies intervened in mid-2005 and early 2006 to exert their influence and change the desired outcome to a short list rather than outright selection of a single site.

**Box 7.3 Defining Characteristics of the SKA in the Request for Proposals to Site the SKA**

- Large Number-Small Diameter (LNSD) concept: 1 km core diameter + 40 stations within 5 km diameter + 60 remote stations out to 3000 km
- Small Number-Large Diameter (SNLD) concept: 1 km core diameter + 20 stations within 5 km diameter + 30 remote stations out to 3000 km
- Central 5 km configuration supplied to proposers
- Maximum baseline >3000 km
- Visible sky—above 30° for all stations for >4 h/day
- Data transport from remote stations at 100 Gbit/s (minimum), 1 Tbit/s (final)
- Link from Facility Support Centre to national and international SKA data centres at 100 Gbit/s (minimum)
- Power
  - Central site 12 MW (peak)
  - Facility Support Centre 2 MW (peak)
  - Remote Station 150 kW (peak)

The global criteria for the evaluation of the proposed telescope sites were set out in the RfP[25] as follows:

1. the ability of the SKA to maximise the science return of the instrument if located at the proposed site;
2. the construction cost to project at the proposed SKA site
3. the operational cost to project for the proposed SKA Facility; and
4. physical and political issues

The specific criteria within each category (see Box 7.4) were discussed in detail in the RfP, but no weights were assigned at this point. (These were generated in the run-up to the selection in July 2006.)

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[25] hba.skao.int/SKAHB-436 *Request for Proposals for Siting the SKA*, Supporting Paper for the 13th ISSC meeting, March 2005.

**Box 7.4 Specific Evaluation Criteria for Potential SKA Sites**

**The quality of science:**

(a) Short- and long-term radio-frequency interference and protection issues.
(b) Array configuration and performance.
(c) Ionospheric and tropospheric conditions.

**Infrastructure, climatic and costing issues:**

(a) Climatic issues.
(b) Physical site-characteristics for Stations.
(c) Impact of land-use and urban centres.
(d) Existing infrastructure.
(e) Data interconnects.
(f) Costs—capital and operating.

**National attributes for siting the SKA:**

(a) General issues.
(b) Government and departmental interaction with SKA community.
(c) Support for astronomy and the SKA Facility by national and regional governments.

It is safe to say that the "quality of the science" criterion had the highest weight in the minds of ISSC members. Three particular issues were matters of debate in the lead-up to the Request for Proposals:

1. the relative advantages and disadvantages of the two main array types in contention—Large Number-Small Diameter (LNSD) and Small Number-Large Diameter (SNLD) (see Chap. 6 on SKA Design). Proposers were instructed to generate one overall layout of the array consisting of the central 5 km diameter area and remote stations on spiral arms and two specific configurations within the overall layout to allow for the LNSD and SNLD concepts. This became an issue for the Chinese site bid near the end of the proposal submission period (see later in this section).
2. The RFI environment (see Sect. 7.3.2), and
3. The tropospheric environment.[26] [27] In-situ interferometric measurements of tropospheric phase fluctuations were not feasible on the short timescale to the site decision. As a proxy, the ISSC decided that archival meteorological data including satellite data should be assembled by the site proponents to characterise the water vapour content throughout the year. In addition, the Simulations WG was to study the capabilities of self-calibration as a means of removing the effects of

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[26] hba.skao.int/SKAHB-437 *Minutes of the 11th ISSC meeting*, January 2004.

[27] hba.skao.int/SKAHB-433 *Minutes of the 12th ISSC meeting*, July 2004.

differential phase fluctuations, as well as the influence of possible variations on imaging dynamic range.

## *7.3.5 Responses to the Request for Proposals*

### 7.3.5.1 USA

In early-2005, the chair of the US SKA Consortium, Yervant Terzian, informed the ISSC that the US would not be able to respond to the SKA siting RfP by the end of the year.[28] Behind that bland statement, it was clear that there were significant differences of opinion about the desirability of the NRAO taking charge of the site bid process with a core centred on the VLA in New Mexico (see Sect. 3.3.3.8). However, the Consortium noted that the US could provide an outstanding site for high frequencies and it may be possible to take advantage of that later, were the SKA to divide between low- and high- frequency arrays. A decade later, preparation began on proposals for the "new generation VLA" that has been inspired by early ideas for SKA-high.

### 7.3.5.2 Argentina-Brazil

The proposal[29] was submitted by the Argentine and Brazilian SKA Committees led by Marcelo Arnal (Argentina) and Jacques Lepine (Brazil). A radio-quiet high altitude valley located near the Andes Ridge in the Argentinean Province of San Juan was proposed for the central five kilometres of the SKA layout (Fig. 7.6) with remote stations stretching across the north-eastern territories of Argentina and into south Brazil (see Fig. 7.7). As mentioned in Sect. 7.3.2.2, the intended SKA core location was within a National Park that already had been designated a Protected Astronomical Reserve and hosted two optical telescopes and one solar radio telescope.

Key factors in support of the proposal were:

- legislation was already in force in the Astronomical Protected Reserve to prevent the installation of transmitters detrimental to radio astronomy;
- negligible water vapour content at the altitude of the Central Site (2300 m);
- relatively low land acquisition costs; a major astronomical facility only 12 km away from the selected Central Site able to provide support and initial infrastructure such as roads, communications, and accommodation;

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[28] hba.skao.int/SKAHB-33 *Minutes of the 13th ISSC meeting*, March 2005.

[29] hba.skao.int/SKAHB-438 *A proposal for siting the SKA in the Territories of Argentina and Brazil*, 2005.

**Fig. 7.6** The proposed central site for the SKA in San Juan Province in Argentina (Credit: R.P. Millenaar, ASTRON, 2005; see also Millenaar, R., 2016)

- proximity to some of the front-line twenty-first Century astronomical facilities located in South America (primarily in Chile just across the border with Argentina) allowing large common sky coverage and simultaneous observations with these facilities; and
- strong support from governmental authorities and from scientific federal agencies and major national academic institutions.

A major attraction of the bid (to potential members of the SKA HQ staff reading the proposal) was the promise of "pleasant weather, superb regional wines, excellent natural food and world class ski centres within driving distances, add an extra value assuring the quality of daily life for all SKA headquarters personnel"!

The proposal noted that the relatively close location of the Central Site to the magnetic equator and the possibility of unstable ionospheric conditions caused by energetic electrons that could affect the quality of low frequency observations. A subsequent detailed study provided by the Argentina-Brazil Consortium showed that this was a "disabling" characteristic for the proposed location (see discussion in Sect. 7.3.8.1).

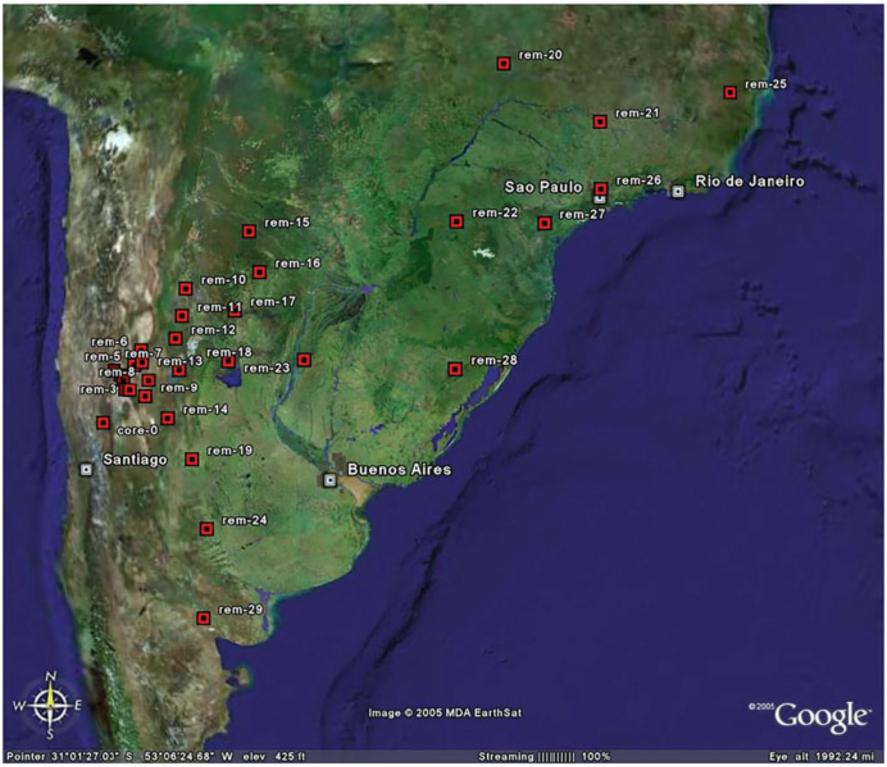

**Fig. 7.7** Proposed array layout for Argentina-Brazil (hba.skao.int/SKAHB-438 *A proposal for siting the SKA in the Territories of Argentina and Brazil*, 2005) (Credit: the Argentina-Brazil SKA Committee)

### 7.3.5.3 Australia and New Zealand

The proposal[30] was submitted by Brian Boyle, Australian SKA Director, on behalf of the Australasian SKA Consortium. It envisaged the core site for the SKA located at Mileura Station (see Fig. 7.8) in the State of Western Australia, almost 700 km from Perth and remote SKA array-station sites spanning the continent of Australia (see Fig. 7.9). In addition, SKA array-stations could be located in New Zealand at Warkworth and Ardmore in the North Island near Auckland and Rangiora and Awarua in the South Island to extend the maximum continental east-west baseline of 3200 km to over 5500 km to provide even higher angular resolution observations.

Key factors noted by the Australasian Consortium in support of their proposal were Australia's radio-quietness across the whole extent of the SKA, state and federal Government commitments to preserve this environment in the long term,

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[30] hba.skao.int/SKAHB-439 *Proposal for Siting the SKA in Australia*, 2005.

**Fig. 7.8** The proposed central site for the SKA core near Mileura Station in Western Australia (Credit: R.P. Millenaar, ASTRON, 2005; see also Millenaar, R., 2016). The location of the central site was changed to Boolardy Station on Wajarri Yamaji Country, approximately 80 km west of Mileura, in 2008 to avoid potential interference from mining activities

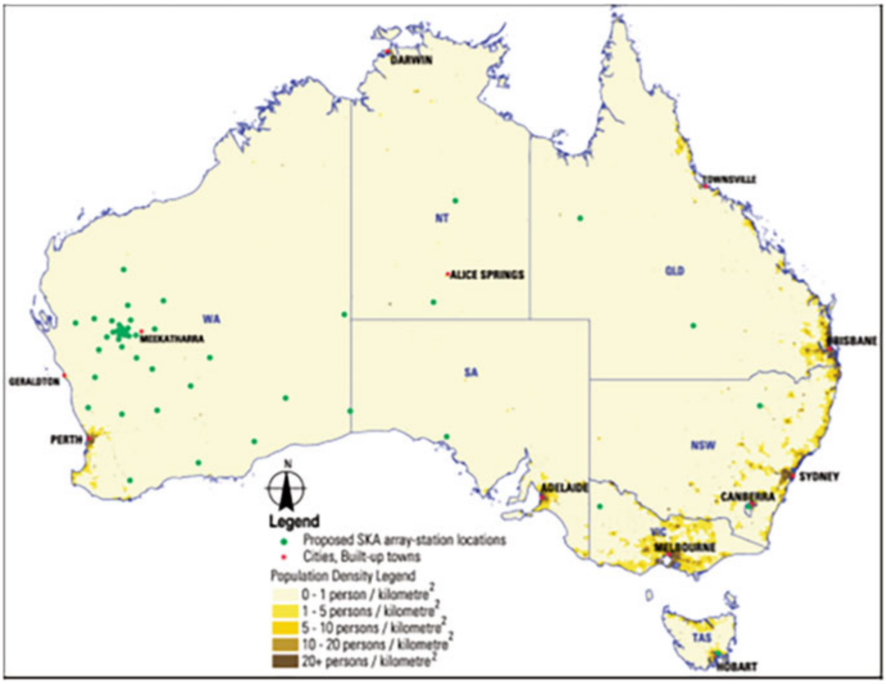

**Fig. 7.9** Proposed array layout for Australia with the core site centred at Mileura (hba.skao.int/SKAHB-439 *Proposal for Siting the SKA in Australia*, 2005). The locations of individual array elements are shown as green dots. (Credit: CSIRO Radio Astronomy Image Archive SKA008)

the stability of the ionosphere and low water vapour content of the troposphere in the winter months, the high-quality existing infrastructure and political and economic stability, and the international strength of Australia's radio astronomy community. Both LNSD and SNLD array types could be accommodated. The planned extended

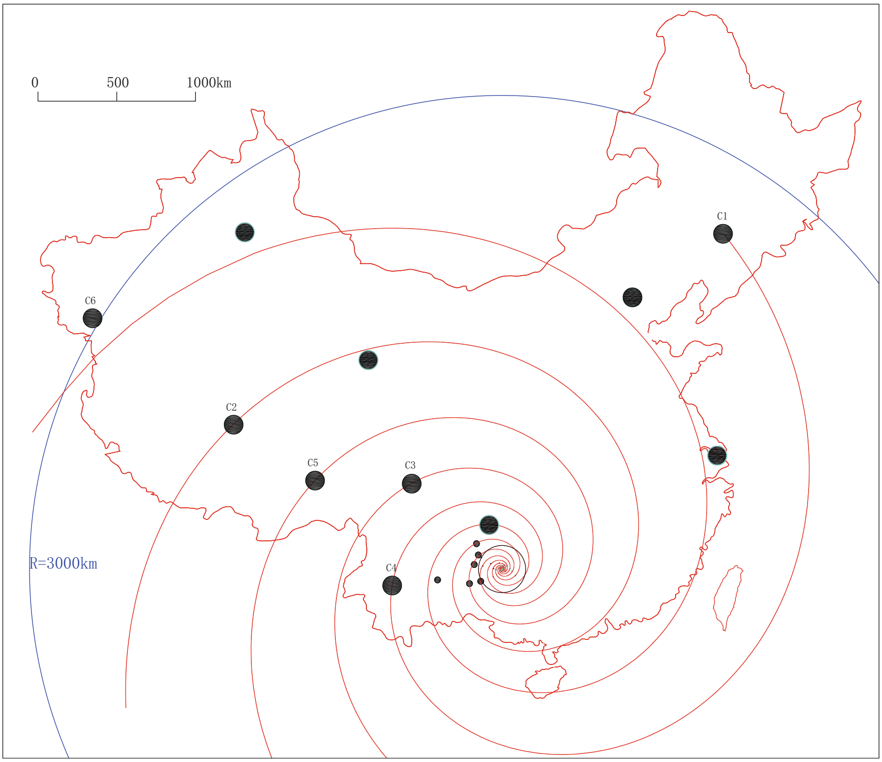

**Fig. 7.10** Proposed array layout for China (hba.skao.int/SKAHB-440 *A proposal for siting the SKA in China*, 2005). The large-scale distribution of karst depressions. The blue arc is at 3000 km from the central karst depression. (Credit: National Astronomical Observatory of China)

New Technology Demonstrator (xNTD) project which transformed into ASKAP (see Sect. 4.3.3.1) a year later was mentioned as an important factor in establishing a site that satisfied geophysical, radio-quietness, environmental, governance and regulatory requirements prior to the SKA.

#### 7.3.5.4 China

The proposal[31] was submitted by the National Astronomical Observatories of China and proposed a configuration for the SKA centred around the Dawodang karst in Guizhou Province in south-west China (see Fig. 7.1 left). Several hundred possibly suitable depressions were identified for the remote stations within a distance of a few hundred kilometres (see Fig. 7.10). This depression, and the core region around it,

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[31] hba.skao.int/SKAHB-440 *A proposal for siting the SKA in China*, 2005.

lies in a remote mountainous area with a sparse population. The Guizhou Radio Managing Bureau together with the national Radio Regulatory Department had agreed to establish a radio quiet preserve with a diameter of 200 km centred on Dawodang depression.

A key supporting factor for the proposal was the RFI environment of the candidate sites with the hills around each depression providing a natural shield against radio interference. This had been shown by a series of on-site monitoring sessions for radio interference to investigate the ability to satisfy the RFI requirements for building the SKA (see Sect. 7.3.2).

The proposal did note that since the depressions are the result of a long geological history and are naturally distributed, there was no possibility to fit their configuration to the arbitrary distribution in the core area set out by the ISPO Configuration and Simulation WG in any exact way. The final choice of the depressions would have to be optimised to produce an acceptable reception pattern for the array. By its very nature, the depression geometry did not support an LNSD configuration, a fact that ultimately led to this proposal not being short-listed as we discuss in the next section. The zenith angle limitations of the spherical structure would also lead to limited tracking duration for southern declination radio sources and, consequently, relatively poorer overlap for simultaneous observations with other major astronomical facilities.

Furthermore, Guizhou Province and the proposed central region are located in a sub-tropical humid monsoon climate that would not trouble an SKA operating at low frequencies but would be a substantial drawback for the higher frequencies in the science requirements. Guizhou also suffered from the same problem as the Argentina-Brazil proposal that it is close to the magnetic equator with the attendant ionospheric stability problem potentially impacting the scheduling of low-frequency observations in particular.

#### 7.3.5.5 South Africa

The South African proposal[32] was submitted by Rob Adam on behalf of the Department of Science and Technology and proposed to site the SKA core site in the arid Karoo area in the Northern Cape Province (see Fig. 7.11). Remote stations were proposed in other parts of South Africa as well as in Namibia, Botswana, Mozambique, Mauritius, Madagascar, Kenya and Ghana to achieve the 3000 km baseline requirement (see Fig. 7.12).

Key factors in support of the bid were the quiet RFI environment at the central site and at a representative sample of remote station locations within 150 km where RFI measurements were carried out in support of the site bid. The very low population density and lack of economic drivers in the Karoo area, the terrain screening of the central core area in the direction of Cape Town almost 500 km away and the prospect

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[32] hba.skao.int/SKAHB-441 *South African Bid to Host the Square Kilometre Array*, 2005.

**Fig. 7.11** Proposed central site for the SKA in the Karoo Desert in the Northern Cape province of South Africa. (Credit: R.P. Millenaar, ASTRON, 2005: see also Millenaar, R., 2016)

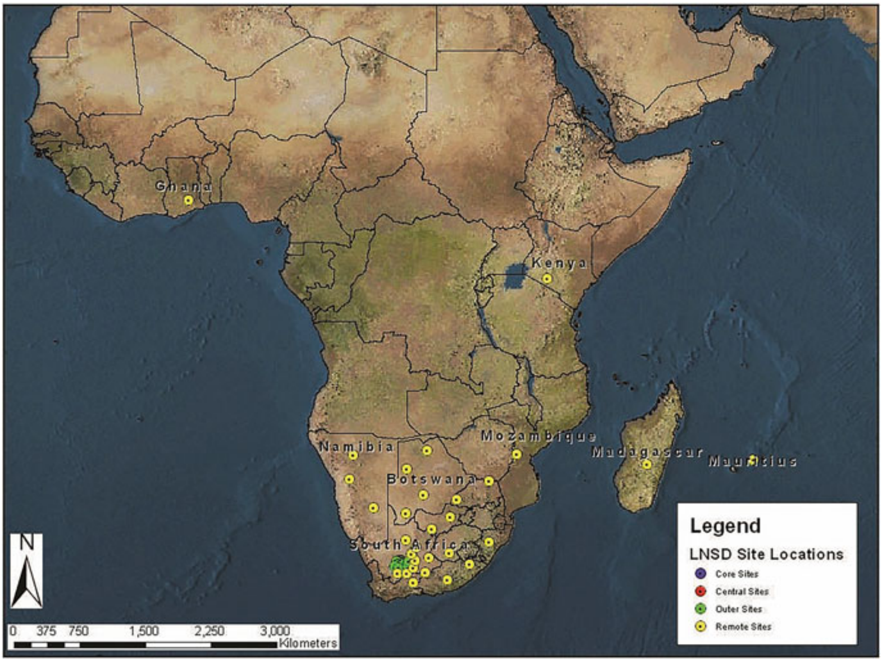

**Fig. 7.12** Proposed array layout for Southern Africa submitted in December 2005 in response to the Request for Proposals from the International SKA Steering Committee (credit: SKA South Africa) (hba.skao.int/SKAHB-441 *South African Bid to Host the Square Kilometre Array*, 2005)

of further improvement provided by regulatory measures via the Astronomy Geographic Advantage Act, were all factors supporting the claim of RFI quietness.

With an altitude of over 1000 m at the central site and its location in the arid Northern Cape Province, there is a low precipitable water vapour content in the troposphere above the site which makes it suitable for high frequency observations with the SKA. The ionosphere is stable over Southern Africa apart from low elevation observations in the west where the South Atlantic Anomaly comes into play.

As with Australia and China, South Africa realised that designing and building a pathfinder telescope on the proposed site would provide added weight to their proposal in terms of demonstrating an active site. The Karoo Array Telescope (KAT) served that purpose and was the forerunner of their precursor, MeerKAT (see Sect. 4.3.3.2).

### *7.3.6 Reflections on the 2005 Site Proposals*

It is interesting to see which of the selection criteria were emphasised in the individual proposals. Australia put in a confident proposal, no weaknesses, which reflected their view and that of almost all in the community at the time that they were the front-runners. Argentina-Brazil were defensive on the configuration and ionosphere, and China was defensive on the configuration, ionosphere and troposphere. The South African proposal was also confident but did choose to devote the first page of the Executive Summary to a statement from the President of the Republic, Thabo Mbeki, giving his support for projects like the SKA, as well as a list of government entities providing science-support infrastructure and political support for South African participation in the SKA. This suggests they had taken on board the funding agencies' view (see Sect. 7.3.7) that site selection was not up to the science community alone and that politics would play a role in site selection. It was therefore important to dispel any feeling in the outside world that local political support was a weakness in the proposal.

Also noteworthy is how the attitude and ambition of South Africa evolved in the space of a few years from being one of participation in a global scientific project, to playing a leading role[33], to playing <u>the</u> central role in the project as evidenced by the site proposal itself (see Sect. 7.3.5.5). As the final sentence of the Executive Summary of the Site Proposal said: "South Africa has the will, the capacity and the sites to construct, operate and maintain the SKA over its lifetime in support of the global astronomy partnership that it represents."

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[33] hba.skao.int/SKAHB-442 *Memorandum on the Request for Proposals for a Site for the Square Kilometre Array*, B. Fanaroff, 2004.

## *7.3.7 The Funding Agencies Intervention*

### 7.3.7.1 The Heathrow Meeting in June 2005

At the time of the Request for Proposals in Sept 2004 and for nine months thereafter the SKA project was proceeding smoothly towards a definitive selection by the ISSC of a single site for the telescope. The informal view of all ISSC members was that Australia was the obvious choice for the SKA site since it was a country with traditional strength in radio astronomy and vast tracts of RFI-free space to locate the telescope. The US was in second place, also a traditionally strong radio astronomy country, but located in the northern hemisphere and with far less open space than Australia. So, when the US withdrew, the result of the competition appeared a foregone conclusion, with politics playing a minor role.

However, as described in Sect. 3.4, the feeling of "plain sailing" changed fundamentally in June 2005 following the first interaction with funding agency and government ministry representatives who were meeting as a group at Heathrow airport to discuss future large astronomical facilities. It was made clear to the ISSC that SKA site selection in September 2006 (by the ISSC) was premature and that the funding agencies must be involved.

After considerable debate, the ISSC agreed that the outcome of the RFP process should change from a "final decision" on the location of the SKA to a decision on the ranking of the four sites based on scientific, technical and infrastructure cost grounds.[34] This was to form the basis of a recommendation on acceptable sites the ISSC would submit to the governments and funding agencies involved in the SKA in September 2006. Thereafter, further characterisation of the physical characteristics and RFI environment of the sites would be carried out in parallel with round-table discussions on scientific and geo-political issues including radio quiet zones, cost implications and cost-sharing possibilities, prior to a final decision on the site by the end of 2008.

A decision with ramifications for the site selection was made at the 14th meeting of the ISSC in Pune, India in November 2005. The LNSD dish concept was chosen as one of the three elements of the Reference Design to take forward to the funding agencies in early 2006.[35] Effectively this removed the Chinese site proposal from contention less than two months from proposal submission deadline since it envisaged a small number of large diameter spherical dishes in karst depressions in southwest China. However, during the ISSC meeting, the Chinese delegate, Bo Peng, informed the meeting that not including the FAST concept in the Reference Design was not a problem as long as the Chinese delegate at the planned governments/agencies SKA meeting in The Hague in February 2006 saw a picture of FAST during the meeting. No doubt this relaxed reaction was motivated by Peng's further

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[34] hba.skao.int/SKAHB-37 *Issues Concerning the Request for Proposals for Siting the SKA*, Supporting Paper for the 14th ISSC Meeting, August 2005.

[35] hba.skao.int/SKAHB-23 Minutes of the 14th ISSC meeting, November 2005.

announcement that the FAST project had just been approved formally by the Chinese Academy of Sciences with fifteen new positions and an initial budget of 10 million Chinese Yuan. However, it was not the Chinese intention to withdraw their proposal for the SKA site and Peng was keen to ensure it was evaluated in the same way as the other three.

#### 7.3.7.2 The Hague Meeting in February 2006

This was the first funding agency meeting devoted entirely to the SKA. It was notable for the proclamation by the chair, Richard Wade (STFC, UK), at the end of the closed session that the site selection process should result in a short list of acceptable sites since the agencies felt the project would benefit from a period of negotiation ahead of the decision, if needs be with "blood on the floor".

Accordingly, the ISSC modified its approach from ranking to short-listing the proposals. It did, however, accept that short-listing was a non-confrontational way of selecting scientifically acceptable sites, even if the "blood on the floor" approach to the final negotiations leading to selection was not consistent with the collegiate culture of the SKA project (see Box 7.6). A fuller discussion of the Hague meeting is given in Sect. 3.4.3.

**Box 7.6 ISSC Versus Funding Agency (Soft Versus Hard) Approach to Site Selection**

The ISSC's original approach that it would make the final selection of the site independent of higher-level political considerations reflected a certain naiveté that was quickly dispelled at Heathrow. However, it is interesting to speculate whether the "softer" approach of "round-table discussion" proposed by the ISSC in August 2005 would have led to a different outcome for the site selection than the hard competition mandated by the funding agencies. One such outcome of the ISSC approach might have been a compromise between the top-ranked sites, Australia and South Africa, whereby a mutually—acceptable sharing of the spoils was achieved without the rancour of the final stages of the selection process in 2012. With Australia in the pole position in 2007-8, they would have been in the stronger position to fashion the compromise more to their liking.

One negative consequence of the competitive relations between Australia and South Africa engendered by the governmental/funding agency entry into the site selection process was the move in Australia to make the post-2006 internal deliberations on their site proposals confidential. This blocked the normal process of community consultation and stifled innovation.

### 7.3.8 *Evaluation of the Proposals*

In parallel with the changing position on the outcome of the site selection, the ISSC and ISPO worked out the details of the evaluation process sketched in the Request for Proposals, and the procedure to be followed to come to a short-list. A sub-committee of the ISSC (Wim Brouw (ASTRON (The Netherlands), Phil Diamond (Jodrell Bank Observatory, UK), Schilizzi (convenor), Jill Tarter (SETI Institute, USA), Yervant Terzian (Cornell University)) re-worded the criteria by which to judge the proposals, established their individual weights in the evaluation process and selected the Analytic Hierarchical Process (AHP) as a quantitative method of comparing the sites for each criterion.[36] Mindful that the full ISSC membership, including site representatives, would vote on the short list, an external committee, the International SKA Site Advisory Committee (ISSAC), was formed to carry out an independent evaluation of the proposals and report to the ISSC.

Members appointed to the ISSAC were all well-known figures in international astronomy and included Richard Hills (UK, chair), Jacob Baars (Germany), Jacqueline van Gorkum (USA/Netherlands), James Moran (USA), Ernest Seaquist (Canada), Govind Swarup (India), and Robert Williams (USA). Schilizzi, as SKA Director, acted as Advisor to the ISSAC.

Protocols were agreed for each of the entities involved in the site evaluation—ISSC, ISPO, ISSAC, and the Site Evaluation Working Group (SEWG) and Simulations Working Group Task Forces—to define their roles and work to be done, and to ensure the selection procedure was understood and followed by all parties. The ISPO was again the clearing—house for all queries or issues raised by any of the parties during the evaluation phase.

#### 7.3.8.1 ISPO-Led Evaluations

Detailed evaluations of different aspects of the proposals began early in January 2006. These were carried out[37] by a sub-group of the SEWG on ionospheric conditions, the RFI Assessment Task Force on the RFI environment, the Regulatory Task Force on Radio Quiet Zone regulations, the Configuration Simulations Task Force to calculate Figures of Merit, and an external consultant (Parsons-Brinkerhoff) on power generation costs.

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[36] hba.skao.int/SKAHB-445 *SKA Site Selection Process*, Schilizzi, R. T., Brouw, W. N., Diamond, P. J., Tarter, J. C., Terzian, Y., 2006, Supporting Paper for the 16th ISSC Meeting, August 2006.

[37] The SEWG sub-group was chaired by Subramanium Ananthakrishnan; the RFI Assessment Task Force by Steve Ellingsen; the Regulatory Task Force by Willem Baan; and the Simulations Task Force by Steven Tingay.

These evaluations, and those carried out in parallel by the ISSAC, led to several requests for additional information or questions of clarification for the potential sites.[38] All sites had to provide more information on tropospheric opacity, costs of providing and operating access roads, costs of power generation and distribution, and costs of data connectivity to the SKA. Specific questions were asked of Argentina, Australia and China, one of which—information on ionospheric scintillation related to the core site in Argentina—had a profound effect on that country's prospects of selection for the short list. Ionospheric scintillation is a frequency-dependent effect that causes phase distortions in the incoming cosmic radiation, particularly at the low frequencies envisaged for the Epoch of Reionisation array (which later became SKA-low). Of concern to the SEWG sub-group was that the geomagnetic equator of the Earth swings south of the geographic equator in the vicinity of Brazil and Argentina and this was known to cause enhanced scintillation.

To respond to the request, Marcelo Arnal and colleagues in Argentina commissioned an ionospheric scintillation impact report from NorthWest Research Associates in Tucson, Arizona, USA.[39] The report pointed out that the latitude of the proposed location for SKA was just south of the "southern equatorial anomaly". This is a region of potentially severe ionospheric scintillation that shows a strong diurnal variation as well as a seasonal variation which peaks in intensity near the equinoxes. The scintillation also increases with the 11-year solar cycle, driven by increases in the solar output of extreme ultraviolet, or EUV, radiation.

To back up this general statement, 72 day-of-year versus time contour plots of the expected worst-case $S_4$ intensity-scintillation index for four frequencies of interest (100, 250, 600, and 1000 MHz) were included at nine viewing geometries (overhead, and 30° and 60° elevation at 0°, 90°, 180°, and 270° azimuth from true north). This was done for both solar minimum (defined as a sunspot number of 10) and solar maximum (150) conditions (see example at 100 MHz in Fig. 7.13). The plots showed there was a considerable risk that severe distortions would occur particularly for observations to the north, and that these distortions would be experienced even at frequencies as high as 1 GHz. In the final analysis by the ISSC (see Sect. 7.3.8.4), this was seen as a disabling characteristic for the Argentina-Brazil bid.

#### 7.3.8.2 ISSC Internal Site Evaluation Process

In proposing that the Analytic Hierarchy Process (AHP) of pair-wise comparison of candidate sites be used by the ISSC, the sub-committee noted that this approach had been used in site selection processes for LOFAR and the Australian SKA core site. In

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[38] hba.skao.int/SKAHB-446 *Further questions for clarification. II,* International SKA Project Office, July 2006.

[39] hba.skao.int/SKAHB-447 *Ionospheric Scintillation Impact Report*, NorthWest Research Associates, Inc., prepared for the Instituto Argentino de Radioastronomia*,* 2006.

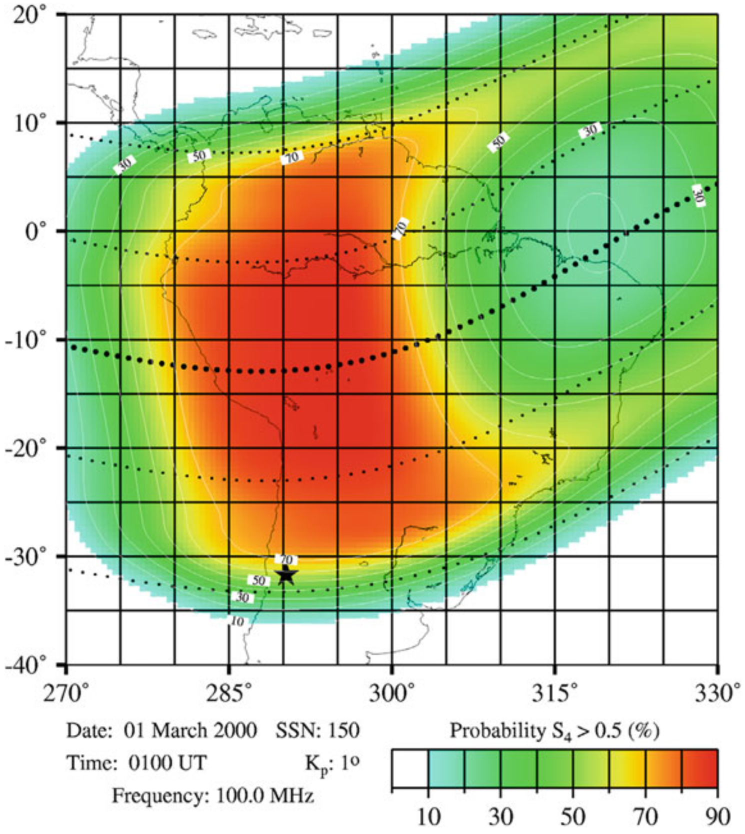

**Fig. 7.13** Scintillation coverage map superimposed on South America (credit: NorthWest Research Associates, prepared for the Instituto Argentino de Radioastronomia)

contrast, the South Africans had used a “fatal flaw” analysis to select their core site.[40] This latter approach also formed part of the final decision process for the SKA site, but with the less confrontational name of “disabling characteristics” .

AHP is a multi-criterion decision support tool[41] that allows groups knowledgeable about the subject to convert their well-informed qualitative judgements into a quantitative structure. It is well-suited to a site selection process where many factors are relevant to each site criterion and judgements on complex comparisons need to be quantified.

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[40] hba.skao.int/SKAHB-445 *SKA Site Selection Process*, Schilizzi, R. T., Brouw, W. N., Diamond, P. J., Tarter, J. C., Terzian, Y., 2006, Supporting Paper for the 16th ISSC Meeting, August 2006.

[41] Wikipedia https://en.wikipedia.org/wiki/Analytic_hierarchy_process, accessed 11 September 2022.

There were two phases to the application of AHP to the SKA[42]: (1) ISSC agreement on the selection criteria and weights proposed by the sub-committee, and (2) independent analysis of the relative merits of the sites against these criteria by the ISSC members in order to rank the four sites.

Despite the adoption by the ISSC of the LNSD concept as part of the Reference Design just before the proposal deadline, and the consequent change in acceptable configurations, the selection criteria were not adjusted to respect the considerable resources and effort spent by proposers in generating their RfP responses which included both the LNSD and SNLD options.[43] However, one exception was the category of "political issues" in the RfP (called "National attributes for siting the SKA" in Box 7.4) which were no longer considered since they did not fall under scientific, technical and infrastructure cost, and were deferred to the post-short-list stage of site selection.[44]

The final evaluation criteria for selection of the site short-list and weights are shown in Table 7.1. The set of weights generated by each ISSC sub-committee member independently were the same within the statistical errors.[45]

All but one of the 21 ISSC members carried out their own AHP analysis and sent the results independently to the SKA Director by mid-August 2006. All analyses received returned the same result: (1) Australia, (2) Southern Africa, (3) Argentina-Brazil, (4) China.

#### 7.3.8.3 ISSAC Review and Report

The International SKA Site-selection Advisory Committee (ISSAC) provided a ranking on the basis of the selection criteria[46] based on assessing the same information received by the ISSC as well as interviews with delegates from each site. On advice from the ISSC, the ISSAC did not consider questions relating to political support for the project or to the possibility of financial contributions linked to the choice of site.

The Executive Summary of the ISSAC report stated:

> The ISSAC has studied the documentation provided by the four candidate sites and heard presentations from representatives of each of the proposers. The Committee also took account of a set of factual reports and summaries provided by the International SKA Project. The ISSAC assessed the strengths and weaknesses of the sites on each of the criteria set out in the request for proposals. Our conclusion is that two of the sites, those based in Australia and the Republic of South Africa, clearly stand out as the best. They are both excellent sites and the Committee believes that they are both fully capable of meeting the full range of the

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[42] hba.skao.int/SKAHB-54 *Minutes of the 16th ISSC meeting*, August 2006.

[43] hba.skao.int/SKAHB-448 Minutes of the ISSC Mid-term Teleconference, July 2006.

[44] hba.skao.int/SKAHB-54 Minutes of the 16th ISSC meeting, August 2006.

[45] hba.skao.int/SKAHB-54 Minutes of the 16th ISSC meeting, August 2006.

[46] hba.skao.int/SKAHB-449 *Report of the International SKA Site-selection Advisory Committee,* Hills et al., 29 July 2006.

**Table 7.1** Final evaluation criteria and weights for SKA site short-listing

| | |
|---|---|
| **1. Short-term and long-term radio frequency and protection issues** | **0.200** |
| 1.1 RFI environment as a function of frequency band | (0.100) |
| 1.2 prospects for establishment of a Radio Quiet Zone for the Core | (0.100) |
| **2. Array configuration and performance** | **0.075** |
| 2.1 Figures of Merit: uv plane coverage, beam-shapes | (0.028) |
| 2.2 coverage of key astronomical objects | (0.028) |
| 2.3 common visible sky with other major astronomical instruments | (0.012) |
| 2.4 simultaneously visible sky with other major radio telescopes | (0.007) |
| **3. Ionospheric conditions** | **0.200** |
| 3.1 TEC analysis (vertical and slant) | (0.017) |
| 3.2 ionospheric scintillation | (0.083) |
| 3.3 spread-F | (0.083) |
| 3.4 TIDs | (0.017) |
| **4. Tropospheric conditions** | **0.175** |
| **5. Climate and basic infrastructure** | **0.050** |
| 5.1 climate | (0.017) |
| 5.2 physical characteristics | (0.003) |
| 5.3 impact of land-use and urban centres | (0.016) |
| 5.4 transport access | (0.007) |
| 5.5 facility support centre | (0.007) |
| **6. Data interconnects** | **0.050** |
| 6.1 connectivity plan | (0.050) |
| **7. Capital costs** | **0.125** |
| 7.1 land acquisition, fencing, etc. | (0.008) |
| 7.2 roads | (0.016) |
| 7.3 power provision | (0.064) |
| 7.4 data connection costs | (0.037) |
| **8. Operating costs** | **0.125** |

requirements of the SKA, including scientific, technical and practical issues. There are some discernible differences between these two sites: for example, Australia can accommodate long East-West baselines more easily and currently has somewhat lower levels of interference, while South Africa has a rather more benign climate, and some aspects of the infrastructure are better. If the heaviest weighting is given to the factors which directly affect scientific performance, Australia has a small but measurable advantage over South Africa.

The two other sites, in Argentina-Brazil and in the People's Republic of China, are also very good sites for radio astronomy. In particular Argentina would be favoured for a project that was focused on the higher radio frequencies but is disadvantaged by ionospheric effects and radio interference at low frequencies. The karst landscape and low levels of interference in the Guizhou Province of China make it ideal for large reflectors like the FAST project, but the terrain presents difficulties for the construction of the SKA, which has stringent requirements for the placing of the antennas, and especially for the configuration of the SKA which is based on a large number of small antennas. The ISSAC therefore concluded that neither Argentina and Brazil nor China represent competitive sites for the SKA.

This report was transmitted to the SKA Director on 1 August 2006 in whose care it was held in confidence until the ISSC internal evaluation had been completed 2 weeks later. After the release of the report to the ISSC and proposers, both Argentina and China took the opportunity to rebut comments made by the ISSAC. Argentina noted that one of the RFI sources at 100 km distance was to be removed later in 2006, while China objected to the speculation that mobile phones would soon be a significant source of RFI for an SKA sited in China. Subsequent experience at the FAST site has shown that the Chinese objection was well-founded.

The ISSAC report, together with the AHP result from the ISSC and the analyses of the submissions by the ISPO working groups and consultants, formed the primary material taken by ISSC members to the 16th ISSC meeting in Dresden, Germany in late-August 2006 where the site short-list decision would be made.

#### 7.3.8.4 ISSC Decision on the Short-List of Acceptable Sites

The order of business for the ISSC meeting in Dresden was carefully choreographed by the ISSC Executive Committee comprising Phil Diamond (chair), Wim Brouw, Brian Boyle, Jill Tarter and Richard Schilizzi in order to create a robust, fair, open and transparent process.

The first agenda point was formal approval of the definition of an acceptable site as *'An acceptable site is one for which the usable frequency range, configuration, sky coverage, and physical characteristics allow the key scientific goals of the project to be achieved efficiently over the lifetime of the telescope'.*

The proceedings began with an open session with all members, site proponents, and the ISSAC Chair, Richard Hills, present (see Fig. 7.14). At each stage, there was an opportunity for questions, discussion and comment. Schilizzi provided an overview of the analyses of the site proposals carried out by the ISPO working Groups and task Forces (see previous section), followed by Hills with a report on the ISSAC process and its outcome (see previous section), and finally Schilizzi with a report on the ISSC AHP outcome (also described in the previous section). No large variations in the conclusions were found as a result of varying the weights of the main selection criteria, in particular by making the cost, ionosphere and troposphere weights equal to zero in a variety of combinations.

A closed session followed with only ISSC members, ISSC Secretary and SKA Director present in order to generate a short list of sites that were "acceptable" taking into account potential disabling characteristics. An open vote was held on the ranking of the sites, using a two-step procedure:

1. Each ISSC member was allocated 12 virtual votes that he/she could distribute to each site with no allocation exceeding 6 votes. A clear order was established: from top down, Australia, South Africa, Argentina—Brazil and China.

**Fig. 7.14** The ISSC members and observers, taking a break from deliberating on the site shortlisting at its meeting in Dresden, Germany, in August 2006. Front row, left to right: Bo Peng, Bryan Gaensler, Peter Dewdney, Ken Kellermann, Anne Green, Gloria Dubner, Joe Lazio, Justin Jonas, Yervant Terzian, Richard Hills (ISSAC Chair), Phil Diamond (ISSC Chair), Wim Brouw. Back row left to right: Richard Schilizzi, Russ Taylor, Jill Tarter, Brian Boyle, Peter Wilkinson, Bob Preston, Jim Cordes, Wim van Driel, Thijs van der Hulst, Peter Hall, Dave De Boer, and Arnold van Ardenne. (Credit: Franco Mantovani, also ISSC member)

2. Each member then filled in a matrix of the first six major criteria *vs*. site. If a site was regarded as unacceptable with respect to a particular criterion, this was noted in the appropriate matrix element. If more than 75% of the ISSC felt a site was unacceptable with respect to the same criterion, that was counted as a disabling characteristic. If less than 25% of the ISSC felt a site was unacceptable on the basis of a particular criterion, that was to be ignored. Any vote between 25% and 75% triggered discussion and a formal majority vote on the acceptability of that site.

As a result, all sites had at least one disabling characteristic indicated by at least one ISSC member. Australia and South Africa had less than 25% of the votes for any potential disabling characteristic and were included in the short-list. China was seen by more than 75% of the vote to have no viable configuration option as an SKA site and was removed from the short-list. The Argentina—Brazil ionospheric properties were seen by between 25% and 75% of the vote as being a disabling characteristic, thereby needing further discussion and a majority vote. Note that the actual percentage of the vote in each case was not recorded in the minutes of the meeting.

Subsequent discussion centred on whether the ionospheric limitations could be bypassed for any of the Key Science Projects, but none were found; in particular, it was felt that no Epoch of Reionisation (EoR) observer would select the Argentina-Brazil site for an EoR telescope. The formal vote confirmed this, which left a short-list of two acceptable sites: Australia and South Africa.

## 7.4 Site Short-Listing Outcome

The ISSC Chair, Diamond, summarised the outcome as follows:

> There seems to be good consistency between all the input information, an indication that we have a fair and robust process overall. There is no question that all four proposed sites were amongst the best sites for radio astronomy in the world. However, following a voting process, the ISSC has ranked the sites in the following order (best first): Australia, South Africa, Argentina- Brazil and China. In the short-list selection the ISSC found no disabling characteristic for Australia and South Africa and declared them short-listed.
>
> For the proposal from China the configuration options were considered to be a disabling characteristic for the SKA as envisaged, and China was removed from the short-list. However, the site is exceptional in its low RFI properties, and should be preserved at all costs as the site for large collecting area, single dish radio astronomy.
>
> For the Argentina—Brazil proposal, the ionosphere was considered a disabling characteristic for important parts of the SKA Key Science Projects, and Argentina—Brazil was not included in the final short-list. The Argentina site is a great site for high-frequency radio astronomy and would get the support of the ISSC for any proposal to put a high-frequency instrument there.

The candidate site representatives all noted that they accepted the outcome and regarded the process as being robust, fair, open and transparent.

The SKA Funding Agencies Working Group approved the short-listing outcome, and the accompanying summary of the strengths and weaknesses of the four sites, at a meeting a month later, in September. The project moved on to the next phase of site selection which was every bit as complicated and difficult as had been predicted by Richard Wade earlier in the year.

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# Chapter 8
# Site Selection Story, 2006–2012: Decision

## 8.1 Introduction

By the end of the short-listing process in August 2006, described in the previous chapter, it would be fair to say that most people expected Australia eventually to win the site competition. However, the process to arrive at the final site selection was not at all clear. How long would/should it take? Should site selection be carried out before the technical design was finalised? How much additional site characterisation would be required? How would the site negotiations be carried out? What roles would the funding agencies and the International SKA Steering Committee (ISSC) play? The governing principle was, however, clear—the final selection process should be conducted in a timely, transparent and considered manner.

The ISSC assumed it would evaluate all selection criteria and make a recommendation to the funding agencies who would then carry out negotiations with the recommended site. From the ISSC point of view it was very much a winner-takes-all scenario. In subsequent years, the roles of the ISSC and its successor, the SKA Science and Engineering Committee (SESC), and the funding agencies in the site selection decision became better defined and, jointly, a process was established with buy-in from the two candidate sites that for the most part was carried out satisfactorily. However, both candidate sites hedged their bets by initiating large precursor projects (see Sect. 4.3.3) as a scientifically valuable back-up if they did not win the competition. In Australia, the leadership saw the precursor, ASKAP, as essential in influencing the site decision and that led to considerable time pressure on the ASKAP design such that construction began before the design was completed. This was not the case for MeerKAT in South Africa as the KAT-7 interferometer was seen as being sufficient to demonstrate the Karoo site's potential. In the event, the national investment in infrastructure and know-how in the pre-cursors became a significant argument influencing the final decision by the Board of Directors and Members of the SKA Organisation (SKAO) to utilise both sites for the SKA, a result that was unexpected at the start of the final selection process in late-2006.

R. T. Schilizzi et al., *The Square Kilometre Array*, Historical & Cultural Astronomy,
https://doi.org/10.1007/978-3-031-51374-9_8

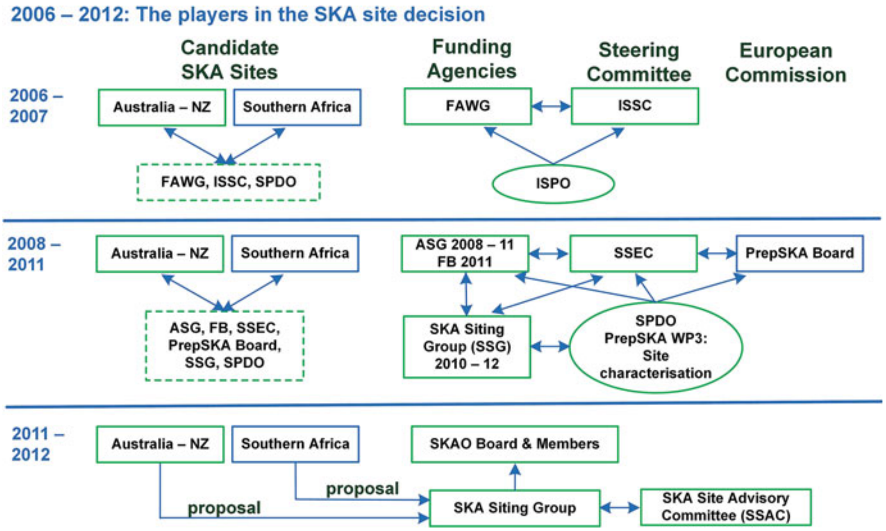

**Fig. 8.1** The players in the SKA site decision process and many of the communication and reporting channels established as part of the process. Communication channels are indicated by double-ended arrows, reporting channels by single-ended arrows. The dashed boxes in the Candidate SKA Sites column include the ensemble of entities that were in communication with the two sites during the periods depicted in the top two panels. Acronyms used in the figure are: *FAWG* Funding Agencies Working Group, *ASG* Agencies SKA Group, *FB* Founding Board, *ISSC* International SKA Steering Committee, *SSEC* SKA Science and Engineering Committee, *ISPO* International SKA Project Office, *SKAO* SKA Organisation, *SPDO* SKA Program Development Office, *PrepSKA* Preparatory Phase for the SKA, *SSG* SKA Siting Group, and *SSAC* SKA Site Advisory Committee

During the site decision process, there were many communication and reporting channels established among the funding agencies groups, the steering committee (ISSC, SSEC), the central project office (ISPO, SPDO), the PrepSKA Board overseeing the site characterisation activities led by the SPDO, the site decision-specific committees formed towards the end of the process (SKA Siting Group, SSG, and SKA Site Advisory Committee, SSAC), and the candidate SKA sites (Australia and South Africa). Figure 8.1 shows the players in the site decision process and the communication and reporting channels linking them.

The main elements of the story from 2006 to 2012 are the players and their interactions, the tortuous path towards an acceptable date for the site selection and an acceptable selection process, the further characterisation of the sites and difficulties encountered, preparation for the final site submissions, the evaluation of the proposals, and finally the decision. This was all played out against a backdrop of competing national interests both within the project and at high political level internationally, and self-imposed constraints of tight schedules for both the SKA project as a whole and the precursors.

We go through these elements in this chapter.

## 8.2 Timing of the Site Decision

### *8.2.1 Revised Goal: 2008*

Prior to the first consideration of SKA by the funding agencies at Heathrow airport in June 2005, ISSC discussions of the project timeline foresaw final selection of the site in 2006 (see Sect. 7.3.7.1). At Heathrow, the funding agencies made it clear that site selection was an aspect in which they would need to be involved. This led the ISSC to modify its position in August 2005[1] from an outright selection to a ranked list of the four potential sites in 2006 followed by further characterisation of the physical characteristics and RFI environment of the sites. Finally, round-table discussions involving the ISSC, funding agencies and potential sites on scientific and geo-political issues, would take place prior to a decision by the end of 2008. Thereafter, preparation and roll-out of site infrastructure would take place in 2009–10 followed by start of SKA Phase 1 construction in 2011.

The Hague meeting of funding agencies in February 2006 (see Sects. 3.4.3 and 7.3.7.2) clarified their involvement in the site selection process and this led to a shift in the ISSC position from the ranked list of potential sites to a short-list of acceptable sites. The ISSC also modified its concept of a subsequent "round-table discussion" to "international negotiations" but left the final decision on the site as late-2008 in order to maintain the goal of a construction start in 2011.

### *8.2.2 Second Revision: 2010*

However, at their meeting in Prague at the IAU General Assembly in August 2006, the Funding Agencies Working Group (FAWG) made it clear that the ISPO and ISSC was too focussed on maintaining the 2011 construction start goal at the expense of considering the details of achieving the milestones on the way. There was broad support for the views of the Australian delegate, Martin Gallagher, that site selection in 2008 was optimistic and incompatible with project approval practice in the various countries likely to be involved in the SKA. Site selection in 2009 or 2010 appeared more realistic from their point of view.

Discussion of the FAWG view by the ISSC in the succeeding months produced no strong arguments to maintain the 2008 date, despite an initial clear majority for pushing back on this to the funding agencies in a non-confrontational way.[2] And in November 2006, the ISSC finally accepted that the final site selection, technology procurement, and governance decisions for the SKA were inextricably linked, and

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[1] hba.skao.int/SKAHB-23 Minutes of the 14th ISSC meeting, November 2005

[2] hba.skao.int/SKAHB-54 Minutes of the 16th ISSC meeting, August 2006.

produced a landmark strategy paper[3] that proposed the SKA site selection decision be set to not later than 2010 to best match the international funding opportunities and perceived decision-making time scales. The ISSC also noted that despite the development of precursors at the proposed sites, a final site choice by 2010 would need to take into account the time required to build up initial SKA-specific infrastructure in addition to that in place for the precursors.

During 2007 and 2008, site-related discussions in the ISSC, and subsequently the SSEC, focussed on the more practical concerns of the additional site characterisation studies to be carried out in PrepSKA Work Package 3. As discussed in Sect. 8.4, these studies included RFI monitoring and tropospheric monitoring, as well as formal recognition of radio-quiet zones around the candidate SKA sites in both countries. As far as site infrastructure was concerned, a report from a Tiger Team led by the SKA Project Engineer, Peter Hall, (CSIRO, Australia) concluded that 3–4 years would be required to develop a “green-field” site, but with re-use of the associated precursor site infrastructure for SKA Phase 1 construction, development times as short as 2 years were possible. The latter would still allow a construction start in 2012.

At the same time, the funding agencies were taking the first steps towards consensus on a decision-making framework that would serve the project in the implementation phase following PrepSKA as well as coming to grips with their responsibilities for the three ‘Policy’ work packages in PrepSKA (see Sect. 4.4.1). Arguments for the 2010 site selection continued to be refined and now included the expectation that SKA project would have a clearer focus as a whole which could allow the scope of the precursor telescope construction on the selected site (ASKAP in Australia or MeerKAT in South Africa) to be reduced thus freeing up additional resources for the international design effort. Also planning for SKA infrastructure could begin earlier.

### *8.2.3 Third and Final Revision: 2012*

The 2010 site selection date did not hold. In 2009, the SSEC and the funding agencies returned to the site selection date after further examination by the SSEC of the project-wide interim milestones leading to the start of SKA Phase 1 construction. This resulted in the adoption of a revised milestone of mid-2011 for the SSEC recommendation on the preferred site and a final decision by the funding agencies and governments in 2012.[4,5,6]

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[3] hba.skao.int/SKAHB-450 *Proposal for a Forward Strategy for the International SKA Project*, ISSC, supporting Paper for the ISSC Mid-term Teleconference, November 2006.

[4] hba.skao.int/SKAHB-110 Minutes of the 2nd Meeting of the SSEC, February 2009

[5] hba.skao.int/SKAHB-71 Minutes of the 3rd Meeting of the SSEC, October 2009

[6] hba.skao.int/SKAHB-451 *On the Selection of the Site for the SKA*, SSEC, Supporting Paper for the 3rd SSEC Meeting, June 2009

The arguments supporting this further delay were threefold: (i) it was not clear that governments, funding agencies and the SSEC would have sufficient information to make a choice in 2010 which would be well before further characterisation of the candidate sites was completed in PrepSKA; (ii) it was not clear whether any SKA-specific site development would take place before there was a commitment at government level to construct the SKA; and (iii) a 2011 date for the SSEC recommendation would allow governments and funding agencies to discuss options for governance, procurement, and funding resulting from the PrepSKA policy work packages in conjunction with the SSEC recommendation, before making the final site decision.

This was the final revision of the site decision timeline.

## 8.3 Developing the Site Selection Process

### *8.3.1 Slow Steps at the Start, 2007–2008*

As far as the selection process itself was concerned, the FAWG noted in May 2007 that there was an urgent need for discussions on several key decision areas including the process and timescale for deciding on the eventual site for the SKA. A decision on the site would need to be made in 2009 or 2010 if the construction of the SKA Phase 1 array was to begin in 2012, given the lead times for the selection of the site, installation of infrastructure on the site, establishment of an appropriate management capacity and structure, and development of a funding plan for the Phase 1 array before construction could start.

However, this urgency did not translate into concrete action on the site selection process until October 2009 due to the arrival of the PrepSKA funding in 2008 and the need for the funding agencies to map out their approach to the policy work packages - governance, procurement, and funding - for which they had responsibility.

Also required on the part of the funding agencies was a strategy for interaction with the whole SKA project, including the site selection process. To accomplish this, the funding agencies continued, in parallel with their PrepSKA workshops, to hold meetings to review project progress and align the project with agency thinking on timescales including that of site selection as well as funding and implementation scenarios. In November 2008 in a meeting in Washington D. C., the Funding agency representatives discussed the broad concepts behind developing a selection process and used the European Spallation Source as an example to suggest that an external expert group could be employed to make factual recommendations. In SKA's case, these factual recommendations would be based on the results of PrepSKA Work Package 2 (telescope design) and 3 (site characterisation). Other factors including political aspects, already existing infrastructure and operations support issues would need to be considered. Some funding agency participants felt that site selection should be decided by science and engineering considerations rather than by externally primarily politically driven influences. However, the consensus view was that the SSEC was the appropriate body to receive the technical site evaluation reports and to recommend a site based on technical merit to the funding agencies.

A concrete outcome from the Washington discussion a few months later was the first version of an SSEC document outlining current thinking on the site selection process. Further development of this pivotal document[7] took place at succeeding SSEC and funding agency meetings, both separate and joint, in the first half of 2009, and underpinned the site deliberations throughout the following 3 years until the decision. We now discuss the main points in more detail.

## *8.3.2 SSEC Views on Site Selection Issues*

The SSEC document set out the defining physical characteristics of a desirable SKA site, the likely selection criteria, timescales for infrastructure development, and noted two over-arching considerations—that site selection and approval of construction funding were linked, and that the site selected for SKA Phase 1 (10% of the final SKA collecting area) must be able to accommodate the construction of the full SKA array (SKA Phase 2). Unresolved issues were also addressed, amongst which were when could or should the site decision be made (see previous section), how would the decision be made and what were the potential outcomes of the decision process.

### 8.3.2.1 How the Site Decision Would Be Made

In mid-2009, it was generally understood by the Agencies and the SSEC that the SSEC would evaluate all selection criteria including infrastructure capital costs, operations costs, decommissioning costs and national attributes, and then make a motivated recommendation to the governments and funding agencies for ratification. The SSEC document noted that the governments and funding agencies must by then have established a process for making decisions on the SKA. (Unknown to the SSEC at the time, the IFAG-ASG was in fact spending considerable time in closed session meetings coming to a consensus on a decision-making structure for the project as a whole, as described in Sect. 4.6.)

The SSEC recognised that if they were unable to make a clear recommendation, a process of negotiation organised by governments and funding agencies would need to be initiated in which additional criteria for selection might need identification and agreement. Examples of additional criteria were the level and timeliness of the host country contribution to the project, and the level of support around the world for one

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[7] *hba.skao.int/SKAHB-451 On the Selection of the Site for the SKA*, SSEC, Supporting Paper for the 3rd SSEC Meeting, June 2009

or the other country. In the event, the over-riding post-recommendation issue was how to keep both candidate countries involved in the project.

#### 8.3.2.2 Potential Outcomes of the Site Selection Process

Two potential outcomes were discussed:

1. "Winner takes all"

Under this scenario, the selected country hosts the SKA. The non-selected country continues to develop its precursor array, and hopefully continues to contribute to the realisation of the SKA scientifically, technically, and as a supplier of technology or services to the SKA.

2. "Win-win"

The selected country hosts the SKA, but a large remote station for the SKA is installed in the non-selected country to contribute even longer baselines to the SKA for high angular resolution observations, matching typical Very-Long-Baseline Interferometry measurements. It would be up to the non-selected country to decide whether to continue development of its precursor array. The SSEC document noted that the scientific merit of a large remote station 6000 km from the SKA core needed further discussion.

Alternatively, the SKA could be divided between the two countries, with Phase 1 and Phase 2 of SKA-low (70–500 MHz) in one country, and Phase 1 and Phase 2 of SKA-mid (300 MHz—10 GHz) in the other. Under this scenario, governments and funding agencies would have to foot the bill for the complete infrastructure, operating, and decommissioning costs in the two locations. Initial estimates of the capital costs of infrastructure on one site were €200 M[8] meaning the capital costs of the SKA would go up by an extra ~€200 M in the two-site scenario, and there would be additional operating costs.

Three additional caveats were noted: the "extra" €200 M figure was uncertain in part because the infrastructure costs of the low-frequency array could be lower. A benign RFI environment was of greater importance for the low-frequency array than at higher frequencies. Finally, it was realised there might be scientific ramifications to decoupling the locations of the low and mid-frequency telescopes for transient source investigations, but this would need to be studied. Not mentioned in the SSEC document was an additional, industrial ramification - the 'winning' site(s) would become the default suppliers of infrastructure works.

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[8] hba.skao.int/SKAMEM-96 *Report on SKA Infrastructure Development*, SKA Memo 96, SKA Program Development Office Infrastructure Tiger Team, 19 September 2007

### 8.3.3 SKA Siting Group, October 2009–March 2011 and how the Funding Agencies Took Ownership of the Selection Process

In its meeting in July 2009,[9] the ASG recognised it would need to drive discussions on defining a process for site selection discussion as this was a clear 'threshold issue' for progress with the project.

This came to pass in October 2009[10] when the ASG joined the battle with all guns blazing. John Womersley (ASG chair, STFC, UK) made it clear to a joint meeting of the ASG and SSEC that site selection was an area where both groups needed to work together closely to agree on the selection processes and their milestones. He noted that selection must be informed by a rational scientific/technical recommendation that would be incorporated into a wider and probably more political decision process. "With a well-defined process, the 'losers' should feel disappointed but not in any way cheated." (See comments in Box 8.1).

**Box 8.1 The Language of International Meetings**

Some thought was given to avoiding emotive terminology in international meetings on the SKA, not always with success.

Some examples

(i) In its August 2006 meeting to select the site short-list (see Sect. 7.3.8.2), ISSC members agreed to replace earlier use of "fatal flaw" by "disabling characteristic" to describe a characteristic that made it impossible to choose the site.

(ii) In preparation for the February 2006 Funding Agencies-ISSC meeting in The Hague, the ISSC used the neutral term "negotiation" to describe discussions following a ranking of acceptable sites (see Sect. 7.3.7.2. At the end of the Hague meeting, the chair of the Funding Agencies Group used the colourful term "blood on the floor" to describe the style of negotiation expected among the sites on a short-list (see Sects. 3.4.3 and 7.3.7.2).

(iii) Despite having effectively created a two-horse race to select the site in 2006 (see ii) above), the Agencies SKA Group (ASG), at its July 2009 meeting, disparaged "winner-loser" terminology in the 2009 SSEC document discussing possible outcomes of the site selection process (reference 1 below). The ASG noted that the use of the words "win" and

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[9] hba.skao.int/SKAHB-453 Minutes of the Agencies SKA Group Meeting (closed session), July 2009

[10] hba.skao.int/SKAHB-71 Minutes of the 3rd SSEC meeting, ASG report, October 2009

**Box 8.1** (continued)

"winner" in site discussions was not helpful, since it implied that there was a "loser" (reference 2 below). However, in what was no doubt a slip of the tongue, the ASG chair still used the word "loser" in remarks about site selection outcomes at the subsequent ASG meeting in October 2009 reference 3 below).

References

1. hba.skao.int/SKAHB-451 *On the Selection of the Site for the SKA*, SSEC, paper for the 3rd SSEC Meeting, June 2009
2. hba.skao.int/SKAHB-453 Minutes of the ASG meeting, July 2009
3. hba.skao.int/SKAHB-454 Minutes of the ASG meeting, October 2009

Vernon Pankonin (US National Science Foundation) outlined the first thoughts on an ASG-SSEC working group for SKA Siting based on information from the European Spallation Source (ESS) project. It was clear from the outset that this SKA Siting Group would define the site decision-making process but not make the decision itself.

The ASG felt that strong leadership of the site selection process was essential, co-chairs were to be avoided, and that the ASG should provide the chair.[11] This flowed from earlier internal discussions on governance and decision-making in the ASG where concern was expressed about a risk of conflict if the SSEC and ASG had different ideas about the evolution of the current governance towards the final governance and decision-making in the SKA program. The ASG concluded that the roles and responsibilities in the (evolution) process should be explicitly agreed with the SSEC, particularly with respect to long-term governance, project funding and the site selection process, all three of which the ASG felt were their responsibility.

Despite lingering concerns from some members of the SSEC (see Box 8.2) there was no argument from the SSEC as a whole on this score.

**Box 8.2 SSEC Thoughts on Site Selection Process**

**Ken Kellermann (National Radio Astronomy Observatory, USA), 1 February 2010, in a Memo to Vernon Pankonin and colleagues on the draft Terms of Reference for the SKA Siting Group** (see reference 1 below).

(continued)

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[11] hba.skao.int/SKAHB-454 Minutes of the Meeting of the Agencies SKA Group, October 2009

**Box 8.2** (continued)

'My biggest concern is that the choice of site for the SKA be made by the project on the basis of what is considered to be best for the SKA, and to the extent possible that we defuse any sense of a competition or contest between Australia and South Africa. . . . As I believe normal for activities of this kind, the project management (SSEC, ASG, and SPDO) should be responsible for acquiring all relevant data on site suitability, and not rely on reports, advertizing, or lobbying by the site proponents. We are not conducting a contest. Outside advice by experts experienced in various areas of site selection will be valuable and will be needed to inform the recommendation; but they should not make any recommendation or decision. The responsibility for a recommendation is with the SKA project which will have to live with it, and I do not believe that it will be appropriate to delegate this responsibility to an external group or to governments.'

**Michael Garrett, (ASTRON, The Netherlands) comments at an SSEC Executive Committee, March 2010** (see reference 2 below).

Garrett noted that the influence of the ASG on the site recommendation is a sensitive matter.

References

1. hba.skao.int/SKAHB-96 Kellermann, K., I., Comments on the Pankonin Committee Draft Terms of Reference for the SKA Siting Group
2. hba.skao.int/SKAHB-97 Garrett, M. A., Minutes of the SSEC Executive Committee, March 2010

In subsequent months, initial Terms of Reference for the SKA Siting Group[12] were drafted by Pankonin with feedback from Bernie Fanaroff (SKA South Africa), Martin Gallagher (Australian Government), Ken Kellermann (SSEC), Elena Righi-Steele (European Commission), Richard Schilizzi (SKA Director), and Yervant Terzian (SSEC) and discussed at some length in March and June 2010 in funding agency and SSEC meetings. The proposed membership structure caused little controversy, but this was not the case for the proposed objectives and working approach.

On membership, it would be a small group—the SKA Siting Group (SSG)—coordinating the process with equal representation, three each, from the ASG and the SSEC, the SKA Director as a non-voting adjunct member, and liaison contacts in both candidate site countries (see Box 8.3). Members of the SSG were to be

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[12] hba.skao.int/SKAHB-456 Terms of Reference for the SKA Siting Group (SSG), supporting paper for the fifth SSEC meeting, October 2010

acceptable to both candidate host countries, and countries directly involved with the two site proposals could not be SSG members.

**Box 8.3 SSG Membership**

***Agencies SKA Group**:* Simon Berry (Science and Technology Facilities Council, UK), Vernon Pankonin—Chair (National Science Foundation, USA), and Patricia Vogel (Netherlands Organisation for Scientific Research).

***SKA Science and Engineering Committee*****:** Russ Taylor (University of Calgary, Canada), Yervant Terzian (Cornell University, USA), and Anton Zensus (Max Planck Institute for Radioastronomy, Germany).

***Adjunct member*****:** Richard Schilizzi (SKA Director).

***Site Resource Liaisons*****:** Australia: Michelle Storey (CSIRO), Brian Boyle (CSIRO); South Africa: Bernard Fanaroff (SKA South Africa), Adrian Tiplady (SKA South Africa).

Argument did come from the SSEC at the March 2010 meeting on the objectives of the SSG (see Box 8.4), the fourth objective in particular. While there was no dispute that individual SSG members could not serve on both the body making the site recommendation and the one making the decision—put succinctly by Womersley as ‘It is not good practice for a body to make recommendations to itself’—there was dispute about the body to make the motivated recommendation. With the successful short-listing process managed by the ISSC in 2006 in mind, the SSEC had long thought it would assume a similar role in the final stage of site selection and argued for this against the alternative of the SSG or the SSG augmented by a ‘Site Evaluation Committee’ (SEC) whose members would be selected for their expertise and experience in selecting sites for international scientific facilities, in particular astronomy facilities, and for their independence from governmental bodies and from candidate site host countries. SSEC members and the SKA Director pointed out that the SSEC had greater knowledge and experience of the SKA than the SSG or SSG + SAC and should be responsible for the science and engineering recommendation.

**Box 8.4 SSG Objectives**

**Initial (October 2009)**

1. Establish a roadmap to site selection, and direct and oversee the implementation of the roadmap up to the issuance of the report and possible recommendation that is based on the comparative evaluation of the sites.
2. Establish scientific and technical criteria and more broadly based selection factors applicable to both sites to be used for identifying a preferred site,

(continued)

**Box 8.4** (continued)

and which are in the best interests of the SKA as an international scientific facility.

3. Provide direction and oversight for a contrast and compare analysis of the site relevant data and information, existing and updated, based on the agreed scientific and technical criteria and more broadly based selection factors and utilising appropriate methods of Multiple Criteria Decision Making.
4. Look towards making a recommendation on a preferred site based on the scientific and technical criteria and more broadly based selection factors and the analysis of the data and information. However, if the analysis does not support a motivated recommendation, present a comprehensive report that sets out the differences between the sites based on the scientific and technical criteria and the more broadly based selection factors.

**Revised (June 2010)**

1. Establish a roadmap to site selection and manage the implementation of this roadmap up to the issuance of a report and recommendation from the SSEC on the preferred site;
2. Establish scientific and technical criteria and non-scientific/technical criteria and selection factors applicable to both sites to be used for identifying a preferred site, and which are in the best interests of the SKA as an international scientific facility;
3. Provide oversight of the site selection evaluation which is to be managed by the SSEC; concurring with a plan prepared by the SSEC for the site evaluation prior to implementation, and receiving regular progress reports and the final report and recommendation from the SSEC; and
4. Validate adherence to the agreed site selection process and transmit the report and recommendation on the preferred site to the SKA governing organisation for the site decision.

After an evening's reflection, Pankonin and the ASG put two options to the SSEC: (1) the SSEC does not agree to a joint (with ASG) SSG. The SSEC would then be responsible for managing the site selection process, analysing the site characterisation data, and for making the recommendation on the preferred site. (2) The SSEC agrees to establish a joint SSG with the two objectives of establishing the roadmap for the site selection and establishing the scientific and technical criteria and more broadly-based selection factors to be used in a comparative analysis of the candidate sites. The SSEC would be responsible for analysing site data collected as part of PrepSKA WP3 activities and for making a motivated recommendation on the preferred site based on this analysis.

Not surprisingly, the SSEC accepted option 2 with an eye on the wider political picture of maintaining a positive and close relationship with the funding agencies. Revised objectives were agreed in June 2010[13] (see Box 8.4), one consequence of which was that the SSG would not itself originate or develop solutions for preferred sites for the SKA.

It was agreed that a mutually accepted "process" would be needed to get buy-in from all collaborators in an international project. Neither the project steering committee nor an informal group of funding agencies had any line management authority over individuals/organisations in the collaborating countries. Chief among the agreed guiding principles were:

- The primary interest of the SSG was to identify the most suitable site for the SKA as an international scientific facility;
- SSG members were to adhere to principles of fairness, impartiality, transparency and freedom from governmental influence in the site selection process in carrying out their work;
- There were to be no direct communications between the SSG and the candidate host countries, except through the designated Resource Liaison persons. Requests for data and information from both candidate host countries will be made through the SPDO;
- No direct communications between individual members of the SSG and representatives of the candidate host countries were to take place on siting matters; and
- The SSG was to inform the ASG and the SSEC of progress in the conduct of its business, and when appropriate, request direction and guidance.
- The SSG would convene an independent, expert Site Selection Advisory Committee (SSAC) to review the report and recommendation from the SSEC on the preferred site to ensure that the recommendation is appropriately motivated by the data and information available. Members of the SSAC would be appointed by the SSG, with nominations from the ASG and the SSEC and giving due consideration to representation over a global geographical distribution.
- The SSG will review the report for fairness, impartiality, transparency, freedom from government influence and compliance with agreed process, and forward it to the SKA governing organisation.

### 8.3.4 Site Evaluation Plan

All the discussion and planning in 2009 and 2010 had to be converted into action in 2011 in order to meet the goal of having a recommendation on the preferred site by early-2012. The site selection roadmap[14] set out a schedule for gathering information

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[13] hba.skao.int/SKAHB-103 Minutes of the 5th meeting of the SSEC, October 2010

[14] hba.skao.int/SKAHB-455 Baseline Roadmap for SKA Site Selection, supporting paper for the 6th SSEC Meeting, March 2011

from the candidate sites and evaluating their responses relating to the selection factors. Initial evaluations were to be prepared by expert panels, consultants and the SPDO, and then used by the SSEC to reach a motivated recommendation on the preferred site. The recommendation would be reviewed by the SSAC to confirm that it was appropriately motivated by the available data and information before going to the SKA legal entity for the decision.

Completing these activities by early-2012 turned out to be a very tight schedule due to a number of factors. There was a large amount of material to be assembled by the sites and assimilated and analysed by the reviewing bodies. Also, there had been delays in completing the analysis of the in-situ Radio Frequency Interference (RFI) measurements, and in installing the tropospheric monitoring equipment and carrying out what was a truncated measurement campaign (see Sect. 8.4).

The main tasks for the SSG[15] were: (i) to define the evaluation process, schedule, and selection factors and their weights; (ii) call for submissions from the sites; (iii) appoint expert panels and external consultants to evaluate the site responses on individual selection criteria; (iv) appoint the SSAC; (v) oversee the evaluations of the submissions by the independent experts, consultants, SPDO, SSEC and SSAC; and (vi) transmit the final recommendation to whichever formal entity was in place for the SKA in early 2012.

The main tasks for the SSEC set out in March 2011[16] were to evaluate the responses from the sites, provide a comprehensive report summarising their analysis of the differences between the two sites based on the agreed criteria, and make a motivated recommendation to the SSG on a preferred site by 31 December 2011.

### *8.3.5 Site Selection Factors and Weights*

The ASG and SSEC required that the scientific and technical selection criteria as well as the other non-scientific/technical criteria should be defined to not exclude a variety of solutions for a preferred site or sites for the SKA.[17] In other words, while maintaining the vision of a single-site for the SKA, the governing bodies did not want to exclude other options, a priori.

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[15] hba.skao.int/SKAHB-456 Terms of Reference for the SKA Siting Group (SSG), supporting paper for the 5th SSEC meeting, October 2010

[16] hba.skao.int/SKAHB-457 *Proposal for Evaluation of the Candidate Sites for the SKA* by the SSEC, R. T. Schilizzi, A.R. Taylor, Y. Terzian, A. Zensus, supporting paper for the 6th SSEC Meeting, March 2011.

[17] hba.skao.int/SKAHB-456 *Terms of Reference for the SKA Siting Group (SSG),* supporting paper for the 5th SSEC meeting, October 2010,

**Table 8.1** Initial and final SSG weights for the three main selection categories

| *Category* | *Initial Weight %* | *Final Weight %* |
|---|---|---|
| *A. Science and technical factors* | *60* | *75* |
| *B. Other selection factors* | *20* | *25* |
| *C. Implementation plans and costs* | *20* | *Not applicable* |

#### 8.3.5.1 Scientific and Technical Factors

Not surprisingly, the scientific and technical criteria mirrored those developed for the short-listing process 5 years earlier. Whereas consideration of other ‘political’ factors had been deferred in 2006, this time the other non-scientific and technical factors were specified in detail, and weights assigned after considerable discussion in the SSG. The Australian delegation to the ASG had a different view. They contended that the best way of distinguishing between the sites was to use selection factors most likely to discriminate between the sites rather than an ab-initio approach that included all potential selection factors required to enable ground-breaking science to be carried out, some of which were unlikely to be influential in making a choice because the sites were roughly equivalent. In that time of growing competition, the Australians would have considered that they would have a clear advantage in a small number of key criteria to be selected and given greater weight in the evaluation, one example being radio frequency interference. There was also the pragmatic consideration about the time required to prepare responses to all the selection factors of lesser importance.

In the end, the ab-initio approach was taken by the SSG with weights given to all relevant selection factors. But it is fair to say the details of selection factors and their weights caused heated discussion in the ASG and its successor in April 2011, the Founding Board.

#### 8.3.5.2 Other Non-scientific and Technical Factors

Early thoughts by the SSEC[18] on non-scientific and technical factors (originally called ‘indicative national attributes’) centred on topics such as

1. Political and economic structure and stability
2. Entry visas for all
3. Ease of government interactions
4. Import/export issues and taxes
5. Access for foreign companies
6. Land claims
7. General support of science and technology

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[18] hba.skao.int/SKAHB-103 Minutes of the 5th SSEC meeting, October 2010.

8. Academic astronomy population
9. Availability of engineers and technical personnel

These were eventually reformulated by the SSG to the five selection factors shown in Category B in Table 8.1 below.

#### 8.3.5.3 Cost Factors

Another contentious issue emerged in March 2011 after a draft version of the Request for Information had been circulated to the sites. This concerned how to evaluate the costs of locating and operating the telescope in each candidate country and whether they could be used to discriminate between the sites. The site countries contended they would not be able to generate detailed estimates for infrastructure development and operations costs in the relatively short time between the Request for Information and the deadline for submission of responses. And without the detailed information on infrastructure, it was not clear how much weight could be given to costs in the site evaluation. Complaints came from both sites about the competing demands on the site country resources as far as infrastructure was concerned, from the SPDO for relevant information affecting the telescope design being carried out in PrepSKA, and from the SSG for cost estimates. Added to this, the site countries had a legitimate grumble[19,20] that the site selection process had changed fundamentally from that originally planned in PrepSKA WP3. Site proponents were now responsible for information assembly for the Request for Information, cost estimation, and risk identification and that also put pressure on resources. Independent external consultants were originally identified for these tasks, but this was no longer affordable within the PrepSKA budget available to the SPDO.

These extra demands on resources reinforced the Australian concerns about the site selection approach. This led the Australian SSEC members, in a telephone meeting in January 2011,[21] to suggest that the SSG timeline was not feasible given the amount of work involved and the need to engage industry to carry out some of the tasks. They again advocated that the site evaluation should carry out more risk analysis and that key discriminators between the sites be identified. By this time, the SSG had identified “cost” as one of the three main selection factors, and under the pressure from the sites felt obliged to discuss whether the cost category should be abandoned altogether.

The concept of a host country premium was discussed by the SSG in the context of potential issues during the final negotiation with the successful candidate site, but not as an explicit selection factor in the evaluation phase.

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[19] hba.skao.int/SKAHB-103 Minutes of the 5th SSEC meeting, October 2010

[20] hba.skao.int/SKAHB-460 Minutes of the SSEC teleconference, January 2011

[21] hba.skao.int/SKAHB-460 Minutes of the SSEC teleconference, January 2011

### *8.3.6 SKA Siting Group in Action, April 2011–January 2012*

In the 10 days before the pivotal ASG-SSEC-Founding Board meetings in Rome from 29 March to 1 April 2011 (see Sect. 4.4.2), the SSG issued three crucial documents for discussion—the Request for Information from Candidate SKA Sites, Establishment of SKA Site Selection Factors and the Baseline Roadmap for SKA Site Selection. At the same time, an SSEC sub-committee comprising Schilizzi, Taylor, Terzian and Zensus issued a draft Proposal for Evaluation of the Candidate Sites for the SKA by the SSEC.[22] In Rome, the SSEC approved all three SSG documents in their meeting on 29 March, but there was considerable pushback from the candidate host site countries in the separate ASG meeting that led to an existential moment for the SSG and a major change in approach to evaluation of the site proposals.

At the ASG meeting,[23] both Australia and South Africa reiterated their concerns that the additional information being requested on implementation plans and costs placed too great an additional burden, in terms of resources and effort, on the host candidate sites. The Australian delegation also returned to its contention that there were other ways to distinguish between the sites.

The Australian delegation also felt they had not had sufficient time to consider the critical SSG documents in detail since delegates had been in transit when documents were circulated. They proposed a few weeks' delay to allow further consultation before final approval by the Founding Board. The South African delegation did not want a delay and were concerned that this could allow the host candidate sites to propose changing the weightings in their own favour. However, the ASG Chair, John Womersley, did allow a two-week delay for a review of the selection factors by the SSG after further consultation with the host candidate sites but he cautioned that it would be a concern if the selection outcome were to be finely tuned to the factor weightings. Specific instructions to the SSG were to review the selection plan with the aim of 'refining the process', increasing communication bandwidth, shortening the time to decision, and towards 'making all parties broadly content' with the process.

This approach was confirmed at the first meeting of the Founding Board on 2 April 2011. It was also noted that Pankonin had indicated he might wish to step down as Chair of the SSG given that the NSF would not be participating in the Pre-construction Phase and was not a member of the Founding Board.

Following these discussions and an ad-hoc meeting in Rome with the Site Liaison representatives, the SSG fundamentally revised its approach to the Site Evaluation Plan. After initially feeling that the ASG request to revise the approach was a vote of no confidence in the committee (which reinforced Pankonin's view that he should

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[22] hba.skao.int/SKAHB-457 *Proposal for Evaluation of the Candidate Sites for the SKA by the SSEC*, R. T. Schilizzi, A.R. Taylor, Y. Terzian, A. Zensus, supporting paper for the 6th SSEC Meeting, March 2011. See also Sect. 8.3.4.

[23] hba.skao.int/SKAHB-461 Minutes of the closed session of the Agencies SKA Group meeting, 30 March 2011

step down), the SSG moved on to critically re-examine all its previous work on defining the process to select the SKA site. Three potential paths forward were contemplated: (i) make minor adjustments to the path already set out in the Roadmap and Selection Factors documents, (ii) effectively abandon the process and turn site selection over immediately to political negotiation, and (iii), the middle way, substantially revise the activities and schedules in the Roadmap, but retain the information gathering and consultant analysis and follow the Selection Factors document with some revision. The SSG opted for the third alternative, recognising that the infrastructure and cost elements could not easily be compared and so these elements should be de-coupled from the science and technical factors.

The revised plan[24] recognised that the Founding Board and SSEC remained the authorities to oversee, jointly, the site selection process until the end of 2011 when the Board of the new legal entity would take over this responsibility. The plan proposed substantive changes to the process addressing three principal concerns:

1. ensure that the process retains the integrity of a technical and defensible assessment of the qualities of the candidate sites.
2. streamline the process and shorten the timeline proposed in the Baseline Roadmap; and
3. take account of the likelihood that SKA site selection would shortly enter a phase of turbulence in which high—level political and financial aspects would play a major role as well as considerations based on quantifiable technical, scientific, and other factors.

The SSG noted views expressed by the candidate sites in letters to Womersley[25] that the impact of the site characteristics on science capability was under-emphasised and that the approach to identifying plans for infrastructure implementation was not structured in a way that would deliver the desired optimised plans. The SSG reaffirmed its position that the science, technical and other selection factors must be uppermost in the evaluation to underpin negotiations in the political arena, while due consideration must also be given to an assessment of how the candidate sites plan to deliver basic infrastructure and cost of delivery since these aspects were essential to any evaluation. In particular, the SSG was still concerned that the candidate sites might shape their responses towards presenting implementation plans optimised for cost rather than scientific capability.

With this in mind, the SSG recognised that the original division of selection factors was not appropriate and that these planning-based elements should be a separate category of assessment since they were to be based on the Model of the SKA (see Sect. 8.3.7 on the Request for Information), rather than primarily on measurements and factual information. The information contained in the implementation plans and costs was regarded as very important to an informed decision on the preferred site. But the SSG noted that there would be relatively greater uncertainties

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[24] hba.skao.int/SKAHB-462 *A Revised Plan for SKA Site Selection*, SKA Siting Group, May 2011

[25] hba.skao.int/SKAHB-462 *A Revised Plan for SKA Site Selection*, SKA Siting Group, May 2011

**Table 8.2** Selection factors and weights, as set by the SSG

| Factor # | | Factor Name | Weight (%) |
|---|---|---|---|
| A | 1 | Ionospheric turbulence | 21 |
| | 2 | RFI measurements | 27 |
| | 3 | Radio quiet zone protection | |
| | 4 | Long-term RFI environment | |
| | 5 | Array science performance | 17 |
| | 6 | Physical characteristics of the sites | 5 |
| | 7 | Tropospheric turbulence | 5 |
| B | 8 | Political, socioeconomic, and financial | 2 |
| | 9 | Customs and excise | 6 |
| | 10 | Legal | 3 |
| | 11 | Security | 3 |
| | 12 | Employment | 6 |
| | 13 | Working and support environment | 5 |
| C | 14 | Provision and cost of infrastructure components based on the model of the SKA | N/A |
| | 15 | Provision and cost of internal and external data transport based on the model of the SKA | N/A |
| | 16 | Provision and cost of electrical power based on the model of the SKA | N/A |
| | 17 | Consolidated costs of capital and operations expenditures | N/A |

in the information on plans and costs than in the information for the Science and Technical factors and Other selection factors. This made it inappropriate to apply numerical comparison techniques based on weights to the plans and costs. In addition, the costs of the implementation plans at each site to the project were likely to be the subject of negotiations concerning additional host country contributions to the costs, otherwise known as “host country premiums” .

The revised weights proposed by the SSG were 75% for science and technical factors and 25% for other factors[26] (see Table 8.1). Implementation plans and costs were to be evaluated by external consultants in terms of their feasibility, achievability and risks, and no weights were assigned. Table 8.2 shows the detailed list of selection factors and weights[27] adopted by the Founding Board and SSEC.

A further recommendation by the SSG[28] was that an SKA Site Advisory Committee (SSAC) be charged with performing the assessment and evaluation of the data and information and with providing the motivated recommendation on a preferred site, rather than the SSEC. This was a major break with past practice established for the site short-listing in 2006 and the assumption in the intervening years.

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[26] hba.skao.int/SKAHB-462 *A Revised Plan for SKA Site Selection*, SKA Siting Group, May 2011

[27] hba.skao.int/SKAHB-463 *Report and Recommendation of the SKA Site Advisory Committee (SSAC)*, February 2012, Paper for the 4th Meeting of the SKAO Board of Directors, 19 March 2012

[28] hba.skao.int/SKAHB-462 *A Revised Plan for SKA Site Selection*, SKA Siting Group, May 2011

It reflected a concern that had been growing in the SSG over the preceding months that.

> it may be increasingly difficult for a stakeholder/user---representative group such as the SSEC to be engaged in the type of process we have initially proposed and that the current methodology places a difficult burden on SSEC members in their role of advising on the preferred site.

Put in other words, there was a concern that after so many years of interaction and consensus building on technology, science and site matters in the SSEC, it would be difficult for individual members to be completely independent in their evaluation. Removing the SSEC stage in the long line of evaluations also addressed the desire voiced by the ASG and Founding Board to reduce the time taken for the whole process, although this was not the major driver for the SSG proposal.

The SSEC did not strongly contest this development and, after South African fears had been assuaged that they were being “de-benefited”[29] by the attention paid to the Australian criticisms of the weighting of selection factors, the SSG revised plan was duly approved by the Founding Board and SSEC in May 2011. At the same time, the SSG mandate was reaffirmed and the Founding Board convinced Pankonin to carry on as Chair, to the good of the SKA project.

Following a careful selection process for the SSAC membership in the months that followed, a diverse group was appointed consisting of scientists, business executives, and experts on international science policy: James M. Moran, *Chair,* Subramaniam Ananthakrishnan, Jacob W.M. Baars, Jocelyn Bell Burnell, Willem N. Brouw, Ian Corbett, James Crocker, Thomas Garvin, Stefan Michalowski, Ernest R. Seaquist, Peter Tindemans, Jacqueline van Gorkom, and Roger J. Brissenden, *Executive Secretary.* Moran, Baars, Seaquist, and van Gorkum had been members of the International SKA Site Advisory Committee for the site short-listing process in 2006.

The SKA Site Advisory Committee was given its formal marching orders in its Terms of Reference (ToR).[30] These were to review the data and information obtained on the candidate sites, assess reports by expert panels and consultants, carry out an evaluation of the strengths and weaknesses of the sites, and formulate a recommendation on a preferred site for the SKA. The analysis and evaluation should be open to different site selection options if the data and information supported them. In keeping with the guiding principle of transparency of process, the SSAC was required to generate its own evaluation plan based on its ToR for approval by the Founding Board, SSEC, and the two sites. In particular, the SSAC was to determine the methodology for evaluating the selection factors and assessing the implementation plans and costs. The main aspects of this plan are described in Sect. 8.6.1.

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[29] hba.skao.int/SKAHB-464 Minutes of the Founding Board meeting, 20 May 2011

[30] hba.skao.int/SKAHB-463 *Attachment 2, Report and Recommendation of the SKA Site Advisory Committee (SSAC)*, February 2012, Paper for the 4th Meeting of the SKAO Board of Directors, 19 March 2012

### 8.3.7 *Request for Information from the Candidate SKA Sites*

The Request for Information was a major milestone in the life of the SKA project and was issued formally by the SKA Siting Group on 31 May 2011. As discussed above, in the interests of transparency, a draft had been sent earlier to Australia and South Africa for comment, and this had unforeseen consequences for the evaluation process in terms of how cost factors were approached. The Request for Information set out the schedule to site selection and the selection factors and included a Model for the SKA developed by the SPDO to serve as a benchmark for the information requested. The selection factor weights were not included as they were still under active discussion by the SSG and yet to be approved by the Founding Board and the SSEC. Approval was forthcoming a month later.

The Model of the SKA included all three receptor technologies then under consideration (dishes, low-frequency aperture arrays, and mid-frequency aperture arrays, see Fig. 8.2). A model rather than a final design was provided since the final size and scope of SKA Phase 2 was not scheduled to be decided until 2016. The Request for Information noted that despite this uncertainty, it was expected that infrastructure with similar characteristics and scale to the model of the SKA would be required for the “as-built” telescope. This included a core and the mid region out to 200 km as well as 25 stations, each containing multiple antennas of all three receptor technologies, distributed over a distance of *at least* 3000 km.

Site-specific configurations were developed by the SPDO in conjunction with the candidate sites (see Sect. 8.4.4), but these had not been published at the time the

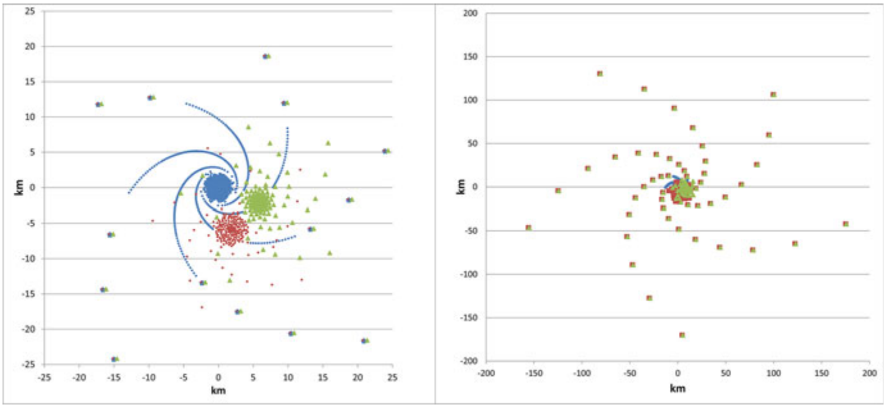

**Fig. 8.2** Generic array configurations for SKA at distances out to 25 km from the core (left) and 180 km from the core (right). The three separate colours in the left panel represent the dish array (blue), the low-frequency aperture array (red) and the mid-frequency aperture array (green). On the expanded scale shown in the left panel, the cores for each receptor type are separated as are the “remote” receptor stations on the spiral arms. On the scale shown in the right panel, the three central arrays are superimposed on each other in the centre of the diagram, and each dot in the spiral arms marks the location of the remote stations for all three receptor types

Request for Information was released on 31 May 2011 due to delays in reaching agreement on the methodology for generation of RFI mask constraints by the candidate sites.[31] Within a distance of 180 km from the core centre (core, inner and mid zones) they were similar to the generic configuration, but account had been taken in each Candidate Site country of specific constraints from the terrain and requirements to protect against radio frequency interference. The Request for Information noted that the site-specific configurations were to be used where required in the responses to questions.

The Request for Information noted that selection factors and broader implementation plans had been chosen that were likely to (i) differentiate between the sites, (ii) have a major impact on the cost or performance of the SKA, and (iii) could be assessed objectively.

#### 8.3.7.1 Science and Technical Selection Factors

Information requested was:

1. *Physical characteristics of the sites* likely to affect the system design and influence the capital and operating costs, and performance of the telescope. This included (a) environmental parameters such as temperature, humidity, rainfall, wind, and solar radiation, potential hazards such as wildfires, and seismic activity, as well as restrictions due to indigenous use, ownership, or customs; (b) geotechnical information on sub-surface strata and temperatures and water table; and (c) severe weather events.
2. *Radio Frequency Interference (RFI) environment (current and long-term) and Radio Quiet Zone (RQZ) protection.* RFI measurements were carried out by site staff according to an agreed protocol using identical equipment at the same time in each array centre, and separately at four remote stations that had been chosen as examples of likely interference environments (see Sect. 8.4.2). ASTRON in The Netherlands was responsible for data analysis. For the RQZ, a report covering all aspects of its establishment including technical properties such as frequency range and allowed emission levels; timeline for RQZ establishment; applicable legislation; spectrum management regime; plans and prospects for the establishment of radio protection zones around remote stations, and spectrum usage both current and future.
3. *Ionospheric and tropospheric characteristics.* Desk studies of the ionospheric characteristics of the two sites carried out during the short-listing process in 2006 were updated. Described in Sect. 8.4.3, special purpose interferometers to monitor tropospheric opacity were acquired from the NASA Jet Propulsion Laboratory and installed at each site in 2011 after considerable delay. This meant only a

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[31] hba.skao.int/SKAHB-466 Minutes of the 6th SSEC Meeting, WP3 Report, R. Schilizzi, March 2011

truncated measurement campaign was possible before the SSAC began its evaluation.

4. *Array science performance and associated figures of merit.* A three-stage process was originally envisaged for the evaluation of the performance of an SKA located in either candidate site for typical observations to be carried out by the telescope. Stage 1 defined the 'ideal' or generic configuration for the SKA from image processing and other considerations. Stage 2 adjusted the generic configuration to take account of specific constraints ("masks") for each site country and iterate using a cost model for the infrastructure to optimise the configuration in terms of Figures of Merit.[32] Chief among the Figures of Merit adopted for evaluating the configurations were (1) UVGAP and PSFRMS which together measure how well the array configuration simulates a completely filled aperture whose diameter is equivalent to the largest separation of receptors in the array, and (2) Electro-Magnetic Interference risk. Stage 3 foresaw simulations by the science community being carried out using the optimised array configuration to show the proposed science case was feasible. In the end, there was insufficient time to assemble the required resources for this final stage without delaying the agreed site decision timescale, and evaluation of the performance of each array was made in terms of the Figures of Merit.

The candidate sites were expected to provide information on the physical characteristics of the sites, and on RQZ protection in item 2 in the form of separate reports. As part of PrepSKA Work Package 3 on Site Characterisation (see Sect. 4.4.1 and Sect. 8.4.2), the SPDO was to provide reports on the RFI measurements (item 2), the ionospheric and tropospheric turbulence (item 3), and the array science performance (item 4). External consultants were to contribute to reports on ionospheric scintillation (item 3), and the long-term RFI environment (item 2).

#### 8.3.7.2 Other Selection Factors

Information requested concerned:

1. *Political, Socio-Economic and Financial issues.* The chosen site country should be characterised by a stable, mature and transparent socio-economic and financial environment to manage the expected large transactions for the SKA with minimal risk and ensure the large investment in the SKA delivers the best possible science. The candidate site had to provide an outline of the political, socio-economic and financial situation of their country and also of any other countries which had agreed to host remote stations as part of the SKA facility.
2. *Customs and Excise.* The Request for Information noted that the SKA is a global mega-science project involving scientific institutes and industry from many

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[32] hba.skao.int/SKAHB-467 *Figures of Merit for SKA configuration analysis*, R. P. Millenaar, R. C. Bolton, 7 December 2010, Paper for the 7th Meeting of the SSEC, July 2011

countries around the world, and the importance of prompt movement of goods, products and materials in and out of the Candidate Site country and countries hosting the remote stations. The sites had to supply information on the intended taxation and duty status to be afforded to the SKA organisation and its employees during the lifetime of the project as well as any import/export restrictions.

3. *Legal issues.* The Request for Information noted that the global SKA Organisation will be responsible for the construction, operation, verification and decommissioning of the SKA facility in the host country and in other countries where remote stations will be located and will be operational in multiple jurisdictions. Any legal Issues that may affect the construction and operations of the SKA in the countries that will host the core and remote SKA stations were to be described.
4. *Security issues.* Candidate sites were expected to describe their plans for achieving a secure construction and operating site and a secure near-site housing compound for the operations and maintenance staff.
5. *Employment.* Information was to be provided on issues that related to the recruitment of international and domestic staff and the resulting cost of that plan during construction and operation of SKA, as well as any relevant legislation or regulations that the SKA organisation would need to follow.
6. *Working and support environment.* The Request for Information noted that a critical element in the success of the SKA would be the attractiveness of the working and living environment for an international and well-educated staff, and availability of skilled local workforce. This included the ability of staff to find secure, good quality housing and healthcare, provision for schooling, and acceptable transport and communications links to the rest of the world. Information addressing these issues was required.

It is interesting to note that industrial support and capability was not included in the list of other selection factors despite the availability of the SPDO-developed capability survey tool mentioned in Sect. 10.9.1. The reasons for this omission are not clear.

#### 8.3.7.3 Implementation Plans and Costs

These were requested for:

1. *Basic infrastructure components* such as roads, buildings, airstrip, dish foundations, aperture array site preparation;
2. *Electrical power*—provision for generation, transmission and distribution, rollout schedule, operations plan, capital costs, and indicative operations costs for 30 years; and
3. *Data transport*—provision of connectivity from receptors to data processor, processor to super-computer centre, and super-computer centre to data centres in other parts of the world, and capital cost of implementing and commissioning these networks as well as operational costs of running the networks both for the central area of the array and remote stations.

### *8.3.8 Responses to the Request for Information*

Australia-New Zealand[33] (A-NZ) and Southern Africa[34] provided reports before the mid-September deadline on all these points apart from the RFI measurements, the ionospheric and tropospheric turbulence, and the array science performance which were the responsibility of the SPDO. External consultants contributed to the report on ionospheric scintillation, and another external consultant provided a report on expected developments in the long-term RFI environment.

The volume of paperwork delivered by the sites was substantial, 1134 pages in the case of A-NZ, and 21,328 in the case of Southern Africa. The larger volume of appendices and pages in the Southern Africa response related, in part, to the provision of comparable documentation for each of the six partner countries providing the most distant stations in the SKA Phase 2 array. A further 6346 pages of reports came from the SPDO and expert panels and consultants (see Box 8.5) for the full list of reports).

The responses and reports were reviewed by Expert Panels, external consultants (see supplementary material SKASUP8–1[35] for a list of people involved), and the SPDO as part of the input to the evaluation process carried out by the SSAC in the last 2 months of 2011. We describe this after an interlude to review the additional site characterisation carried out as part of PrepSKA Work Package 3.

**Box 8.5 Reports Available to the SKA Site Advisory Committee, SKA Organisation Board of Directors and Members**

*Science and Technical Selection Factors*

1. *Ionospheric turbulence*
   Report by the SPDO incorporating reports by external consultants
2. *RFI measurement*
   SPDO reports
   Review and report by Expert Panel on RFI/Electro-magnetic Interference (EMI)
3. *Radio Quiet Zone protection*
   Reports from Candidate Sites
   Review and report by Expert Panel on RQZ/Regulatory Affairs
4. *Long term RFI environment*
   Report by external consultant

(continued)

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[33] hba.skao.int/SKAHB-484 *Australia-New Zealand SKA Coordination Committee, [Response to the] Request for Information from Candidate SKA Sites*, 15 September 2011

[34] hba.skao.int/SKAHB-482 *South African Response to the SSG Request for Information*, 15 September 2011

[35] hba.skao.int/SKASUP8-1 *Expert panels, consultants and advisory committees involved in the SKA site evaluation and selection*

**Box 8.5** (continued)

5. *Array science performance*
   Report by the SPDO on the Figures of Merit for the specific configurations at each candidate site
6. *Physical characteristics of the sites*
   Reports from Candidate Sites
   Review and report by SPDO
7. *Tropospheric turbulence*
   Interim and final reports by the SPDO
   Reviews and reports by Troposphere Expert Panel

*Other Selection Factors*

8. *Political, socio---economic and financial*
   Reports by Candidate Sites
   Review and report by SSAC
9. *Customs and Excise*
   Reports by Candidate Sites
   Review and report by external consultant
10. *Legal*
    Reports by Candidate Sites
    Review and report by external consultant
11. *Security*
    Reports by Candidate Sites
    Review and report by external consultant
12. *Employment*
    Reports by Candidate Sites
    Review and report by SSEC
13. *Working and support environment*
    Reports by Candidate Sites
    Review and report by SSEC

*Implementation Plans and Costs*

14. *Provision and cost of infrastructure components based on the Model of the SKA*
    Reports from Candidate Sites
    Review and report by external consultant
15. *Provision and cost of internal and external data transport based on the Model of the SKA*
    Reports from Candidate Sites
    Review and report by external consultant

(continued)

**Box 8.5** (continued)

16. *Provision and cost of electrical power based on the Model of the SKA*

    Reports from Candidate Sites
    Review and report by external consultant

17. *Consolidated costs of capital and operations expenditure*

    Report by SPDO
    Review by SSAC

## 8.4 Site Characterisation

### *8.4.1 Expected Outcomes*

During the site short-listing exercise, a certain amount of site characterisation (see Sect. 7.3.2) had been carried out at the four contending sites, primarily in-situ measurements of the RFI environment and desk-top studies of the ionospheric conditions affecting low-frequency observations. A more in-depth characterisation of the Australian and Southern African sites was an obvious element to include in PrepSKA Work Package 3. SSEC member, Jill Tarter, noted that “The RFI environment is potentially a political hot potato if we do not appear to have exercised due diligence in carrying out RFI measurements to International Telecommunication Union levels”.[36] This appeared relatively straightforward in prospect in 2007. But the reality was one of initially ambitious in-situ RFI and tropospheric monitoring plans being reduced in scope as delays in delivering hardware and software manifested themselves, exacerbated by a clash in priorities between the SKA site selection schedule and local precursor infrastructure construction plans.

Four expected outcomes of the PrepSKA Work package 3 were identified at the start:

1. (a) Statements on the current levels of RFI in the candidate countries, (b) the measures taken at government and local level to protect radio astronomy measurements with the SKA at each site, and (c) the sustainability of the sites for science on the long term in the face of potential RFI threats;
2. A statement on the effects of ionospheric and tropospheric turbulence on measurements with the SKA at each site;
3. An optimum array configuration for the SKA in each location, consistent with the science case;
4. Statements on the potential influences of the physical characteristics of each site on the telescope design, operations and costs, and the infrastructure deployment costs and timescales, and operational models for each site.

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[36] hba.skao.int/SKAHB-63 Minutes of the 17th ISSC Meeting, March 2007

A Site Characterisation Working Group (SCWG) , led by SKA Site Engineer, Rob Millenaar (ASTRON, The Netherlands), was formed to coordinate the work, replacing the Site Evaluation Working Group led by Yervant Terizan. Members came from the two candidate sites, the ASTRON institute, the chairs of the SPDO Simulations and Operations Working Groups, and other experts involved in site characterisation. The SPDO Project Engineer and SKA Director were ex-officio members of the SCWG (see Box 8.6). A number of SCWG Task Forces were also formed to advise the SCWG, and the project as a whole, on RFI Monitoring, Radio Quiet Zones and Regulatory Issues, and Array Configurations.

**Box 8.6 Site Characterisation Working Group**
Albert-Jan Boonstra (ASTRON), Brian Boyle (CSIRO), Peter Dewdney (SPDO, ex-officio), Bernie Fanaroff (SKA SA), Rob Millenaar (chair, SPDO), Richard Schilizzi, (SPDO, ex-officio), Michelle Storey (CSIRO), Adrian Tiplady (SKA SA), Yervant Terzian (vice-chair, Cornell University).

### *8.4.2 Radio Frequency Interference Measurements*

A detailed Memorandum of Agreement on Radio Frequency Interference (RFI) Monitoring, 2008–2011[37] (MoA) was signed in April 2008 by Brian Boyle (CSIRO ATNF), Bernie Fanaroff (National Research Foundation, South Africa), Michael Garrett (ASTRON, Netherlands Institute for Radio Astronomy), Richard Schilizzi (SPDO), and Philip Diamond (University of Manchester acting as legal entity representing the SPDO). The parties agreed to carry out a campaign of monitoring RFI at the two candidate SKA sites, both in the core sites and at representative remote stations, with the prime objective of informing the decision on site selection. They further agreed to accept the outcomes of the campaign as being the result of an open and fair process.

Key to the planned campaign was that measurements take place with identical hardware and control software and at the same time in the two candidate sites to ensure that solar cycle influences were the same for both locations. Carefully worded annexes were included in the MoA setting out agreed protocols for the measurement procedures, the monitoring campaign itself, instrumental and data requirements, and reporting. In 2008 when the MoA was signed, plans for MeerKAT and ASKAP were well underway and potential interference from construction activities in the core of each site was noted as a real possibility. The Measurement Plan attempted to provide a work-around for this, but delays in delivery of the hardware led to a clash of national versus international priorities that became a major limit on the success of the RFI campaign. A truncated set of measurements was all that was possible.

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[37] hba.skao.int/SKAHB-468 Agreement on Radio Frequency Interference (RFI) Monitoring, 2008–2011, March 2008

Another understanding among parties to the MoA was that the remote sites chosen for monitoring would be representative locations selected on the basis of reference configurations then under development by the SPDO Working Groups for the SKA in Australia and in Southern Africa. The remote sites would not be monitored to same level of sensitivity as the core sites since the former are less vulnerable to the effects of RFI. The remote locations were to be selected to allow investigation of Electro-magnetic Interference (EMI) from population centres, effects of terrain shielding and accuracy of propagation modelling for distant transmitters. There was no hint in 2008 that remote station RFI, in particular that from distant transmitters, would assume the importance it did 4 years later in the SKA Site Advisory Committee recommendation to the SKAO Board of Directors.

#### 8.4.2.1 The RFI Campaign as Planned

Development of hardware and software was expected to last 1 year and the actual RFI monitoring and initial data analysis a further year. The measurement plan foresaw high sensitivity measurements between 80 MHz and 2 GHz to International Telecommunications Union recommended levels (ITU-R RA.769 + 15 dB)[38] at the core sites for about 6 months, and a similar amount of time for the remote stations. Working to RA769 levels meant the sensitivity would be up to 10,000 times better than for the 2005–6 campaign. Six months were set aside to complete of the final data analysis and report in order to meet the March 2011 deadline. The MoA was modified in May 2009[39] to take account of the expected increased bandwidth of the spectrometer which allowed reduced measurement time for the same sensitivity. Fifteen weeks rather than the original 6 months was assigned to the monitoring campaign at the core sites, during which time precursor construction would be halted for all but 2 weeks.

#### 8.4.2.2 The RFI Campaign in Practice

The SPDO's role was one of coordination and supervision without any direct authority to influence national resource allocation and timescales. The SKA Site Engineer, Rob Millenaar, coordinated execution of the Instrumentation Plan including cross-calibration of the two sets of equipment to be used at the candidate locations, the RFI measurements themselves, and he supervised the reduction and analysis of the data and production of the final report.

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[38] *Protection criteria used for radioastronomical measurements*, ITU Recommendation RA769, https://www.itu.int/dms_pubrec/itu-r/rec/ra/R-REC-RA.769-1-199510-S!!PDF-E.pdf (accessed April 2022)

[39] hba.skao.int/SKAHB-469 *Supplementary Agreement on Radio Frequency Interference (RFI) Monitoring 2008–2011*, May 2009. The only version of this document available to the authors is a draft which does not include revised versions of the Annexes.

CSIRO ATNF was responsible for the design and assembly of a digital Fast Fourier Transform (FFT) spectrometer receiver system with which to measure the RFI environment. SKA South Africa (SKA SA) was responsible for the provision of two self-contained mobile monitoring systems to be deployed at the sites comprising radio frequency antennas and a trailer to house the electronics with its control software. Integration of the receiver system with the antennas and control software was to take place in South Africa. The design, testing and integration of these sub-systems took place on a best-efforts basis against mounting schedule pressure posed by the precursor construction deadlines, first for the MeerKAT precursor, KAT-7, in early-2010, and then delivery of the ASKAP antennas in September that same year. Despite the pressure, it is noteworthy that the collaboration to develop the RFI monitoring system remained collegial throughout.

Central to the Australian spectrometer design was a ROACH board developed by the SKA SA digital electronics team, led by Francois Kapp, as part of the CASPER collaboration (see Sect. 6.6.4.1). More than a year delay in the delivery of these boards to CSIRO had the consequence that spectrometers were delivered only in February 2010 to South Africa. A further delay of several months in South Africa was caused by the difficulty in achieving effective shielding of the trailer to reduce self-generated RFI to the levels required for the sensitive measurements of external RFI to be carried out.

The KAT-7 milestone had been passed by then, but the ASKAP deadline remained in force squeezing the time available for the RFI measurements. Postponement of the campaign until the end of the year after the ASKAP construction peak was unacceptable to the international project if the RFI results were to be available at the specified time in the site selection schedule. In the end, the simultaneous RFI campaign took place for only 4 weeks in August–September 2010, after agreement in the SSEC that the resulting reduced sensitivity to RFI was acceptable.

Remote station measurements were carried out in both countries almost a year later in mid-2011 (see Fig. 8.3) after a long period of internal discussion in South Africa on the locations for these measurements. Only 5 days of monitoring was needed per “remote” location to match the reduction in sensitivity adopted for the core location measurements.

ASTRON was responsible for the software to analyse the data, a non-trivial task. As with most software, delays were inevitable and, in the end, completion of the analysis and report in 2011 was on the critical path for the site selection process as a whole (see also Box 8.7).

### 8.4.3 Monitoring of Tropospheric Turbulence

Radio waves passing through the Earth’s atmosphere are affected by fluctuations in the distribution of neutral gas in the troposphere—water vapour in particular—that cause three effects, refraction, absorption and scattering of the radiation (Thompson et al., 2017). These effects degrade interferometric measurements of radio sources

**Fig. 8.3** (Left). Rob Millenaar standing in front of the RFI measurement station at Boolardy on Wajarri Yamaji Country in Western Australia (Credit: R.P. Millenaar, ASTRON, 2008). (Right) RFI measurement station in the Karoo Desert, South Africa (Credit: R.P. Millenaar, ASTRON, 2008)

including the quality of images and accuracy of radio source position measurements. Initially, the ISSC did not plan any direct measurements of tropospheric turbulence to investigate the sites' suitability for high frequency astronomical observations.[40] The prevailing view was that any such measurements would be useful only if carried out for several years to obtain statistically meaningful data, and that time was not available before the site decision in 2011. In any case, removal of tropospheric effects was possible using phase referencing to nearby calibrator sources.

This changed in April 2009 when the International Engineering Advisory Committee (IEAC, see Sect. 6.2.2.3) recommended that it would be prudent to carry out direct measurements for 1 year, particularly through the summer months, for sites expected to operate at frequencies up to 20 GHz. We note that the possibility of building SKA-high on a different, higher altitude site was not under discussion at this time. The NASA Jet Propulsion Laboratory (JPL) in the US was planning to manufacture a number of interferometric tropospheric phase monitoring systems designed by Larry D'Addario for its own projects (see Fig. 8.4 (upper panel), and two SKA systems were added on (at a cost of $130 k) in February 2010. However, the expected delivery date of August 2010 did not materialise, and this meant it was no longer possible to get the desired 1 year's worth of data, including the critical southern hemisphere summer months of December to March, before the site evaluation began in September 2011. The instrumentation arrived at the sites (see Fig. 8.4

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[40] hba.skao.int/SKAHB-129 Report by the ISSC Working Group on tropospheric site testing, Burke, B. F., Ekers, R. D., Kellermann, K. I., and Hall, P. J., Minutes of the 12th ISSC Meeting, July 2004.

**Fig. 8.4** (upper panel) Larry D’Addario adjusting a tropospheric monitoring antenna in a test installation on the roof of the Jet Propulsion Laboratory building in Pasadena, California, USA (credit: R.P. Millenaar, SPDO, 2010). (Lower left) One of the two elements of the tropospheric phase measurement interferometer deployed in the Karoo Desert, South Africa (credit: R.P. Millenaar, SPDO, 2011). (Lower right): One of the two elements of an identical interferometer deployed at Boolardy on Wajarri Yamaji Country in Western Australia (credit: R.P. Millenaar, SPDO, 2011)

lower left and right) in January 2011 but was not installed until March–April due, ostensibly, to lack of available local resources (see Box 8.7). Measurements at both sites were made for as long as possible before the deadline for reports to be received by the SSAC.[41] This amounted to 5 months (June to October 2011).

The results, such as they were, underwent analysis at the SPDO by Millenaar before evaluation by an expert panel in November and subsequently by the SSAC. However, this information had less influence than the RFI monitoring on the site recommendation by the SSAC, due to the relatively low weight (5%) given by the SSG to this selection factor.

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[41] One of the unexpected issues with the tropospheric monitoring equipment was that it had been designed for the northern hemisphere (specifically USA) satellite broadcasting environment and frequency usage. It took some time to find a usable satellite for the South African site.

**Box 8.7 Why Did the RFI and Tropospheric Measurement Campaigns Fall behind Schedule?**

Optimistic timescales for hardware design, development and testing of the RFI and tropospheric equipment and software came up against the hard deadline of SKA site selection and the hard deadlines set by the construction schedules for the national precursor telescopes, ASKAP and MeerKAT. Money was not the main issue, rather it was the collision of schedule deadlines and consequent lack of technical readiness (see Reference below).

Exacerbating the problem were resource availability and planning constraints that created considerable friction between the SPDO and the national projects during the PrepSKA era and contributed to the delays in completing the RFI and tropospheric equipment. The SPDO was aware that much was being asked of the Australian and South African teams but was frustrated that not only these groups but others in the global collaboration had not provided promised PrepSKA resources in a timely fashion for the international project.

*Reference:* Justin Jonas, priv. comm. to Richard Schilizzi, 26 January 2010.

### *8.4.4 Array Configuration Design: Buffer Zone Controversy*

Developing a realistic array configuration for each candidate site was a major challenge for the SPDO and the sites and led to an existential moment for the Southern African candidature in 2010.

A Configuration Task Force (CTF),[42] formed in 2009 and led by Millenaar, carried out simulations and optimisation of array configurations with the assistance of experts in the community. The aims were to establish configurations at each site for RFI studies as well as to carry out preliminary land acquisition studies, infrastructure planning and costing including data transport and power distribution. The strategy was to include placement constraints in the configuration software by means of "mask" information provided by the sites, and then search for allowable configurations that maximised the science capability and minimised infrastructure costs. A three-core site layout comprising dishes, dense aperture arrays and sparse aperture arrays, was adopted as the starting point (see Fig. 8.2).

The CTF generated configurations for the multiple cores, the intermediate region out to 180 km and remote stations out to 3000 km. There was at times lively debate among CTF about the array configuration of the core area for long baseline snapshot imaging and the need for redundant spacing of antennas in the core to facilitate

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[42] CTF members were Rob Millenaar (SPDO Site Engineer), Rosie Bolton (UCambridge), Anna Scaife (UCambridge), and Matthieu de Villiers (SKA South Africa). The remit of the CTF was to produce a 'configuration' for each candidate country that could be costed for infrastructure, to recommend the locations of remote stations for RFI testing, and to provide feedback to the science community on realistic configuration properties (filling factor, imaging dynamic range, etc).

calibration. Figures of Merit for the SKA configuration were initially discussed at a meeting of the CTF in Manchester in March 2009,[43] and used by the SPDO and the sites in 2010 to optimise the locations of the antennas.[44] The Figures of Merit were formally approved by the SSEC in 2011.[45] They[46] were UVGAP, EMI risk, PSFRMS (Point Spread Function Root Mean Square), sky visibility, UV coverage, and beam shape. All except EMI risk pertained to the theoretical ability of the array to perform the highest quality and most precise measurements of spectral line and continuum sources and pulsars. EMI risk was an additional Figure of Merit introduced to solve a particular problem, as we now describe.

Masks specifying "no-go" areas, or buffer zones, were generated by the sites for sources of EMI as well as geographic features following guidelines agreed by the SPDO and the candidate sites in December 2009. EMI masks indicated where levels of man-made but unintentional electromagnetic interference were too high for placing an antenna, e.g. roads, rail, and human settlements. Geographic no-go areas included bodies of water, rugged terrain, horizon limits and slopes. The EMI masks around farmsteads caused the greatest problem.

The specification adopted for farmsteads was based on CISPR[47] standards for radiated interference from devices including farm appliances and tools as well as vehicles and led to a buffer zone for acceptable levels of EMI for SKA stations of some 13.5 km in radius. This blocked out areas of the Karoo desert in South Africa to such an extent that an array configuration could not be generated for the candidate SKA site. The SKA Director came under pressure in May 2010 from some quarters to halt the site selection process on the basis that the mask issue for South Africa automatically disqualified their site, a "disabling characteristic" in site-shortlisting parlance.[48]

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[43] Australia was unable to send a delegate to the initial meeting due to other commitments (email from David DeBoer to Schilizzi and Millenaar on 14 March 2009) but was kept fully involved thereafter in the development of the Figures of Merit, as was South Africa.

[44] hba.skao.int/SKAHB-470 *Array Configurations for the SKA*, supporting paper for the Teleconference Meeting of the SSEC, July 2010

[45] hba.skao.int/SKAHB-471 Minutes of the 7th SSEC meeting, July 2011

[46] hba.skao.int/SKAHB-467 *Figures of Merit for SKA configuration analysis*, R. P. Millenaar, R. C. Bolton, December 2010, Paper for the 7th Meeting of the SSEC, July 2011.

[47] CISPR: Comité International Spécial des Perturbations Radio, or the International Special Committee for Radio Protection

[48] hba.skao.int/SKAHB-472 Minutes of the closed session of the Agencies SKA Group, June 2010.

The South African SKA Director, Bernie Fanaroff, voiced objections to the rationale and methodology followed for determining the EMI masks in emails to the Project Director and suggested an independent review addressing the South African concerns.[49,50] There was also concern in South Africa that funding for MeerKAT might dry up if the SKA site bid was disqualified.[51] Following a lengthy discussion,[52] the Executive Committee of the SSEC, on the SKA Director's recommendation,[53] invited a sub-group of the Site Characterisation Working Group's Task Force on Radio Quiet Zones and Regulatory Issues ("Review Committee") to review the process, sources of information, standards, models and specifications used to create the EMI masks. The Review Committee comprised Wim van Driel (France, Chair), Masatoshi Ohishi (Japan) and Tom Gergely (USA), all very experienced members of the radio astronomical community specialising in these issues.

While the Review Committee was carrying out its work, the ASG decided in June 2010[54] that both candidate sites would continue into the final evaluation in 2011 and that no individual selection criterion was to be used to eliminate a site from consideration before the final evaluation. The site selection process should proceed as planned with any emerging issues considered as metrics or Figures of Merit within the process. The ASG's decision did not obviate the need for the Review Committee's report since it needed to be established whether the appropriate process and mask sizes had been adopted in the first place.

A Figure of Merit for EMI risk was defined[55] in such a way that it increased the closer a potential interference source, such as a farmstead, is located to an antenna. This approach allowed configurations to be designed with antennas in areas that would otherwise would have been blocked by applying the agreed EMI buffer zones around potential interference sources.

This opened the way to generate a configuration for Southern Africa.

In its report,[56] the Review Committee concluded that the procedure to determine the size of the buffer zones was generally sound and in agreement with ITU recommendations and CISPR standards. However, they pointed out that there was considerable room for interpretation and so assumptions made when creating the masks might not be valid for the SKA. They recommended further study of the

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[49] hba.skao.int/SKAHB-473 B. Fanaroff, letter via email to R. Schilizzi, 19 April 2010

[50] hba.skao.int/SKAHB-474 B. Fanaroff, letter via email to R. Schilizzi, 4 May 2010

[51] J. Jonas, telephone conversation with R. Schilizzi, 14 May 2010

[52] hba.skao.int/SKAHB-475 Minutes of the SSEC Executive Committee Meeting on 21 May 2010

[53] hba.skao.int/SKAHB-476 *The problem concerning the EMI mask in South Africa*, SPDO, 19 May 2010, Paper for the meeting of the SSEC Executive Committee on 21 May 2010

[54] hba.skao.int/SKAHB-472 Minutes of the closed session of the Agencies SKA Group, June 2010

[55] hba.skao.int/SKAHB-467 *Figures of Merit for SKA configuration analysis*, R. P. Millenaar, R. C. Bolton, December 2010, Paper for the 7th Meeting of the SSEC, July 2011

[56] hba.skao.int/SKAHB-477 *Report of the Review Committee on EMI buffer zones for the Candidate SKA*, Paper for the Meeting of the SSEC Executive Committee, July 2010

CISPR standards particularly those relevant to wall attenuation and to the height of radiators used in propagation models, preferably supported by field measurements. These further studies, by the SPDO, led to a reduction of buffer zone radius from 13.5 to 10.5 km such that an antenna located less than 10.5 km from a farmstead would have a non-zero EMI risk. No field measurements were possible due to budget and time limitations.

Following the agreement on the way forward, two approaches on costing array configuration infrastructure were considered by the SSEC[57]: (i) Cost a single generic configuration for both candidate sites to provide relative costings for the two sites; or (ii) Cost an optimised array for each site. The optimised array configurations were generated after the weights for the selection criteria (EMI risk, science performance, and cost) were released by the SSG, and then costed by an external consultant.

There was insufficient money available under PrepSKA WP3 to pay for two costings for each approach, and so it was decided that only the optimised (most realistic) array for each candidate sites would be costed by an external consultant. Once the optimised configurations were available, a Tiger Team would carry out simulations of performance of the optimised configurations for a small number of representative radio sources. The optimised configurations were to be ready by November or December 2010 so that the infrastructure costing could be completed by March 2011.[58]

Millenaar and Rosie Bolton (University of Cambridge) visited both countries to assist local experts[59] in designing site-specific SKA Phase 2 array configurations using the generic configuration (see Sect. 8.3.7) as a starting point for the inner 180 km and using the agreed Figures of Merit (Australia, July 2010 and South Africa, September 2010)[60,61]. These configurations included cores for each of the three antenna technologies and adhered to mask constraints but with the agreed, modified treatment of the EMI masks for farmhouses. The locations of the remote stations took account of the availability of land, access and possibilities for connection to infrastructure (fibre, power, roads), minimisation of impact of RFI originating from licensed transmitters (broadcasting, mobile communication), and in Australia the avoidance of severe weather systems in the north and north-west of the country.[62] For the analysis, the maximum baselines were limited to 3000 km for both candidate sites. Additions of stations in New Zealand and further north in the African

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[57] hba.skao.int/SKAHB-478 Minutes of the SSEC teleconference, July 2010

[58] hba.skao.int/SKAHB-478 Minutes of the SSEC teleconference, July 2010

[59] In Australia: Steven Tingay, Simon Johnston and Martin Russell. In South Africa: Adrian Tiplady, George Nicholson, Alex. Fortescue, and Mathieu de Villiers

[60] hba.skao.int/SKAHB-479 *Report on Configuration Task Force visit to Australia*, R. Millenaar and R. Bolton, July 2010

[61] hba.skao.int/SKAHB-480 *Report on Configuration Task Force visit to South Africa*, R. Millenaar and R. Bolton, September 2010

[62] hba.skao.int/SKAHB-481 ***Array** configurations for candidate SKA sites: design and analysis,* R. P. Millenaar, R. Bolton and J. Lazio, November 2011, a report prepared for the SKA Siting Group and the SKA Site Advisory Committee (see Box 8.5).

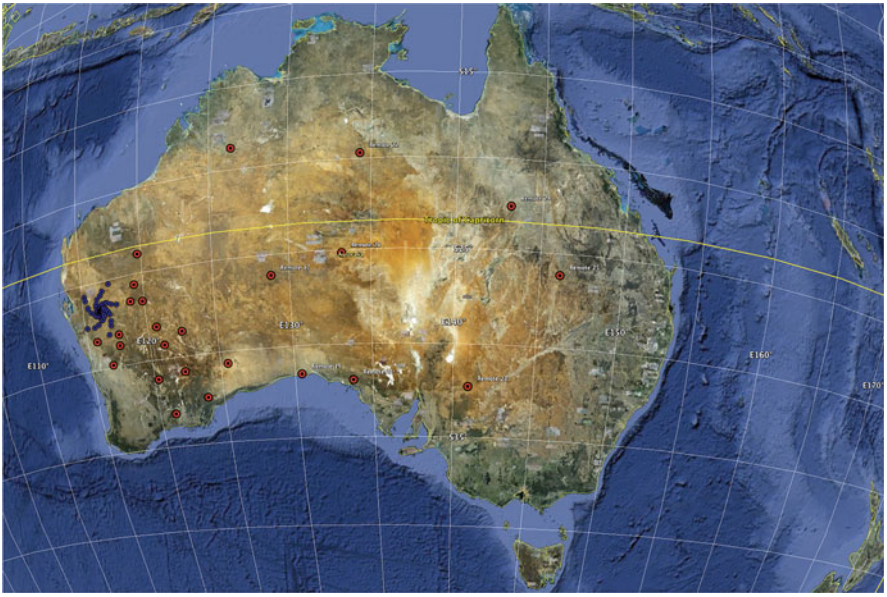

**Fig. 8.5** The SKA array configuration proposed by Australia-New Zealand in 2011 in response to the Request for Information by the SKA Siting Group. The blue dots represent the core and mid regions of the array out to 180 km from the centre of the core, the red dots represent the locations of the remote stations provided in the A-NZ proposal. The white grid is 5 degrees on a side, corresponding to a fixed N-S length of 560 km and an E-W dimension (which varies with latitude) of 510 km along the Tropic of Capricorn (yellow line). (Credit: Fig. 6 in R. P. Millenaar, R. Bolton and J. Lazio, *Array configurations for candidate SKA sites: design and analysis,* 2011, report to the SSG and SSAC, hba.skao.int/SKAHB-481)

continent were not considered in the configuration design but noted as possible locations for an "extended configuration".

Further array optimisation was expected after release of the selection factor weights (EMI risk, science performance, and cost) and costing by an external consultant. In the event, the release of the selection factor weights was delayed until May 2011, as we discuss below, which only left time for costing of the infrastructure as part of each site submission and not by an external consultant.

Figures 8.5 and 8.6 show the configurations for Australia-New Zealand (A-NZ) and Southern Africa submitted on 15 September 2011 as part of the responses to the Request for Information. In A-NZ's case this included minor revisions compared with the July 2010 version.[63] These concerned relatively small changes to the locations of the remote stations to better match the expected availability of optical fibre and road connections. Both adhered to the SSG requirement in the Request for

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[63] These revisions were carried out by Lisa Harvey-Smith (CSIRO, Australia).

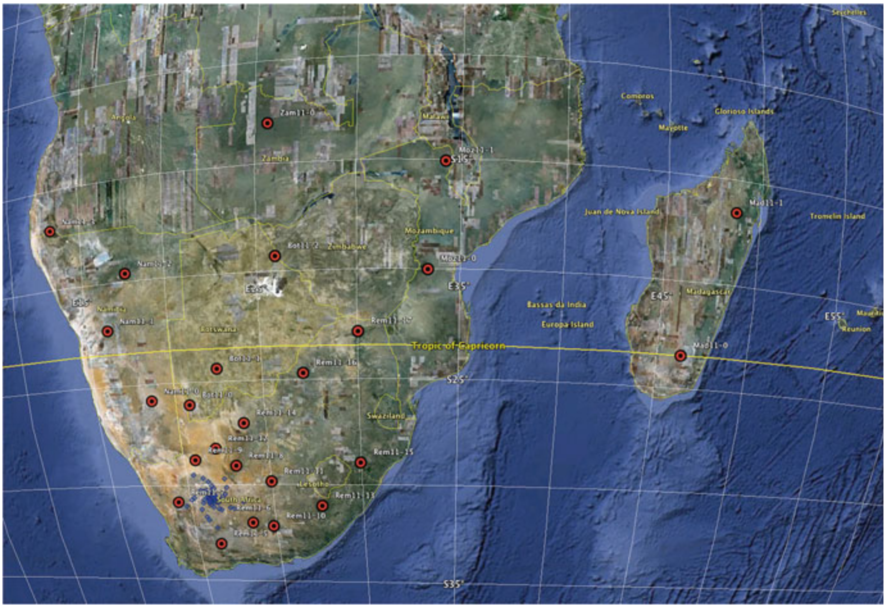

**Fig. 8.6** The SKA array configuration included by Southern Africa in their proposal in 2011. The blue dots represent the core and mid regions of the array out to 180 km from the centre of the core, the red dots represent the locations of the remote stations provided in the Southern Africa proposal. The white grid is 5 degrees on a side, corresponding to a fixed N-S length of 560 km and an E-W dimension (which varies with latitude) of 510 km along the Tropic of Capricorn (yellow line). The Google map coverage in the background was incomplete at the time the diagram was prepared in 2011. (Credit: South African Radio Astronomy Observatory)

Information for baseline lengths of at least 3000 km, if only in the E-W direction (see discussion of this point in Sect. 8.6.3.1).

## 8.5 Site Selection Politics

The SKA was a sufficiently large project concept that, not surprisingly, the site competition attracted the attention of the national and local governments of the potential host countries in both the short-listing (2002–2006) and decision (2006–2012) stages.

This began in China in 1994 with senior astronomers enlisting support from the Governor of Guizhou Province where the Large Telescope would be located. This led 5 years later to initial funding from the national Ministry of Science and

Technology and the Chinese Academy of Sciences for the FAST project[64] in 1999 (see Sect. 3.2.6.2). In Australia, the national government first was made aware of the SKA concept in 1996 via its participation in the OECD Mega-Science Forum (see Sect. 3.2.6.3). This was followed in 1998 by a presentation by Ekers to the Prime Minister's Science, Engineering and Innovation Council chaired by the Prime Minister, and in the early 2000s by active involvement and funding relating to the site bid from the government of Western Australia where the central SKA site would be located. In South Africa, the national government had included astronomy as one of its priorities in the 1990s. President Thabo Mbeki voiced his support for South Africa's bid for the SKA site in the Executive Summary of the 2005 proposal, and support also came from the Northern Cape Provincial Government, the proposed location for the SKA core (see Sect. 3.3.3.7). In Argentina, the national Secretary of State for Science and the Governor of San Juan Province where the core site for the SKA was to be located were active supporters of the 2005 site bid.

At the time of the site short-listing in 2006 and for 2 or 3 years thereafter, the entire global community expected Australia to eventually win the site competition by virtue of its excellent site credentials and its long history as a world-leading country in radio astronomy. In consequence, there was little external political activity to promote their sites on the part of Australia and South Africa. But as time went on, South Africa and Australia adopted different strategies to influence the outcome of the decision-making process while at the same time collaborating in establishing the site selection process described earlier in the Chapter, and fulfilling their responsibilities in PrepSKA Work Package 3 program on Site Characterisation.

South Africa played a low-key long game, bolstered by their confidence that they had built up a good team from the local high-tech and defence industries to design and construct the MeerKAT precursor. Their campaign aimed to turn their inexperience to an advantage by collaborating as much as possible with international SKA partners. This was led by a belief that the longer the site selection process continued before a decision was taken, the more they would benefit from increased expertise, publicity and political support nationally and internationally.

On the political side, the Heads of State and Government of the African Union adopted a Declaration at their 2010 Assembly 'expressing the African Union's unequivocal support for South Africa to lead the bid to locate the SKA in Africa.

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[64] Later in the life of the FAST project (2012–2014), one of the senior astronomers leading the project, Bo Peng, was appointed a vice-governor in Qiannan Prefecture in Guizhou Province to coordinate the FAST construction and local social development which resulted in the Astronomy Town not far from the observatory, He also took the opportunity to establish new astronomy departments in three universities of Guizhou Province. Later, in 2018, Peng was appointed Deputy Director of the Science and Technology Department of the Guizhou provincial government to coordinate science and technology in Guizhou making use of opportunities provided by FAST and SKA, particularly in the field of Big Data.

This Declaration also committed Africa to participate in the global SKA project, and the SKA is recognised as a flagship project by the African Ministerial Council on Science and Technology'.[65]

The Australian approach to the international site politics reflected their confidence that they had the better site and better support structure for a project of the scale of SKA. This became apparent at the 2010 International SKA Forum meeting on 15 June in Assen, The Netherlands where the Ministers of Science from both Australia and South Africa were present. Presentations by the Australian speakers in the plenary session appeared to have been choreographed at government level, more in the style of a bid for the Olympic Games than for part of a scientific project. Considerable emphasis was placed on their view that an Australia-New Zealand site for the SKA would "maximise science" compared to Southern Africa. This message was at odds with the overall atmosphere of global collaboration in SKA that had been emphasised by the South African speakers at the Forum, and it engendered an adverse reaction among many in the audience.[66] It is worth noting that the Forum took place the day following the meeting of the Agencies SKA Group (ASG) where the decision had been made to allow Southern Africa to continue its bid for the site despite the geographic mask issue described earlier in Sect. 8.4.4.

Also interesting to note is that the Australia-New Zealand response to the Request for Information in September 2011 (see Sect. 8.3.8) was formally submitted by the Prime Ministers of Australia and New Zealand, Julia Gillard and John Key respectively, and the Premier of the State of Western Australia, Colin Barnett.[67] In contrast, the Southern African response was submitted by the SKA SA Director, Bernie Fanaroff, and SKA SA Alternate Resource Liaison (to the SSG), Adrian Tiplady.[68]

Lobbying by both countries at top governmental levels took place in 2010 and 2011 during international summit meetings and individual visits to other countries involved in SKA. One example of the latter was the USA. Senior government officials and scientists from Australia and South Africa visited the Office of Science and Technology Policy and the State Department. Prior to visits in 2011 both these government departments requested briefs from the National Science Foundation (NSF) with regard to the NSF's position on US involvement with SKA. If the USA were to become involved in funding for the SKA, the NSF would most likely be the cognisant funding agency. The NSF/USA maintained a neutral stance on the siting issue.

The European view was seen to be critical due to its large presence in the SKA. European Union Development Funds to help enable African countries build strong

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[65] hba.skao.int/SKAHB-482 *Preface to South African Response to the SSG Request for Information*, 15 September 2011

[66] Justin Jonas, private communication to Richard Schilizzi, 19 June 2017.

[67] hba.skao.int/SKAHB-484 *Australia-New Zealand SKA Coordination Committee, [Response to the] Request for Information from Candidate SKA Sites*, 15 September 2011

[68] hba.skao.int/SKAHB-482 *South African Response to the SSG Request for Information*, 15 September 2011

science and engineering foundations and power economic development were a source of concern for Australia as there was suspicion that support for siting SKA in Southern Africa would intensify to satisfy geo-political goals. At university level in Europe, radio astronomy programs emerged with the broad aim of promoting physics in the developing world including the African continent. Bernie Fanaroff played the "developing nations" card successfully in several talks in Europe about Southern Africa's participation and aims in the SKA project. This led to disquiet from the Australian Government's perspective, one example being when Fanaroff was invited to give a talk at the University of Oxford in May 2010 by Steve Rawlings, Head of Astronomy, and PrepSKA Coordinator. From the Australian perspective this appeared to be a conflict of interest and required email confirmation from the Chairs of the PrepSKA Board and the ASG that there was no need for concern.[69]

## 8.6 Site Evaluation, Recommendation, and Final Site Decision

### *8.6.1 Evaluation*

Despite the volume of information supplied by the sites in response to the Request for Information far exceeding expectations, the SSG decided to distribute it all to the panels and consultants, with two exceptions. These were unrequested items, a "Motivated Alternative Configuration" from Australia-NZ, and an "Acquisition Differential Cost Report 2010" from Southern Africa. The former was extensive and provided cost and implementation plans for an alternative array configuration thought suitable for the SKA in Australia (with a remote telescope station in New Zealand) and thought to cost 50% less than the Model Array included in the Request for Information. The Acquisition Differential Cost Report provided a cost comparison carried out in 2010 by a global design, engineering and advisory company, Aurecon, of the proposed scenarios for the SKA project in Australia and Southern Africa. The major differences identified, all in Southern Africa's favour, were the power supply solutions for the remote stations and the core site, the location of the Processor Building and the extent of road upgrades and new roads required.

Following its Terms of Reference, the SSAC decided that in the interests of an equitable review both items fell outside the scope of the Request for Information[70,71] and were not considered (see Box 8.8).

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[69] hba.skao.int/SKAHB-485 Emails concerning the Fanaroff lecture at Oxford in May 2010. Note also that 3 years earlier Ekers had been invited by Rawlings in May 2007 to give the prestigious Halley Lecture in Oxford. This took place without objection from the South African Government.

[70] hba.skao.int/SKAHB-486 SSAC message to Australia via SSG and responses_23-25Nov 2011

[71] hba.skao.int/SKAHB-487 SSAC message to South Africa via SSG_23Nov2011

### Box 8.8 Site Submissions: Motivated Alternatives and Differential Costs

A fundamental principle of the SKA Siting Group's work was that it was to oversee a fair, impartial, and transparent selection process, free from governmental influence. To have allowed the A-NZ Motivated Alternative Configuration or the Acquisition Differential Cost Report from Southern Africa would have negated the the whole Request for Information process that had been agreed by both countries after exhaustive discussion. Neither addition was made known to the SSG or the competing site country before submission of the responses in September 2011.

On configurations, the Request for Information issued by the SSG stated that 'site-specific configurations have been developed by the SPDO in conjunction with the candidate sites, but these have not yet been published. Within a distance of 180 km (core, inner and mid zones), they are similar to the generic configuration described below, but account has been taken in each Candidate Site country of specific constraints from the terrain and requirements to protect against radio frequency interference. *The site-specific configurations should be used where required in the responses to questions in the Request for Information.*' (*Italics* inserted by the authors of this book.) The Alternative Motivated Configuration submitted by A-NZ was not one of the "site-specific configurations developed by the SPDO in conjunction with the Candidate Sites" and had not been discussed with the SSG or SPDO before submission.

Why the A-NZ leadership followed this route is not clear. A possible factor is that the site proposal was treated in Australia as a highly confidential document and had not been discussed extensively by the broader and very experienced community before submission. It may also reflect a view in Australia that a good solution for building the SKA was more important than the process, and an expectation that if the SSAC had seen the motivated alternative they would have been independent enough to evaluate it rather than the proposal that met the formal guidelines. The thinking may have gone that, after all, the SSAC was a committee of scientific and engineering experts, not international relations diplomats. In other words, the SSAC should have made a decision based on what the countries were capable of, not just on what was included in the compliant part of the proposal.

The Acquisition Differential Cost Report appeared to be an attempt by Southern Africa to influence the evaluation by the SSAC and could not be accepted by the SSG. The report reflected the view by the South African Government that Southern Africa would have an advantage over A-NZ where infrastructure capital and operations costs were concerned, a point emphasised by Minister Naledi Pandor in her speech at the July 2011 SKA Forum meeting in Banff, Canada.

(continued)

**Box 8.8** (continued)

'*In this regard, I should emphasize that the SKA will only progress if cost is recognized as a critical criterion, to be fully and appropriately taken into account for all important decisions related to the further development of the project. To pretend otherwise in a global economic environment marked by austerity measures and concern regarding cost overruns at other large-scale infrastructures, will neither be a realistic, nor a responsible approach, for any funding partner.*'

The expert panels, external consultants and SPDO analysed the information in the site responses in terms of strengths and weaknesses and provided written advice to the SSG which was then passed on to the SSAC. In a further step to ensure fairness, the assessments by the expert panels of the results from the RFI and tropospheric measurements were made on a "blind" basis, i.e. the country of origin of the information/data was not disclosed to the panel members. The SPDO also had an additional task of producing a report on the consolidated costs of capital and operations in which like-for-like cost estimates were assembled from the site submissions and analysed.

As set out by the SSG, the SSAC's over-arching task was to review the almost 30,000 pages of data and information obtained on the candidate sites, assess reports by expert panels and consultants, carry out an evaluation of the strengths and weaknesses of the sites, and formulate a recommendation on a preferred site for the SKA based only on the material with which it had been provided.[72] The analysis and evaluation was to be "open to a variety of site selection solutions, if the data and information provided to the SSAC support them".[73] This point had been transferred to the SSAC from the SSG's Terms of Reference[74] and recognised earlier discussions of a "win-win" solution in the SSEC and ASG/Founding Board.

Interactions of the SSAC with candidate site proponents, governments/government agencies, and other entities were carefully prescribed in the SSAC Terms of Reference to maintain an equitable, fair and transparent process, as had been the case in the shortlisting phase. No interactions between the SSAC and representatives of governments and/or government agencies on site-related issues for the SKA were permitted.

A non-voting Executive Secretary was appointed to facilitate the work of the SSAC while the SPDO was there to provide the technical secretariat in support of the committee's work, and consultation, but not advice, on technical issues as required. The SPDO also acted as the communication channel between the SSAC and the

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[72] hba.skao.int/SKAHB-463 SSAC Terms of Reference, Attachment 2—Report and Recommendation of the SKA Site Advisory Committee (SSAC), February 2012

[73] hba.skao.int/SKAHB-463 SSAC Terms of Reference, Attachment 2—Report and Recommendation of the SKA Site Advisory Committee (SSAC), February 2012

[74] hba.skao.int/SKAHB-456 Terms of Reference for the SKA Siting Group

**Fig. 8.7** The SKA Site Advisory Committee (SSAC) at its final meeting at Meudon Observatory in Paris in January 2012. Left to right: Wim Brouw, Tom Garvin, Peter Tindemans, Jocelyn Bell-Burnell, Stefan Michalowski, Jim Moran (Chair), Ian Corbett, Jacqueline van Gorkom, Jaap Baars, Jim Crocker, Subramaniam Ananthakrishnan, Roger Brissenden (Secretary). Not present: Ernie Seaquist. (Credit: Jaap Baars)

candidate sites with all communications copied to the SSG. Before commencing work, the SSAC set out a rigorous evaluation process, and an equally rigorous decision-making process. Decisions by consensus was the aim but, if that was not possible, a secret vote would follow. In the event of a tied vote, it was the responsibility of the Chair to steer the SSAC to a conclusion, rather than have the casting vote.

It was a mammoth task! At the start of the final stage of the SSAC evaluation in December 2011, members interviewed the site proponents to clarify issues that had arisen in their initial analysis. Subsequently, they evaluated the information, factor by factor, in a three-step process: (i) in-depth analysis by a small sub-group yielding a preliminary score for each site or a strengths and weaknesses analysis for Category C factors, (ii) discussion by the full SSAC (see Fig. 8.7), and (iii) agreement on a final score. Each SSAC member had 20 points to distribute between the two sites for each factor, with more points indicating an advantage.

In three of the seventeen factors, the SSAC, using its own expertise, felt it could improve on some of the findings or conclusions of the expert reports provided. These were Factor 2, RFI Measurements where they carried out an extended desktop study of the interference caused by remote transmitters, Factor 7, Tropospheric Turbulence, where they found an error in the analysis done by the expert panel and Factor 11, Security, where the SSAC disagreed with the SSEC sub-panel's judgement in several areas.

The SSAC did not consider any alternative solutions for the SKA project such as separate locations for the low- and mid-frequency arrays. It evaluated only the materials provided in response to the official Request for Information, and no attempt was made to suggest improvements in the proposed arrays, e.g., array configuration. Despite the somewhat ambiguous overall mandate from the SSG, the SSAC thought it was charged to make a firm recommendation on which site to choose from the two proposals, not to work out a grand compromise that made all parties happy.[75]

### *8.6.2 SSAC Recommendation*

In its report to the SSG,[76] the SSAC unanimously adopted the following consensus statement:

'The SSAC has determined that the SKA could be sited in either Australia/New Zealand or in southern Africa. The SSAC analyzed, evaluated, and scored the 13 Technical, Science, and Other Selection Factors using the Factor weights given. The outcome was in favor of southern Africa. The SSAC also evaluated the strengths and weaknesses of the four Implementation Plans and Costs Factors. This outcome was also in favor of southern Africa. Consequently, the SSAC recommends southern Africa as the preferred site.'

The SSAC noted that two factors drove the recommendation. *First*, the layout of remote stations, an important consideration in Factor 5 (Array Science Performance), was constrained by the geographic and other site-specific factors in both Australia and Southern Africa. The resulting array configuration was judged to be significantly better in the Southern Africa submission giving it both higher resolution in the North–South direction and better image dynamic range for short observations. As a footnote to the earlier controversy surrounding the non-zero EMI risk caused by farmhouses in the central area of the core site in the Karoo region in South Africa (see Sect. 8.4.4), the SSAC judged that the very small increase in system temperature of individual antennas would have very little impact on the science performance.

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[75] hba.skao.int/SKAHB-489 Comments on the SSAC and its work, J. M. Moran, email to R. T. Schilizzi, 12 April 2021

[76] hba.skao.int/SKAHB-463 Report and Recommendation of the SKA Site Advisory Committee (SSAC), February 2012

However, in reaching this decision the SSAC had not realised that the phased array transient science is far more sensitive to this EMI than the interferometric case they had considered.[77] *Second*, the provision and cost of 110 MW of electrical power (Factor 16) strongly favoured the Southern African proposal in the light of its existing power grid and lower generation and delivery costs.

Five of the seven Technical and Scientific Factors were judged to favour Southern Africa. In addition to array configuration, these were: the tropospheric turbulence (because of the higher elevations of the stations in the central region in South Africa), current and long-term RFI environments (based largely on the remote stations), and physical characteristics of the sites. The A-NZ site was judged to have an advantage in the Radio Quiet Zone protection Factor. With respect to ionospheric turbulence (Factor 1), which preferentially affects observations at lower frequencies, the SSAC did not find any significant difference between the sites, based on the data provided. All six of the Other Selection Factors favoured A-NZ. For the Southern Africa bid, much of the concern in these Other Factors derived from the difficulties of coordinating the laws and procedures among the six partner countries in Southern Africa, as well as the security and political challenges in the region.[78]

#### 8.6.2.1 How Robust Were these Conclusions?

The SSAC investigated the robustness of the final result to the scores for the Category A and B Factors by determining its sensitivity to a variety of tests. These included (1) censorship of data outliers; (2) a bootstrap or resampling analysis of all data; and (3) deletion of the scores of individual voting members, one at a time. In all of these tests, there was no significant variation in the result, allowing the SSAC to conclude that the final result obtained from the scores was significant and robust and not the consequence of some peculiarity of the voting procedure or voting body.

The SSG received the report on 16 February 2012, verified that the evaluation process had been carried out to its satisfaction, and transmitted the document the same day to the recently constituted SKA Organisation Board of Directors (see Sect. 4.7).

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[77] Moran, J. M., verbal communication to R. D. Ekers, April 2012

[78] hba.skao.int/SKAHB-463 Report and Recommendation of the SKA Site Advisory Committee (SSAC), February 2012.

## *8.6.3 Final Decision*

### 8.6.3.1 Stage 1: 16 February-3 April 2012

An earlier Board of Directors meeting in January 2012 had approved the sequence of steps leading to the final decision in a general Meeting of SKA Organisation Members, the official owners of the UK Company Limited by Guarantee. The Board became owner of the process after receiving the SSAC and SSG reports. Its first action was the formal consideration of these reports on the way to providing a commentary, including a recommended course of action, to the Members who would make the decision.

The SSAC recommendation that Southern Africa was preferred to Australia-New Zealand came as a bombshell to the members of the Board of Directors, many of whom had been involved in the project for many years. The Australia-New Zealand SKA Coordinating Committee reacted within days with a number of significant concerns with the SSAC report including the assessments for core and remote site RFI, array configuration, and implementation and cost factors.[79] There is every indication that the SSAC recommendation came as a surprise to the South Africans as well. However, they adapted quickly, and formally noted concerns that the agreed process should continue to be followed. In particular, they expressed the desire not to see the SSAC recommendation or the site selection process being unduly influenced by a potential host country. They did not question the SSAC conclusions that were not in their favour.[80] Behind the scenes, some senior South African scientists viewed the SSAC recommendation as a mandate to award their version of the SKA to Southern Africa, and that it was only fair to implement that outcome.[81]

A Board of Directors meeting on 22 February 2012 recognised that some of the concerns raised about the SSAC report deserved consideration to ensure the recommendation was well motivated. They resolved to invite the Chair of the SSAC to interact with the Board at its next meeting (see Fig. 8.8). Board member, Michael Garrett, noted that the SSAC report and recommendation provided an important input to the site decision but might not be the only consideration; all siting options would remain open to SKA Organisation Members to ensure the best possible outcome for the SKA.

In the run up to the next meeting on 19 March in Manchester (SKA-BRD-04), the Chair of the Board of Directors, John Womersley, contacted all Board members with

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[79] hba.skao.int/SKAHB-490 *A-NZSCC Response to SSAC Report*, 29Feb2012, Letter to SKAO Board of Directors Chair, John Womersley, for consideration at the 4th Meeting of the SKAO Board of Directors on 19 March 2012

[80] hba.skao.int/SKAHB-491 *South African response to the SSAC report and recommendation*, 29 February 2012, Letter to SKAO Board of Directors Chair, John Womersley, for consideration at the 4th Meeting of the SKAO Board of Directors on 19 March 2012

[81] hba.skao.int/SKAHB-492 Informal reactions to the SSAC report in Schilizzi, R. T., Notebook 16, 1 March 2012

**Fig. 8.8** SSAC members Jim Moran (Chair, second from left), Roger Brissenden (second from right) and Jocelyn Bell-Burnell (right), together with Vernon Pankonin (SSG Chair) at Mr. Thomas's Chop House, Manchester, before the SSAC presentation to the SKA Organisation Board of Directors, March 18, 2012. (Credit: Jim Moran)

a draft outline of a course of action to be recommended to the Members. The SKA-BRD-04 meeting turned out to be a pivotal event in the history of the SKA, and for many Board members at the time, an existential event. It was clear that the Australian delegation was preparing to fight hard to overturn the SSAC recommendation including diplomatic pressure brought to bear on SKA Organisation Member countries before the meeting. An informal meeting of Board Directors (without the Australian, New Zealand and South African representatives present) was held before the formal meeting to allow the remaining members to raise potential impediments to a consensus on the course of action. At the Board of Directors meeting itself, the Chair of the SSAC, Jim Moran, made a presentation on the SSAC's processes and report. He also responded directly to the A-NZ concerns, clarifying the approach taken by the SSAC in reaching their conclusions on the particular selection factors at issue.[82] In answer to a Board member's question on why A-NZ had submitted a telescope configuration in which the North-South distribution of remote stations did not take advantage of Tasmania as the southernmost location of the array, the Australian delegate noted that neither the fibre

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[82] hba.skao.int/SKAHB-493 Minutes of the 4th Meeting of the SKAO Board of Directors, 19 March 2012

connectivity with Tasmania nor the electro-magnetic compliance had been confirmed there until after the array configuration had been produced and submitted.[83]

A telling comment by Moran at the end of the discussion was that, overall, only a hypothetical change in the balance of total weights between selection factor Categories A and B (see Table 8.1) from 75:25 to 66:34 would have made the vote a tie.

The Board noted that both candidate sites were well suited to host the SKA, and that the SSAC report provided a comprehensive starting point for making a site decision. Despite there being questions about the treatment of data in some areas still unresolved to the satisfaction of all parties, the Board concluded that it would not recommend to SKA Organisation Members that the SSAC re-open or re-assess the input data or restart the SSAC process altogether. Board members felt that any such actions taken in response to the concerns of only one side ran the risk of introducing bias into an otherwise independent process, and even risk the viability of the SKA project as a whole.[84]

A carefully crafted Board Commentary[85] to Members, drafted by Womersley, noted four contentious issues in the SSAC report discussed in detail at the meeting but did not try to resolve them explicitly at that moment. Resolution of site selection issues was the purview of the Members rather than the Board of Directors, as set out in the SKAO Articles of Association.[86]

The first of these issues, and most contentious, was the difference in conclusions reached by the SSAC and the RFI Expert Panel on the RFI environment of remote sites. The SSAC conclusions were based on their internal desktop assessment of RFI using transmitter databases[87] despite the Expert Panel report giving more weight to the in-situ RFI measurements at a sample of representative remote station locations.

The wording actually used by the Expert Panel in an addendum to their report on 19 December 2011[88] to describe their position on desk-top assessments was:

> RFI predictions are only as good as the licensing database (and propagation prediction models) that go into them. Unfortunately, license databases are notoriously inaccurate, unreliable, and unsuitable for accurate predictions.

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[83] In hba.skao.int/SKAHB-481, the SPDO report on the analysis of the configurations for the SSG and SSAC by R. P. Millenaar, R. Bolton and J. Lazio, *Array configurations for candidate SKA sites: design and analysis,* November 2011, the other factor of importance limiting the north-south extension in Australia was the need to avoid locating remote stations in areas that could be affected by the severe weather systems in the north and north-west of the country (see also Sect. 8.4.4).

[84] hba.skao.int/SKAHB-494 Minutes of the closed session of the 4th SKAO Board of Directors Meeting, 19 March 2012

[85] hba.skao.int/SKAHB-495 Conclusions and Commentary from the 4th SKAO Board of Directors Meeting, 19 March 2012

[86] hba.skao.int/SKAHB-117 Articles of Association of the SKA Organisation, 2011, Article 44.3.

[87] hba.skao.int/SKAHB-496 *RFI Impact at Candidate SKA Remote Station Sites* (full edition), R. P. Millenaar, 15 November 2011.

[88] hba.skao.int/SKAHB-497 *Consideration of Predicted RFI at 25 Remote Sites Surrounding Each of the Two Candidate SKA Sites*, Report by Expert Panel on Radio Frequency Interference, 10 November 2011. Includes Addendum to the Report, 19 December 2011.

And the Panel's conclusion was succinct:

> The panel can make no meaningful conclusions about the relative suitability of the set of remote sites for the two candidate sites based on the RFI prediction studies.

These statements came with a caveat that this assessment was 'preliminary at best'. The Panel had had very little time before the final deadline for their report to analyse the much-delayed report from the SPDO on results from additional studies by both candidate sites to attempt to predict interference levels at 25 candidate remote sites surrounding each of the two candidate core sites. The delay was caused by the late submission of relevant information from Southern Africa due to difficulties in obtaining the transmitter details in some of the countries involved.

The second issue also concerned RFI. A new analysis by the SSAC, in which the RFI results were set to be exactly equal between the two sites, showed the overall evaluation outcome still favoured Southern Africa, but with reduced significance. However, the authors of this book note that RFI is a complex phenomenon and changes rapidly with time[89] so the attempt to quantify its impact on a future SKA was fraught with difficulty.

Thirdly, while the SSAC noted the possible advantages of certain design choices suggested within the Southern African submission concerning siting of the Science Data Processor that impacted the results of the analysis of implementation and cost factors, it felt it was outside the scope of the SSAC remit to consider the feasibility of such design options in Australia.

And finally, in a similar vein, there were a number of questions about the impact of the array configuration model set out in the Request for Information, but it was not within SSAC's remit to consider alternative configurations.

There was concern in the Board of Directors that it would be politically damaging, and a perceived waste of public investment already made, if either Australia or South Africa pulled out of the project. This led the Board to encourage the Members to consider scenarios that maximised scientific return from the investment made by both candidate sites, while also delivering what was best for the project. All Board members supported the views expressed in the commentary with the exception of the Australian delegate who abstained on instruction from the Government.

#### 8.6.3.2 Stage 2: 4 April-24 May 2012

The SKA Organisation's Members met for the first time on 3 April 2012 in Amsterdam 2 weeks after the Board of Directors meeting in Manchester. All but two of the Company Members sat on the Board of Directors as well (see Sect. 4.7), so they were well informed on the preceding discussions.

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[89] The recent deployment of very large constellations of low-Earth orbit communications satellites is a case in point.

The final week before the Members meeting had seen a flurry of activity including internal government-level discussions in the countries participating in the SKA project and letters at the end of March from both candidate sites to John Womersley as Chair of both the Board of Directors and SKA Organisation Members. The Australia-New Zealand letter reiterated their grievances about the selection process and the SSAC recommendation and was followed by a response from South Africa a day later stating the Southern Africa standpoint again that the selection process was sound and the SSAC recommendation should stand. These letters prompted Womersley to call SKAO Members in the non-site countries to gather their views about a possible route forward before informing Australian-New Zealand and South African delegates of the direction the wind was blowing.[90]

This resulted in a remarkable convergence of views on the way forward as the Members meeting unfolded.

Womersley opened the meeting with a set of comments to guide discussions on how to proceed towards the decision. Key to the direction of travel was the development of a solution that ‘built on the relative strengths of the two sites in order to maximise past investment and the potential for future investment by several highly committed governments’. To achieve this, he proposed to appoint a science-based Site Options Working Group (SOWG) to investigate the feasibility of a split-site implementation for the SKA. As Womersley recalled in 2020,[91] the points made in the pre-meeting discussions were: (i) a split-site decision is largely neutral in terms of science—both sites were good with no science benefits and no negative science impacts,[92] (ii) two sites may increase costs by 10%, (iii) a split-site decision keeps all the partners involved, hopefully bringing in more than 10% extra resources, iv) however, with a split-site decision there was real concern that the SKA might separate into independent Australian and South African telescopes, so it was important to keep the global vision of the SKA intact. European countries felt they could play a strong unifying role in this.

Such a recasting of the discussion, from a single-site to a dual site, is known in mega-project circles as “peripety” (Engwall & Westerling, 2001), a turn of events that reframes past understanding and opens a clear way forward (Smith & Winter, 2010) (see Text Box 8.9).

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[90] hba.skao.int/SKAHB-498 Womersley, J., email exchange with R. Schilizzi, 16, 17, 18 and 21 September 2020.

[91] hba.skao.int/SKAHB-498 Womersley, J., email exchange with R. Schilizzi, 16, 17, 18 and 21 September 2020. The authors note that another way of phrasing Womersley’s first point is that there would be no scientific advantage or disadvantage for a dual-site compared to a single-site.

[92] hba.skao.int/SKAHB-499 *The Science Implications of an SKA “Win-Win” Siting,* SKA Science Working Group, Supporting Paper for the 3rd Meeting of the SSEC, October 2009

**Box 8.9 Peripety (Crosby, 2012)**

The early stages of R&D (high-tech) projects are dominated by long periods of ambiguity where solutions (and even problems) are not clear and where change is incremental. There follows a short period of peripety, where one solution (or a set of solutions) becomes the obvious candidate as the legitimate path forward. Peripety is a turn of events leading to cognitive transition from ambiguousness into a less daunting state of uncertainty, often recalled as a time when real achievement occurred. It is not simply a change of fortune, but a change of understanding of all that has gone before.

In the discussion, one of the Member representatives reiterated the point that splitting the site would fundamentally change the nature of the SKA and introduce the risk of building two telescopes that did not significantly improve, at least in Phase 1, on the performance of current interferometers. Another felt that the vision of a single-site to host the SKA should be maintained, and that the "win-win" concept did not necessarily involve only a dual-site solution, a point made several years earlier and mentioned in Sect. 8.6.1. (Note the more positive tone of the "dual-site" nomenclature compared to "split-site". This was adopted by the SOWG when it began work). Michiel van Haarlem, Interim SKAO Director-General, emphasised that any dual-site options must be technically feasible and affordable. A decision based on a quick analysis of options could later turn out to be unaffordable which would lead to a de-scope of the project and science goals not being met. The Australian delegation supported the SOWG concept and a split-site option while the South Africans noted that the split-site option had earlier been found to have practical difficulties.[93] Clearly the Australian delegation was by now relieved by the proposed outcome, having realised that more support from European countries would not be forthcoming and this was the maximum that could be achieved at this stage. Majority opinion supported Womersley's proposal for the establishment of the SOWG, and it was adopted by the Members as a formal resolution.

### Site Options Working Group

SKA Organisation Members appointed SOWG members[94] (see *SKASUP8–1*) with a mandate to deliver their recommendations 'in the best interests of the Project in the widest sense' in 6 weeks' time. SOWG Chair was Paul Alexander (UK) while Justin Jonas (South Africa) and Phil Diamond (Australia) provided their respective national perspectives within the wider SOWG mandate. Melanie Johnston-Hollitt (New Zealand), Di Li (China) Luigina Feretti (Italy) and Michael Garrett (The Netherlands) provided independent views on the SOWG deliberations.

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[93] hba.skao.int/SKAHB-500 *On a split site solution for the SKA: A personal view*, Schilizzi, R. T., paper for the meeting of the SKA Founding Board and the SSEC in Banff, Canada, June 2011

[94] hba.skao.int/SKASUP8-1 *Expert panels, consultants and advisory committees involved in the SKA site evaluation and selection*

**Fig. 8.9** The Site Options Working Group listening intently to its Chair, Paul Alexander, at its meeting in Dwingeloo, The Netherlands. Left to right: Justin Jonas, Melanie Johnston-Hollitt, Michiel van Haarlem, Paul Alexander, Simon Berry, and Phil Diamond. Not present in the photo: Luigina Feretti, Michael Garrett (photographer), Joe Lazio and Di Li. (Credit: Michael Garrett)

SKA Organisation Interim Director-General, Michiel van Haarlem, and Project Scientist, Joe Lazio (Jet Propulsion "Laboartory", USA), provided the project perspective while Simon Berry (UK) was Convenor of the SOWG and functioned as its Secretary.

The SOWG met on five occasions during April and May 2012, twice face-to-face, in Manchester (UK) and Dwingeloo (NL) (see Fig. 8.9), and three times by videocon. Its task was to investigate whether viable dual-site implementation options existed for the SKA (Phases 1 and 2) and, if possible, present a preferred option. Any preferred option (or options) had to be financially viable and capable of delivering the SKA science case while making best use of the existing investments and characteristics of both sites. The SOWG was not tasked with, and did not consider, the question of whether dual-site options should be preferred to single-site implementations. Only scientific, technical, and programmatic issues, including cost and implementation risks were considered.[95,96]

The starting point for the SOWG was the work done by the SSAC and earlier work and discussions about implementation options in the SSEC and ASG. The SOWG did not attempt to re-review or re-do the evaluation undertaken by the SSAC. Three options were considered in their analysis: (i) a single-site to be used as a reference for comparison, (ii) two sites split along frequency lines: e.g. locate

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[95] hba.skao.int/SKAHB-501 *Final Report of the Site Options Working Group*, 25 May 2012

[96] hba.skao.int/SKAHB-502 Minutes of the Open Session of the 2nd meeting of SKAO Members, 25 May 2012

SKA-low on one site and SKA-mid on the other, and (iii) two sites split along functional lines, in other words telescopes optimised for different science programs, notably a survey-optimised telescope and a sensitivity-optimised telescope. As their report diplomatically stated, areas of national interest were raised during discussions and noted as such in the report. Also noted were conclusions reached by majority rather than full consensus.

The first SOWG meeting in Manchester set the scene for the following weeks of intense deliberation, negotiation and compromise, with all members, and particularly the site representatives, feeling the pressure of the moment engendered by the high stakes involved. This pressure was increased for Justin Jonas when the South African Minister for Science, Naledi Pandor, paid a brief unannounced visit to the meeting to wish the participants well. Initially all options remained on the table; however there was strong opposition from the Australian representative to the idea of a complete mid-frequency/low-frequency split between Southern Africa and Australia respectively since that would mean no SKA dishes in Australia. That was unacceptable in the light of the ASKAP investment in a dish array.

By the time of the second face-to-face meeting at ASTRON in Dwingeloo, there was general acceptance that the RFI environment at the Boolardy site in Western Australia was likely to be better than in the Karoo in South Africa. This favoured Australia for the low-frequency array and became the starting point for a two-site solution. What also became clear was that the Australian "red-line" of new SKA dishes to augment ASKAP had to be observed to achieve a settlement. The SOWG attempted to take the capital and operations cost estimates for the different options of telescope construction and infrastructure including power provision and fibre links into account, but the six-week deadline for their report precluded any detailed assembly of costs versus options, or a considered assessment of them. It was however clear that the power provision for the Karoo site was not sufficient for the foreseeable future to cope with both a mid-frequency and a low-frequency instrument simultaneously.

The SOWG report,[97] submitted on 21 May 2012, put forward three main conclusions: (1) A dual-site implementation with the two sites hosting different technologies operating at different frequencies, was capable of delivering the SKA Phase 2 science case. However, there was no scientific, technical, cost or operational advantage over a single-site implementation for doing so. (2) For SKA Phase 1, distinct advantages arose from incorporating the MeerKAT and ASKAP precursors and related infrastructure into the SKA in terms of increased scientific capability and the availability to the SKA project of an estimated total investment in excess of €300 M in the precursors. (3) Additional capital costs, as well as additional operating costs and programmatic risk would result from a dual-site implementation for either SKA Phase 1 or Phase 2.

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[97] hba.skao.int/SKAHB-501 *Final Report of the Site Options Working Group*, 25 May 2012

**Table 8.3** SOWG options for SKA Phase 2

| | SKA Element | Location |
|---|---|---|
| Low-frequency aperture array | SKA2_Low | A-NZ |
| Mid-frequency dish array | SKA2_Mid | Southern Africa |
| Mid-frequency aperture array | SKA2_AIP_Mid | Southern Africa or A-NZ |

Note: AIP stands for Advanced Instrumentation Program

In addition to these three conclusions, the SOWG made a key proposal to overcome the concern[98] that a dual-site solution may lead to two national telescopes. This was a proposal to introduce the concept of the "SKA Observatory" , a single facility that may have multiple locations. This became a fundamental pillar for the SKA and has remained a key unifying force in subsequent years: One Observatory—Two Telescopes—Three Sites, the third being the SKAO Headquarters in the UK.

### SKA Phase 2

The majority of the SOWG preferred a dual-site implementation for SKA Phase 2 that split the location of the three SKA elements on the basis of operating frequency. The SOWG thought it possible to distribute the elements—dish array, low-frequency aperture array and mid-frequency array—across the two sites without impact (positive or negative) on the science performance of the SKA. However, science delivery would be negatively impacted if any individual element was split across multiple sites. Table 8.3 shows their proposal.

A minority of the SOWG regarded any identification of a dual-site solution as premature.

These options for SKA Phase 2 were consistent with the detailed analysis presented in the SSAC report and, in particular, matched the mid-frequency capability to the Southern Africa site where the tropospheric stability is better. One caveat was that the mid-frequency aperture arrays were still to be evaluated as part of the Advanced Instrumentation Program, AIP, and their implementation was yet to be confirmed. A majority of the SOWG expressed a slight preference for co-locating SKA2_AIP_AA and SKA2_Mid_Dish (see Table 8.3) based on technical considerations, including the potential to cross-correlate dishes and mid-frequency aperture arrays. However, not identifying the location for the AIP component of SKA Phase 2 at this stage offered advantages in terms of risk mitigation.

A detailed assessment of the additional costs for a dual-site implementation for SKA Phase 2 could not be conducted by the SOWG in view of the six-week deadline for the report set by the Members. However, the dominant costs for each SKA element (low-frequency aperture array, mid-frequency dish array, and AIP, see Sect. 4.6.2) and the directly associated infrastructure appeared, at first sight, independent of the implementation. Retaining flexibility for the location of the AIP component offered risk mitigation advantages.

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[98] hba.skao.int/SKAHB-500 *On a split site solution for the SKA: A personal view*, Schilizzi, R. T., Paper for the meeting of the SKA Founding Board and the SSEC in Banff, Canada, June 2011.

**Table 8.4** SOWG options for SKA Phase 1

| | | Option A | Option B |
|---|---|---|---|
| Low-frequency aperture array | SKA1_Low | A-NZ | Southern Africa |
| Mid-frequency dish array | SKA1_Mid | Southern Africa | Southern Africa |
| Mid-frequency dish survey array | SKA1_AIP_Survey | A-NZ | A-NZ |

Note: AIP stands for Advanced Instrumentation Program

Apart from the capital investment and recurrent operating costs of power infrastructure that were substantially less for South Africa, the operation costs on the two sites were seen by the SSAC as 'virtually the same'. In addition to the site-specific cost differential, there would be increased infrastructure costs for a dual-site implementation compared to a single-site implementation, but these additional costs, while not insignificant, were likely to be less than the overall cost uncertainty for the SKA. The operational cost of a dual-site implementation would also be somewhat higher, but this was unavoidable.

### SKA Phase 1

For SKA Phase1, one of the SOWG's prime considerations was the potential re-use of existing precursor telescopes and associated infrastructure. It was clear that the SKA Low-Frequency Array would have to be built in its entirety, with only the fibre and power reticulation infrastructure reusable on each site. No re-use of the Murchison Wide-field Array, MWA, would be possible. For the mid-frequency dish array, the science requirements for SKA Phase 1 were predicated on an array of 250x15m SKA-designed dishes (see Sect. 6.4) which could be achieved by 190 SKA dishes plus the 64x13.5 m MeerKAT dishes. This left open the possibility of deploying the remaining 60 SKA dishes from the baseline design either in South Africa as MeerKAT+250 SKA dishes, or as a 'high speed survey instrument' in Australia comprising ASKAP+60 wide field of view Phased Array Feed-equipped SKA dishes. The SOWG preferred the latter alternative since it would provide a more powerful survey capability than in the then current science requirements and, in particular, would better address the neutral hydrogen in absorption science driver (see Sect. 5.10.1).

The SOWG came up with options for SKA Phase 1 as shown in Table 8.4.

Long discussion in the SOWG was not able to resolve the question of whether the adoption of a dual-site implementation option for SKA Phase 1 implied this option was preferred for SKA Phase 2. The SOWG saw no scientific or technical reason to link SKA Phase 1 and Phase 2.

The scene was thus set for the final scenes of the SKA site selection story, the second and third meetings of the SKA Organisation's Members on 25 May and 14 November 2012.

**Table 8.5** Proposed final allocation of SKA elements to candidate site countries for SKA Phase 1 and Phase 2 (reproduced with permission of the SKAO)

| Host Country/Countries | SKA Phase 1 | SKA Phase 2 |
|---|---|---|
| Australia | SKA1_AA_low<br>SKA1_Dish_survey | SKA2_AA_low |
| Southern Africa | SKA1_Dish_mid | SKA2_Dish_mid<br>SKA2_AA_mid |

Note 1:
Table 8.5 is presented in the format used in the 7 November 2012 Members' Resolution
Note 2:
AA stands for Aperture Array

#### 8.6.3.3 Stage 3: 25 May-14 November 2012

A few days prior to the meeting of Company Members on 25 May, John Womersley circulated a 'Statement from the Chair and Proposed Actions on 25 May' to the Members in which he laid out the options and issues confronting them. He noted that it was now time to take the decision on the site of both SKA Phase 1 and Phase 2 and concluded that 'the most viable route for the SKA project to succeed ultimately was for Members to agree a dual-site implementation model based on the Site Options Working Group's work'.

He noted that the SOWG had shown that 'a scientifically justified and technically and programmatically viable approach' to a dual-site solution was possible, and that this presented 'the best means of optimising the use of past and ongoing investment relevant to SKA'. It also offered a model that maximised 'the financial viability of the project in the longer term through continuation of the current Organisation membership, and a global character that will be attractive to future Members'.[99]

To focus minds, he proposed the implementation given in Table 8.5 which included selection of SOWG Option A for SKA Phase 1, and co-location of aperture arrays with dishes in Southern Africa for SKA Phase 2. No further expansion of the SKA-Dish Survey Array in Australia was proposed for Phase 2.

At the Members meeting, Paul Alexander set the context for the site selection discussion with a summary of the SOWG conclusions. Comments on this by SKAO Members generated three important clarifications underpinning the dual-site concept. The first was a confirmation that each telescope element in the baseline configuration for SKA Phase 1 would provide world-leading performance in its own right and would not simply be a prototype. The second was that delegates from both candidate sites agreed in principle with the concept of integrating their SKA precursors into the SKA Organisation. The third clarification was that both site infrastructures including the MeerKAT and ASKAP telescopes themselves would be recognised as in-kind contributions to the SKA project.

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[99] hba.skao.int/SKAHB-503 *Statement from the Chair*, J. Womersley, Supporting paper for the 2nd meeting of SKAO Members.

All Members were asked by Womersley to give their views on a dual-site solution as a starting point. As reported in the minutes of the meeting, the reactions of the non-site countries were mixed:

- Canada was comfortable with a dual-site solution and the SKA Observatory concept since that offered a long-term vision which would be applicable to future general science collaborations.
- China stated that the national observatory and astronomical community in China supported a single-site solution in order not to waste the work carried out since 2006 as part of the site selection process to identify a single host site. There was also concern that a dual-site implementation would increase project cost and make the SKA more complex to construct and operate.
- Italy's preference was for a single-site solution but would consider a dual-site solution if mutually agreeable.
- The Netherlands supported the dual-site option recognising that it would potentially increase global support for the project with the associated funding that was needed to cover the additional costs associated with the dual-site solution.
- The UK supported the dual-site implementation recognising the need for re-use of infrastructure in the short-term and the importance of making progress with decisions about SKA Phase 2.

In contrast the site contenders were largely supportive:

- The Australian Government stated it was prepared to incorporate its €100 million ASKAP investment into SKA. Concerning SKA Phase 2, it proposed deferral of the decision on the location of the mid-frequency aperture array in order to mitigate technology risk. The underlying implication was that the assignment of SKA Phase 2 technology to South Africa should be contingent on its performance in SKA Phase 1.
- New Zealand favoured option A (see Table 8.4) in a dual-site implementation for SKA Phase 1.
- South Africa also supported the dual-site implementation as a means of maximising investments made at the candidate sites. However, Members were urged to make a decision about both SKA Phase 1 and Phase 2 siting at this meeting and so keep to the agreed process.

In a subsequent session from which the site country delegates (AU, NZ and South Africa) were excluded, the remaining Members discussed the caveats included in the responses above from Australia and South Africa. Womersley noted that South Africa would not accept the Australian proposal for deferral of a decision on the division of site/technology for SKA Phase 2, as that would require a further site decision in a few years' time. As far as satisfactory performance in SKA Phase 1 as a prerequisite for assignment of a technology was concerned in Phase 2, there was general recognition that satisfactory performance in SKA Phase 1 would be a requirement for the implementation of *any* aspect of SKA Phase 2.

A majority of Members were in favour of a dual-site implementation based on Option A for SKA Phase 1 and an implementation for Phase 2 of the low-frequency

**Fig. 8.10** South African Minister of Science, Naledi Pandor, and Justin Jonas finalising the speech to be given by the Minister to coincide with the release of the press release on the site decision by the SKA Organisation's Members on 25 May 2012 (Credit: South African Radio Astronomy Observatory)

Aperture Array in Australia, and the mid-frequency aperture array and mid-frequency dish array in Southern Africa.

When delegates from the site countries returned to the meeting, the majority view supporting the site technology choice was a bitter pill for the Australian delegation to swallow, and a long conversation with the Minister by phone was required before this was accepted, and approval was given for public release of the Members statement (see Box 8.10).

An interesting insight into how high feelings were running on both sides is that before the Members meeting in Amsterdam, Justin Jonas composed a preliminary draft of the speech to be given in South Africa by Minister of Science, Naledi Pandor, to accompany the announcement of the dual-site decision at the end of the meeting. This was based on John Womersley's 'Statement from the Chair and Proposed Actions on 25 May' discussed above. The South African Department of Science and Technology (DST) rewrote the speech inserting criticism of the decision and this was distributed to journalists ahead of the speech. However, at the last minute, the Minister and Jonas rewrote the DST version restoring the diplomatic tone (see Fig. 8.10), which was delivered, to the initial confusion of the journalists.[100]

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[100] J. Jonas, private communication to R. Schilizzi, 19 June 2017.

### Box 8.10 Press Release from the Members of the SKA Company on 25 May 2012

**Dual site agreed for Square Kilometre Array telescope**

**25 May 2012, Amsterdam, the Netherlands**

The Members of the SKA Organisation today agreed on a dual-site solution for the Square Kilometre Array telescope, a crucial step towards building the world's largest and most sensitive radio telescope.

The ASKAP and MeerKAT precursor dishes will be incorporated into Phase I of the SKA which will deliver more science and will maximise on investments already made by both Australia and South Africa.

The majority of the Members were in favour of a dual-site implementation model for SKA. *The Members noted the report from the SKA Site Advisory Committee that both sites were well suited to hosting the SKA and that the report provided justification for the relative advantages and disadvantages of both locations, but that they identified Southern Africa as the preferred site. The Members also received advice from the working group set up to look at dual-site options.*

The majority of SKA dishes in Phase 1 will be built in South Africa, combined with MeerKAT. Further SKA dishes will be added to the ASKAP array in Australia. All the dishes and the mid frequency aperture arrays for Phase II of the SKA will be built in Southern Africa while the low-frequency aperture array antennas for Phase I and II will be built in Australia.

*"This hugely important step for the project allows us to progress the design and prepare for the construction phase of the telescope. The SKA will transform our view of the Universe; with it we will see back to the moments after the Big Bang and discover previously unexplored parts of the cosmos."* says Dr. Michiel van Haarlem, Interim Director General of the SKA Organisation.

The SKA will enable astronomers to glimpse the formation and evolution of the very first stars and galaxies after the Big Bang, investigate the nature of gravity, and possibly even discover life beyond Earth.

"Today we are a stage closer to achieving our goal of building the SKA. This position was reached after very careful consideration of information gathered from extensive investigations at both candidate sites," said Professor John Womersley, Chair of the SKA Board of Directors. "*I would like to thank all those involved in the site selection process for the tremendous work they have put in to enable us to reach this point."*

Factors taken into account during the site selection process included levels of radio frequency interference, the long term sustainability of a radio quiet zone, the physical characteristics of the site, long distance data network connectivity, the operating and infrastructure costs as well as the political and working environment.

(continued)

**Box 8.10** (continued)

The agreement was reached by the Members of the SKA Organisation who did not bid to host the SKA (Canada, China, Italy, the Netherlands and the United Kingdom). The *Office of the SKA Organisation will now lead a detailed definition period to clarify the implementation.*

Scientists and engineers from around the world, together with industry partners, are participating in the SKA project which is driving technology development in antennas, data transport, software and computing, and power. The influence of the SKA project extends beyond radio astronomy. The design, construction and operation of the SKA have the potential to impact skills development, employment and economic growth in science, engineering and associated industries, not only in the host countries but in all partner countries.

The final scene of the final act was the Members meeting held on 14 Nov 2012 at which the following Resolution on SKA site selection was adopted.

The Members of the SKA Noting:

A. The report and recommendation received from the SKA Site Advisory Committee (SSAC), dated 16 February 2012.
B. The report on the Validation of the SKA Site Selection Process received from the SKA Siting Group (SSG), dated 16 February 2012.
C. The report from the SKA Siting Options Working Group (SOWG) sent to the Members of the SKA Organisation on 21 May 2012
D. The process for selecting the SKA site, laid down in the Articles of Association of the SKA Organisation.

Resolve the following:

1. That the SKA will be built jointly in Australia and Southern Africa (South Africa with Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia, Zambia) (collectively referred to as the host countries) in Phase 1 and Phase 2 and will incorporate the SKA Precursors ASKAP and MeerKAT and related infrastructure on those sites respectively.
2. That instruments based on the different types of detector technologies will be built in the host countries according to the following breakdown:

| Host Country/Countries | SKA Phase 1 | SKA Phase 2 |
|---|---|---|
| Australia | SKA1_AA_low<br>SKA1_Dish_survey | SKA2_AA_low |
| Southern Africa | SKA1_Dish_mid | SKA2_Dish_mid<br>SKA2_AA_mid |

AA_low: the low-frequency aperture array, Dish_survey: the dish survey instrument equipped with phased array feeds, Dish_mid: the mid frequency dish array and

AA_mid: the mid frequency aperture array. The prefix SKA1 and SKA2 reflect the collecting area, baseline coverage and other technical specifications of SKA Phase 1 and Phase 2 as currently understood.

3. That consistent with good project management practice including validation of the implementation, cost and technological outcomes of Phase 1, satisfactory technical performance of SKA Phase 1 at both sites is expected for the implementation of the relevant SKA Phase 2 components as set out in the hosting allocation in the table above.
4. That all future decisions on construction depend on demonstrated progress of the design and financial viability of the construction and operational plans.
5. That the Members of the SKA Organisation will sign (initial) hosting agreements with Australia and South Africa as soon as possible and no later date than 31 March 2013 or a later date as decided by the Board of Directors of the SKA Organisation. These hosting agreements will as far as reasonably practicable be consistent for each site and ensure parity of treatment for each site.
6. The above resolutions constitute the Site Selection Decision for the purposes of Articles 44.3 and 46.1 of the Articles of Association.

## 8.7 Postscript

In the years since the site decision, the details of the 2012 site selection have come under scrutiny primarily as a result of more informed cost estimates for all aspects of the first phase of the project, SKA Phase 1. This has led to reductions in project scope, the major one of these being deferral of the Survey Telescope in Australia. The de-scoping exercise in 2014–5, called "re-baselining", aimed at matching estimated costs to a "cost-cap" of €650 M and led to a reduction of the number of SKA dishes to be deployed in South Africa from 190 to 133, and a reduction in the number of SKA Phase 1-Low antenna stations in Australia each with 256 dipole antennas from 1024 to 512. This left SKA Phase 1 with a substantial margin of improvement over existing telescopes in the same frequency ranges but not the original order-of-magnitude planned. None of the 60 SKA dishes with PAFs planned as part of SKA Phase 1-Survey survived the de-scope, although they are still formally on the books as a deferred element of SKA Phase 1.

The site hosting agreements with the SKAO took 10 years to develop, far longer than thought imaginable in 2012. Along the way, there were attempts on the part of both telescope site countries to operate as independently as possible of the central SKA Organisation, raising the old fears in some quarters that two national telescopes were being created with funding from countries around the world.

In the SKA Observatory/Inter-Governmental Organisation (IGO) era (see Sect. 4.7.4) the structure and responsibilities finally agreed for the relationships with the two telescope sites are as follows: (i) each country will host an engineering operations centre and a science operations centre, and (ii) the local organisation or "site entity" will manage the telescope operations and be responsible for the required land acquisition in the core areas and land lease arrangements. In Australia this is CSIRO and in South Africa the National Research Foundation.

At the time of writing, this structure will govern the interactions of the SKA Observatory with its telescope sites in the IGO era.

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# Chapter 9
# SKA Headquarters: Another Two-Stage Site Selection Tussle

## 9.1 Introduction

Establishment of the International SKA Project Office (ISPO) in August 2003 followed the appointment earlier that year of the International SKA Director, Richard Schilizzi. The ISPO was located at the Dwingeloo Observatory in the Netherlands, home of ASTRON and the Joint Institute for VLBI in Europe (JIVE) , both institutes where Schilizzi had worked. The original intention of the International SKA Steering Committee (ISSC) was that the Director should not be located at their home institute to avoid any perception of bias. However, it was soon recognised that was not a feasible requirement since the contract was for 2 years with the prospect of annual extensions thereafter, and this did not provide sufficient job security for a major change in circumstances. The ISPO remained in Dwingeloo.

Its staff grew slowly. Peter Hall was appointed the International SKA Project Engineer in 2004 on secondment from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Australia Telescope National Facility in Sydney where he continued to spend part of his time. Astrid Marx was appointed Office Manager in Dwingeloo on secondment from ASTRON, also in 2004. By April 2006, it had become clear to the ISSC that with the site short-listing decision imminent (see Chap. 7) and the telescope system design phase (see Chaps. 3, 4, and 6) planned to follow from 2008 to 2010, the project was entering a new phase[1] and the time had come to increase the ISPO staff numbers substantially to meet the needs for global project coordination. To start the process, funds were identified for an Executive Officer in Dwingeloo to support the ISSC and International SKA Forum[2] Secretariats and a system engineer to work with Hall for 1 year in Sydney. Of the two, only the Executive Officer post was filled, by Colin Greenwood, in mid-2007. This began

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[1] The Transition Era from 2006 to 2012 described in Chap. 4.

[2] International SKA Forum—see Sect. 4.2.1.

R. T. Schilizzi et al., *The Square Kilometre Array*, Historical & Cultural Astronomy,
https://doi.org/10.1007/978-3-031-51374-9_9

a long involvement with the SKA project by Greenwood which continues at the time of writing this book.

In parallel, the ISSC decided there should be a competitive selection round for the location of the ISPO and the larger number of staff members. The selection process took place in 2007 and was followed 4 years later with a second selection round in 2011 for the location of SKA Headquarters during the Pre-Construction Phase that was planned to start in 2012. We now describe the two competitions. Our primary source material has been SKA project documents and presentations[3,4] at the SKA History Conference in 2019.

## 9.2 The 2007 Selection

A Call for Expressions of Interest to host the ISPO[5] and its projected staff complement of twenty-eight was issued in May 2006 by the ISSC Chair, Phil Diamond. A budget of about €20 million for the four-year period from 2007–2010 was foreseen to be needed to support ISPO Central Design and Integration Team (CDIT) and overall project management activities. This was to be contributed primarily by the national funding agencies backing the institutes represented in the ISSC.

Responses came in July from ASTRON (The Netherlands), Cornell University (USA), the National Radio Astronomy Observatory (USA), the University of Manchester (UK), and the SKA South Africa Project Office. In reality, however, there was no prospect of obtaining the hoped-for €20 million in 2006 and the ISPO consolidation idea lapsed until early in 2007 when the European Commission Framework Program 7 (FP7) funding opportunity emerged for an SKA "Preparatory Phase", PrepSKA (see Sect. 4.4). This held out the prospect of funding for the CDIT activities for the expected 4 years of design and site characterisation.

The ISSC thought it essential to complete the selection of the headquarters location before the formal PrepSKA proposal was to be evaluated in late-June 2007. This prompted the new ISSC Chair, Brian Boyle, in March 2007, to invite proposals[6] to host the International Headquarters of the SKA Project with a deadline 6 weeks later. This call was issued after consultation with the Director and the sites that were expected to bid.[7] Box 9.1 sets out the selection criteria that were to be used.

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[3] hba.skao.int/SKAHB-505 *International SKA Project Office HQ selection in 2007*, A. Zensus, Presentation at the SKAHistory2019 Conference, 2019

[4] hba.skao.int/SKAHB-506 *SKAO HQ Selection in 2011*, S. Berry, Presentation at the SKAHistory2019 Conference, 2019

[5] hba.skao.int/SKAHB-507 *Call for Expressions of Interest in Hosting the International SKA Project Office*, ISSC, April 2006

[6] hba.skao.int/SKAHB-508 *Call for Proposals to Host the International SKA Project Office*, ISSC, 1 March 2007

[7] hba.skao.int/SKAHB-509 Minutes of the 17th meeting of the ISSC, March 2007. The Call for Proposals was issued before ISSC members had had time to approve it, in Brian Boyle's words "to

**Box 9.1 Selection criteria for the location of the SKA Headquarters, 2007**

1. An outstanding astronomy and engineering research environment
2. Appropriate office space and infrastructure including laboratory space for the proposed staffing level
3. The ability to establish a cost-effective financial structure for the office, including the ability to receive monies from the proposed FP7 preparatory study
4. The ability to establish an appropriate employment status for ISPO staff
5. The ability to establish a clear and distinct status for the ISPO within the host institution; and
6. Proximity to international travel hubs.

This time, responses came from ASTRON, The Netherlands, the University of Manchester, and the National Astronomy and Ionosphere Centre (NAIC) at Cornell University. Although the PrepSKA project was not yet funded there was a general assumption among ISSC members that it would be funded and would cover a major fraction of the ISPO cost, provided the office was located in Europe. This led NRAO to decide not to submit a proposal, but did not deter Cornell University. SKA South Africa decided it was not appropriate to bid for the headquarters location.

The ISSC appointed a Review Committee comprising three ISSC members: Brian Boyle (chair), Justin Jonas, and Anton Zensus, and two external members: Michael Grewing, a senior European astronomer and former Director of the Institut de RadioAstronomie Millimétrique (IRAM), and Ethan Schreier, a senior US astronomer and President of Associated Universities Incorporated (AUI), to evaluate the proposals. The Review Committee unanimously ranked the University of Manchester marginally ahead of ASTRON.[8] The Cornell proposal was ranked third mainly because of the financial risk relating to the uncertainty over PREPSKA funding for a non-European location for the ISPO.

The Review Committee report stressed that the Manchester and ASTRON proposals were very well matched, with the relative ranking strongly dependent on the weighting applied to the different selection criteria, estimated levels of risk associated with office construction activities, and to consideration of factors outside those listed under the essential selection criteria. They recommended that the ISSC open negotiations with the University of Manchester to host the ISPO but retain the option to open negotiations with ASTRON should issues emerge with the University of

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give proposers enough time to prepare". At the 17th ISSC meeting, Jill Tarter voiced unhappiness at this lack of consultation which in turn led Boyle at the end of the discussion to propose a motion to the ISSC that "The ISSC endorses the call for proposals but admonishes the chair for sending it out too soon.". The motion was carried unanimously!

[8] hba.skao.int/SKAHB-510 Summary of the ISSC Teleconference on 4 May 2007 on the Selection of the Host Institute for the ISPO. This document includes the Review Committee Report.

Manchester that would have influenced the relative rankings between ASTRON and Manchester.[9]

The ISSC teleconference to review the report and decide how to proceed was, unsurprisingly, contentious. Discussion centred on whether sufficient information had been supplied by the proposers on financial issues and infrastructure to be made available at the host location, as well as the relative weight of the selection criteria used and the potential political advantage in selecting one or the other of the top-ranked locations. The latter centred on the relative economic size of the UK and the Netherlands, and ability to lead funding efforts from a position of strength.

The ISSC voted on two motions, the first "The ISSC has sufficient information to make a decision on the host institute for the ISPO and to open negotiations with the first-ranked location", and second "the ISSC accepts the Selection Committee's ranking of potential host institutes for the ISPO and authorises the ISSC Chair to open negotiations with the University of Manchester. Both were carried by fifteen votes to two.[10]

In the event, a Memorandum of Understanding between the University of Manchester and the ISSC was agreed on 20 June 2007 and formally signed on 4 October 2007 (see Fig. 9.1). Two of the three ISPO officers[11] (Schilizzi and Greenwood) moved to the University of Manchester in early-2008 at the start of the new SSEC-SPDO era for the SKA.

In parallel with this, two further agreements were finalised in November 2007. The first was an International Collaboration Agreement between the European SKA Consortium, the US SKA Consortium, and the "Rest of The World" (see Sect. 4.4.2.1) to establish the SKA Science and Engineering Committee (SSEC) that would replace the ISSC in the PrepSKA era 2008–2011. The second was a related Memorandum of Agreement to establish the SKA Program Development Office (SPDO) to replace the ISPO in the PrepSKA era, signed by the "parent" legal entities for the two Consortia and the individual ISSC institutes in the Rest of the World.[12] This set out the roles and responsibilities for the SPDO.

The change from "Project" to "Program" in the SPDO name came about on request from the US delegate on the Funding Agencies Working Group, Vernon Pankonin. The US view of the SKA was as a collection of activities under a common umbrella for which "Program" was a more appropriate descriptor rather than a

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[9] hba.skao.int/SKAHB-510 Summary of the ISSC Teleconference on 4 May 2007 on the Selection of the Host Institute for the ISPO.

[10] hba.skao.int/SKAHB-510 Summary of the ISSC Teleconference on 4 May 2007 on the Selection of the Host Institute for the ISPO.

[11] Peter Hall, ISPO Project Engineer, took up a new position at Curtin University in Australia.

[12] Cornell University, USA, on behalf of the US SKA Consortium; the Joint Institute for VLBI in Europe (JIVE), The Netherlands, on behalf of the European SKA Consortium; the University of Calgary, Canada; the Commonwealth Scientific and Industrial Research Organisation, Australia; and the National Research Foundation, Republic of South Africa.

**Fig. 9.1** Signing ceremony on 4 October 2007 at Jodrell Bank Observatory for the Memorandum of Understanding between the International SKA Steering Committee and The University of Manchester on hosting the SKA Program Development Office. From left to right: Philip Diamond, Director of the Jodrell Bank Centre for Astrophysics (standing), Alan Gilbert, President and Vice-Chancellor of The University of Manchester, and Brian Boyle, Chair of the International SKA Steering Committee. (Credit: Martin George)

clearly focussed “Project” led by one country or entity.[13] In addition, a point was made about the spelling of “Program”. The US participants felt that European influence had been exerted in 1998 in the spelling of “Kilometre” in the name of the telescope, and now it was time for North American spelling of Program to be used. Such are the items of discussion occupying attention at the highest levels of international endeavours.

## 9.3 The 2011 Selection

As the end of PrepSKA came into view in mid-2010, the many parallel streams of activity described in Chap. 4 began to come together as the Agencies SKA group (ASG), SSEC and associated institutes focussed on the transition of the project into the Pre-Construction Phase planned at the end of 2011. The Project Execution Plan[14] and related Business Plan[15] set out the many aspects involved in resourcing and delivering

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[13] However, "project” rather than the “program” remained the most common way to refer to the increasingly focussed SKA activities.

[14] hba.skao.int/SKAHB-115 Project Execution Plan for the Pre-construction Phase for the Square Kilometre Array (SKA), R. T. Schilizzi et al., January 2011

[15] hba.skao.int/SKAHB-118 SKA Business Plan, November 2011

the pre-construction phase work including the required structure and size of the central SKA Project Office to manage the project and its enormous engineering design task. At this point, there were eighteen staff in the SPDO and the projection in the PEP was that this would grow to sixty-two in the next phase of the project.

As was the case for the transition to new governance arrangements at the start of PrepSKA in 2008, the change to a legal entity in 2011 at the end of PrepSKA was seen by the ASG and SSEC to require another competition for the location of the central SKA Project Office (SPO). The form of the legal entity would follow the choice of location. Work led by Patricia Vogel (Netherlands Organisation for Scientific Research), in PrepSKA Work Package 4 on the appropriate legal structure for the Pre-Construction Phase had concluded that an Inter-Governmental Organisation was not viable in the short-term and a not-for-profit limited liability company or equivalent was the most suitable option. With this in mind, it was recognised that the type of governance structure offered in the candidate country would be a factor in evaluating each candidate site.[16]

An initial Call for Expressions of Interest in September 2010 led to responses from ASTRON (The Netherlands), CSIRO (Australia), the Max-Planck Institut für Radioastronomie (MPIfR, Germany), the Istituto Nazionale di Astrofisica (INAF, Italy) and the University of Manchester. The ASG and SSEC decided that bids for the SKA headquarters from the candidate telescope sites could be prejudicial to the telescope site selection and should not be accepted. There were also concerns, not voiced formally, that locating the headquarters in the same country as the telescope site ran the risk of the SKA being regarded more as a "national telescope" than a global facility. Australia's offer to withdraw their bid if it was considered inappropriate was therefore accepted.

The ASG nominated Simon Berry from the UK Science and Technology Facilities Council (STFC)[17] to set up the process for selecting the headquarters location.[18] A formal Call for Proposals, open to any interested party outside the two SKA candidate host consortia, was issued in December 2010.[19] Box 9.2 sets out the selection criteria.

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[16] hba.skao.int/SKAHB-506 *SKAO HQ selection in 2011*, S. Berry, Presentation at the SKA History2019 Conference

[17] STFC provided the Secretariat for the ASG.

[18] STFC was a co-proposer on the UK proposal which would normally disqualify someone from STFC from establishing the selection process. However, Simon Berry was held in great respect by the ASG and SSEC for his leadership of the PrepSKA Resourcing and Governance work-stream and there was every confidence the headquarters selection process would be transparent and efficient. In any case, the ASG and SSEC approved the selection process before it came into operation. In hindsight, in an interview with Schilizzi in 2018, Berry noted that for such a critical decision in the life of the project, more thought should have been given to this point in order to avoid any perception of conflict of interest. (See hba.skao.int/SKAHB-513 Transcription of the interview Simon Berry and Richard Schilizzi, 10 January 2018).

[19] hba.skao.int/SKAHB-511 SKA Project Office Hosting Proposals Recommendation, Attachment 2, Review Panel, March 2011

**Box 9.2 Selection criteria for the location of the SKA Headquarters, 2011**

1. *Location and physical infrastructure*—geographical location of the proposed SPO, status of any developments, timescales, costs, accessibility and transport for staff and visitors, communication infrastructure.
2. *Technical and scientific environment*—local astronomical scientific and technical environment, research groups, local expertise.
3. *Organisation and legal governance structure*—nature of the organisation, legal framework, proposed timescales, and potential evolution of the legal governance moving forward to the construction phase.
4. *Supporting services*—local procurement arrangements, personnel services (i.e. pension arrangements, visas/work permits for overseas workers and visitors), administrative support.
5. *Other factors*—financial arrangements, capacity for local and international outreach, general desirability for families re-locating i.e. schools, employment opportunities.

Responses were received from (1) ASTRON on behalf of the Dutch radio astronomy community. The SPO was to be located in a new extension to be added to ASTRON's headquarters in Dwingeloo; (2) the MPIfR and the University of Bonn. The SPO was to be located in central Bonn in a modern office building in close proximity to the host institutions; and (3) a UK collaboration between the Universities of Manchester, Cambridge and Oxford and the Science and Technology Facilities Council (STFC)). The SPO was to be located in a new building[20] to be constructed at the University of Manchester's Jodrell Bank Observatory. See Fig. 9.2 for depictions of the ASTRON and Manchester proposals; no photo of the proposed office building in Bonn could be made available to the authors.

A review of the proposals for the SKA headquarters[21] took place at the European Commission in Brussels on 10 March, 2011 following the review of the SKA Project Execution Plan on 8 and 9 March. These reviews were timed to allow both review panel outcomes to be discussed and decided upon at the critical series of meetings in Rome 3 weeks later. These were the meetings at which the SKA Founding Board was established[22] and preparations for the transition to a legal entity began in earnest.

The SKA headquarters review was carried out by Gary Sanders (Chair, Thirty Meter Telescope Corporation), Jim Crocker (Lockheed Martin Space Systems),

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[20] This was a move from the university campus city-centre location where the SPDO had been housed for the previous 3 years.

[21] hba.skao.int/SKAHB-511 *SKA Project Office Hosting Proposals Recommendation*, Attachment 1, March 2011, Review Panel

[22] See Sect. 4.4.2.3.1. The Founding Board replaced the ASG and guided the project in its transition to a legal entity to manage the Pre-Construction Phase in December 2011.

**Fig. 9.2** Left: schematic of the proposed new SKAO HQ wing to be added to the existing building at ASTRON in Dwingeloo, The Netherlands (Credit: ASTRON). Right: A visualisation by Fielden Clegg Bradley Studios of a new building for the SKAO HQ at Jodrell Bank Observatory, UK, with the Lovell Telescope in the background (Credit: The University of Manchester)

Jean-Marie Hameury (Centre National de la Recherche Scientifique, CNRS, France, and a member of the ASG) and Russ Taylor (University of Calgary Centre for Radio Astronomy, Canada, and Vice-Chair of the SSEC). Elena Righi-Steele (Directorate-General Research, European Commission), Schilizzi (SKA Director) and Michelle Cooper (STFC, ASG Secretary) were in attendance.[23] Each of the proposing teams gave presentations to the panel.

The ASG had instructed the review panel to provide a motivated recommendation on the ranking of the three possible locations. That did not prove straightforward, partly due to the high quality of the proposals but also because of a lack of guidance from the ASG on the weighting of the selection criteria.[24] In the event, the panel decided to give all criteria equal weight.

After a difficult discussion on the ranking, the review panel concluded[25] that all three proposals identified viable sites for the SKA headquarters in the Pre-construction Phase with the Manchester/Cambridge/Oxford/STFC proposal ranked higher than the ASTRON proposal and the MPIfR/Bonn proposal in third place.

This outcome led to another difficult discussion at the sixth SSEC meeting in Rome later in March where concerns were voiced by the German and Dutch delegates about some elements of the evaluation process, as well as the communication of the review panel's recommendation on the headquarters location to the proposers. These concerns were passed on to the newly established Founding Board

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[23] hba.skao.int/SKAHB-511 *SKA Project Office Hosting Proposals Recommendation*, Attachment 1, March 2011, Review Panel. Elena Righi-Steele was there as an independent observer in a quality-assurance capacity regarding the evaluation process. Schilizzi provided clarifications of project needs and practices, and Michelle Cooper provided support for the review panel.

[24] In hindsight, Simon Berry saw the failure of the ASG to set weights as an error. See hba.skao.int/SKAHB-506 *SKAO HQ selection in 2011*, S. Berry, Presentation at the SKAHistory2019 Conference

[25] hba.skao.int/SKAHB-511 *SKA Project Office Hosting Proposals Recommendation*, Review Panel, March 2011

at their first meeting a few days later, together with the consensus view of the SSEC that the panel's ranking was accepted.

The Founding Board formally accepted the recommendation to locate the SKA headquarters at Jodrell Bank Observatory and summarised the grounds for that decision[26] as set out in Box 9.3.

**Box 9.3 Grounds for the Founding Board decision on Jodrell Bank Observatory (JBO) as the location for the SKA Project Office in the Pre-Construction Phase**

"*Physical infrastructure:* The UK proposal is completely flexible in that the interior is not finalised, allowing optimum use of space in terms of meeting rooms and technical setup.

*Access for staff and visitors*: JBO is in close proximity to an international airport offering direct connections with many European countries, the US and South Africa. For the other destinations, all three sites were considered equivalent, as they would require one transfer from a large international airport.

*Nature of the organisation*: the UK proposal offered the best combination between independence and support from local, national organisations. This advantage is partly offset by a somewhat less comprehensive technical expertise available compared to the other two sites.

*Capacity for national and international outreach*: the UK proposal had a clear advantage given the JBO experience in this area.

*General desirability for family re-locating*: JBO, being close to a major city in an English-speaking country, was ranked highest.

These more than compensate the weak points of the UK proposal:

*Salary tax exemption*: the Dutch proposal is very clearly superior in offering a 30% tax exemption to non-Dutch citizens.

*Research groups*: The Astron and Bonn proposals are very strong in terms of the local scientific and technical expertise.

*Immigration/visa process*: The UK not being a "Schengen" country is disadvantaged, even though it was noted that under the new immigration rules recently adopted, PhD-level personnel will be considered favourably."

The consequence of this decision was that the legal entity for the SKA project would be a UK Company Limited by Guarantee called the SKA Organisation (SKAO, see Sect. 4.7.1). Two years later in 2013, the new SKAO building (see Fig. 9.3) was inaugurated at the start of the Pre-Construction Phase.

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[26] hba.skao.int/SKAHB-512 *SKA Project Office Hosting*, SKAO Founding Board, Supporting document for seventh SSEC Meeting, July 2011

**Fig. 9.3** *Left*: The inauguration ceremony for the new purpose-built SKA Headquarters building at Jodrell Bank Observatory on 7 May 2013. Left to right—John Womersley (STFC, SKA Organisation Board of Directors Chair), Nancy Rothwell (Vice-Chancellor and President of The University of Manchester), David Willetts (UK Minister of State for Universities and Science), and Philip Diamond (Director-General, SKA Organisation) (Credit: SKA Observatory). *Right*: The SKA Headquarters building with the 76 m diameter Lovell Telescope in the background (Credit: R.P. Millenaar, SKAO, 2013)

## 9.4 Postscript

As noted in previous chapters, the formal scope of this book covers the period from 1990 to the telescope site selection in 2012. However, we briefly mention here a third competition for the SKAO Headquarters location held in 2015 when it was thought that the project would be entering the construction phase within 2 or 3 years. In this case, the SKA Organisation Board of Directors had already decided that the desired governance structure in the construction and subsequent observatory operations phases would be a Inter-Governmental Organisation (see Sect. 4.7.4.3). The UK and Italy entered the competition with the current SKA Headquarters site at Jodrell Bank Observatory and a site in Padua in Italy as candidate locations. After another contentious selection round, the UK site at Jodrell Bank Observatory was chosen as the permanent location for the SKA Observatory Inter-Governmental Organisation (see Fig. 9.4). That story will have to await a further instalment of the history of the SKA.

**Fig. 9.4** The SKA Headquarters building after a major extension completed in 2018. The Jodrell Bank Observatory (JBO) 76 m diameter Lovell Telescope is in the background left of centre. Another JBO telescope (14 m diameter) can be seen in the background right of centre. The original SKA Headquarters building shown in Fig. 9.3 right is on the left of this photo. (Credit: Juande Santander-Vela, SKA Observatory)

# Chapter 10
# Industry Engagement

## 10.1 Early Industry Interactions, 1990s to 2009

While early conversations concerning the proposed SKA were no doubt occurring between universities and institutes and their various industry contacts, the first concerted efforts to engage more formally with industry are reported in the project literature around the early 2000s. Forming a ‘third-leg’ of the project organisation (with the International SKA Steering Committee (ISSC) and International Science Advisory Committee (ISAC)), the International Engineering and Management Team (IEMT) chaired by Peter Hall, then based at CSIRO Division of Radiophysics in Sydney, established contacts with selected companies thought to be interested in engaging with the project. Working at the international level, the IEMT pro-actively approached firms such as International Business Machines, IBM (USA) and Connell Wagner (Australia) in relation to future technologies, mass scale manufacturing, and project management of mega-science infrastructure.

Around the same period, institutes such as Australia’s CSIRO and ASTRON in the Netherlands were able to allocate seed project funding to support their contribution to the international effort, and thus attract broader national industry interest. In the case of ASTRON, a Coopers & Lybrand report “Scouting the Technology and Economic effects [of the SKA]” commissioned in 1998 underpinned an effort to reach out to local industry, with the Dutch Low-Frequency Array, LOFAR, project linked conceptually to the future SKA. This report supported the so-called SKAI (SKA Interferometer, see Sect. 3.2.4) proposal at the €2.5 M level and ran from 1999–2003 under the auspices of the Dutch Ministry of Economic Affairs. Its aim was to facilitate knowledge exchange, cooperation and innovation within and between Small- to Medium-sized Enterprises (SMEs) and ASTRON. Around 45 SMEs became actively engaged under the program’s auspices, many of which endured.

In 2002, ASTRON’s €1.5 M “Northstars” program was approved, running until 2005. Together with interested SMEs as partners, a key element was to design and

R. T. Schilizzi et al., *The Square Kilometre Array*, Historical & Cultural Astronomy,
https://doi.org/10.1007/978-3-031-51374-9_10

build conceptually marketable flat (i.e. phased array) antennas for Ku-band satellite reception using technologies from the SKA R&D program. The increasing number of technology transfer relations necessitated an Intellectual Property Rights (IPR) Policy from 2002 and an active patent and publication policy. This resulted in 14 granted patents around 2009.

A key step for ASTRON was the establishment of the Astrotech Holding Company (ATH) by Arnold van Ardenne, ASTRON's R&D leader. Still running at the time of writing, it was primarily intended to promote industrial innovation through engagements with the Dutch SKA R&D effort. ATH and its networking activities enabled important connections to the commercial world. IBM (a research partner in LOFAR from 2003), Philips, Cisco, and Alcatel all actively participated in the Dutch SKA Forum in 2010.

By 2002, CSIRO was collaborating not only with ASTRON and the Centre for Extra Galactic Astronomy, but also with industry on micro-nano research devices for time-delay beamforming technology applicable to wideband arrays.

A significant milestone in Australia was achieved in 2002 with the formal signing of the Major National Research Facility (MNRF) agreement between the Australian Commonwealth Government, CSIRO, the University of Sydney, Swinburne University of Technology, and several other collaborators. This agreement unlocked a flow of about $A20M into SKA research for technology development, and characterisation of candidate sites, over the following 5 years. Around the same time, the CSIRO was offered a A$500 K SKA engineering consultancy contribution from Connell Wagner, one of Australia's largest engineering and project management companies. This notable spontaneous and sizable contribution enabled further SKA and LOFAR siting studies and was made on the (correct) judgement that further paid work would likely follow (see hba.skao.int/SKANEWS-4).

Events accelerated in 2003, when the International Astronomical Union (IAU) meeting in Sydney proved to be an excellent forum for exposing the SKA project to a wide audience, including an Australian Industry Day attended by 140 delegates. The "SKA2003" roadshow followed in Geraldton, Western Australia where local industry displayed strong interest in future contracting opportunities. This no doubt prompted a first discussion on industrialisation at the co-located ISSC10 meeting.[1]

The following year, Cape Town hosted the 11th gathering of the International SKA Steering Committee (ISSC11) which focussed on remote power solutions for the telescope and identifying a possible fact-finding mission. A locally organised technology workshop gave the SKA community, and local South African academics, engineers, and industry an excellent opportunity to understand the technical demands of the proposed SKA telescope. Meanwhile, in India, SKA2004 also offered opportunities for interaction between local industries and radio astronomers. In particular, a workshop, managed by National Centre for Radio Astrophysics (NCRA), Pune and Raman Research Institute (RRI), Bangalore, highlighted the

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[1] hba.skao.int/SKAHB-515 Extracts on Industry Engagement from the Minutes of ISSC and SSEC meetings from 2003 to 2011

opportunities for research and development in hardware and software technologies, with 20 participants from 10 organisations representing the local software industry and high-technology R & D.

The year 2004 also marked the start of the four-year ASTRON-led SKA Design project (SKADS) , a major step in European cohesion with combined funding from the European Commission (EC) and national funding agencies such as the Science and Technology Facilities Council (STFC).[2] (See also Sect. 10.2.1) Besides the 2-Polarisation All-Digital (2-PAD) aperture array demonstrator, SKADS established the world-first Aperture Array station of 144 m$^2$ (at Westerbork, Netherlands) as well as the 90 m$^2$ station in Nancay, France.

SKADS continued to gather pace and international support during 2004, culminating with a European Industry Day held at Dwingeloo, Netherlands in December. This event marked a significant phase for industry engagement, building on a series of Dutch industry days held since 2002. Organised by the International SKA Project Office (ISPO) and ASTRON, it attracted about 40 delegates, including 10 representatives of large multinational companies.

The event presented the SKA project to major potential industry partners in order to stimulate early interest in the project by highlighting European SKA activity; looking for examples of best-practice in industry-science links; addressing matters surrounding intellectual property and other legal issues; and seeking input to the development of a strategy for SKA-industry liaison. Companies represented at the gathering included Alcatel, Cisco, Hewlett-Packard, IBM, and Philips. After presentations by the SKA speakers, company representatives gave their views on the project, including perspectives on how it might interest industry sectors and thus offered much useful intelligence on successful industry engagement.

A few thorny topics were already exercising the minds of those present, including High Performance Computing (HPC) and associated power demands, Radio Frequency (RF) systems and networks, the potential for dual usage of the infrastructure, and the substantial challenges in meeting international legal requirements. Lawyer Stephen Kahn, contributed specific expertise for mega-projects depending on industry involvement in both pre-competitive and procurement phases (including handling the contractual ‘lock-out’ problem).[3]

The event coincided with the transition of the IEMT industry group into an ISPO Engineering Working Group sub-group, known as the Industry Liaison Task Force (ILTF) and chaired by Peter Hall, the International Project Engineer. This group was introduced at the 2005 ISSC13 meeting and was assigned the role of advising the project on industry matters. The ten member ILTF was charged with generating a

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[2] The SKADS effort was based on phased array receivers. Catalyst funding for SKADS was provided by the EC amounting to 27% of the total of €38 M funding over the next 4 years. The main technological design aim of UK SKADS was to produce a dual polarisation all-digital (2-PAD) phased array ‘tile’ approximately 1 m by 1 m. The UK invested £5.6 M (€8.3 M) funding provided by PPARC.

[3] hba.skao.int/SKAMEM-80 ISPO Engineering WG-Industrial Liaison Task Force, Hall, P. & Khan, S., 2006

white paper on industry policy by the end of 2005 and extending the commentary of SKA Memo 52 on industry interactions beyond pre-competitive alliances. An interesting aspect of the ILTF's industry studies involved a visit in 2005 to IBM's Zürich research laboratories, and to the European Organisation for Nuclear Research (CERN) in Geneva where the infrastructure of the Large Hadron Collider underlined the concept of "mega-science". It was clear to the ILTF that there was much to be gained by nurturing links with both IBM and CERN. (See also Sect. 10.4).

A report of industrial contacts and future plans tabled at the ISSC14 meeting held in Pune, India, featured IBM prominently as a "serious enquiry" with much discussion about possible forms of cooperation. A sample Term Sheet was reviewed at the meeting, sparking further questions concerning intellectual property (IP)—a topic that to remain somewhat problematic through the procurement development phases.[4] The Term sheet re-appeared at ISSC15 without resolution.

Throughout 2006, the ISPO was active in extending SKA community insight into industry collaboration and engagement issues, as well as taking a main role in producing the ILTF's white paper and drafting a collaborative R&D agreement with IBM. This template was considered an enabling step for demonstrator projects but also proved useful later in furthering understanding of critical issues such as IP procurement strategy and high-level Memoranda of Understanding (MoU). In addition to continuing to facilitate (pre-competitive) collaboration initiatives, the ISPO was clearly positioning itself to take the lead in preparing the SKA project for efficient, timely and economical delivery by industry—an essential exercise in terms of the original concept of an instrument mainly assembled from commercial off-the-shelf (COTS) components. This aspiration was however to remain unfulfilled, as the subsequent conceptual design work remained largely within institutional walls and there was limited appetite to benefit from industry expertise in mass produced product integration.

Nonetheless, industry engagement continued to ramp up with the sixth Australian industry SKA briefing held in Perth in December 2006, hosted by the Western Australia Government's Department of Industry & Resources. Notable at this meeting was the growing competitive spirit driven by the single site concept design and repeated aspirational remarks around opportunities for Australasian industry. The commercial mood of Western Australia business (colloquially known as "WA Inc") added to the sense of excitement an environment of booming state development. An example of this somewhat 'gung-ho' mindset was demonstrated by Tenix Pty Ltd., a partner in the Australian SKA Industry Cluster Mapping project. Tenix commissioned renowned Sydney Opera House architect Jan Utzon to prepare a schematic design for an SKA Visitor Centre in Western Australia. Tenix bequeathed this design to the Australian SKA project amid much fanfare in November 2006, only to fade from sight within months. Meanwhile, at ISSC16 (in Dresden) industrialisation continued to be discussed, concentrating on the cost benefits of

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[4] hba.skao.int/SKAHB-515 Extracts on Industry Engagement from the Minutes of ISSC and SSEC meetings from 2003 to 2011

mass production, aspects of procurement rules, as well as success from cooperation with IBM—a topic that was later developed further at the first SKA Science and Engineering Committee (SSEC) meeting by telecon in 2008.[5]

Meanwhile, in early 2007, CSIRO sponsored the Australian Symposium on Antennas in Sydney with the aim of bringing together engineers, scientists, and industry representatives to discuss current and future developments in antenna design. The following month CSIRO and ISPO hosted the 3-day Third International Focal Plane Array Workshop, indicating the steep rise in SKA technical interest at this time. The meeting attracted 96 participants, representing astronomers, engineers and industry representatives from Australia, Europe, Canada, USA, South Africa and New Zealand.

By mid-2007, New Zealand had commenced a series of SKA Industry events spurred on by similar events elsewhere, especially in Australia. In July, an Australasian team led by Sergei Gulyaev (Auckland University of Technology, NZ), Brett Biddington (Chair, Australian Telescope Steering Committee), Phil Crosby (CSIRO) and Carole Jackson (CSIRO ATNF), gave a series of presentations to audiences in Christchurch, Wellington, and Auckland. The interest level at these events was reflected by the engagement of the attendees and the support from several key New Zealand organisations, including Canterbury Development Corporation, Connect New Zealand, New Zealand Supercomputing Centre, New Zealand Telecom, and AUT Technology Park (see Fig. 10.1).

The year 2007 also saw the formation of the first formally convened SKA industry group, sponsored through the national Australian Government's AusIndustry program and initially labelled the Australian SKA Industry Cluster (ASKAIC). The ASKAIC was established as an industry-led project to drive a national initiative to understand relevant Australian capabilities, and to develop opportunities within the Australian SKA Pathfinder (ASKAP) and SKA projects. Foundation members included CSIRO, Cisco Systems, and Radio Frequency Systems, as well as defence 'primes' Boeing, BAE Systems, Raytheon, and Tenix, each seeing advantages in involvement with a mega-science project at the cutting edge of new sensing and computing technologies.

Marking a notable development, the value of a formally represented 'cluster' of potential industrial stakeholders was very apparent at the 2008 International SKA Forum held in Perth, WA. The event was attended by around 200 delegates, with strong representation from SPDO, government officials, scientists from around the world, and industry and local stakeholders. This was the first time such a large and diverse global group had met to be briefed on the SKA and participate in discussions on the commercial opportunities of the SKA project.

During this period, Member countries around the world continued to hold periodic gatherings of local SKA project stakeholders, usually supported through

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[5] hba.skao.int/SKAHB-515 Extracts Industry Engagement from the Minutes of ISSC and SSEC meetings from 2003 to 2011

**Fig. 10.1** Australasian industry team leaders. Left to right: Carole Jackson, Phil Crosby, Sergei Gulyaev, and Brett Biddington

attendance of SKA project personnel, and welcoming local industry to contribute project experience and technical advice.

In September 2009, the SKA featured in a one-day UK Government conference held to bring large scientific projects together with representatives from industry. This was to alert potential industrial partners to the fact that major procurements would be forthcoming as the SKA approached SKA Phase 1 construction. Although premature in hindsight, the event offered an important forum for understanding the mega-science project landscape from the viewpoint of industry—an aspect new to many of the scientists and the SKA leadership.

During 2009, ASKAP, focused on industry engagement activities thanks to the ongoing support of the ASKAIC which offered practical help in planning for industry involvement through secretariat services from The Global Innovation Centre. At this point, Australia was leading the way with marketplace offerings through an Industry Opportunities Register (IOR) (Crosby, McGarvie & Mulcahy, 2008),[6] updated regularly as the project developed. The Oportunities Register, coupled with an on-line SKA Capabilities Directory, resulted in 400 Australian

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[6] hba.skao.int/SKAHB-557 *Australian SKA Pathfinder Industry Opportunities Register,* Crosby, P., McGarvie, S., & Mulcahy, M., 2008.

businesses becoming registered, indicating strong local interest and capability. While this initiative was commendable, it exemplified a trend among local scientists and engineers in many SKA Member countries of prematurely over-exciting industry as to the size and schedule of commercial contracts to build the telescope—a situation that strained industry relations in subsequent years.

Across the Atlantic, a workshop on the Canadian SKA programme was held in October 2009 at the University of Calgary. It brought together research teams and representatives from the National Research Council, current and potential industry partners, as well as representatives of government agencies at federal and provincial levels. The focus for Canada was leading-edge technologies and manufacturability, next generation HPC, low noise amplifier (LNA) technologies; signal processing; and integrated receiver system production. Meanwhile in the southern hemisphere, a new (though short-lived) industry group, the New Zealand SKA Industry Consortium was formed, made up of the NZ ICT Group (the industry organisation representing New Zealand's IT software, hardware, networks, services, education and training providers), and New Zealand's Trade and Enterprise Department.

## 10.2 Industry Engagement from 2009 Onwards

In 2009, following almost a decade of steadily building relationships with industry through the ISPO phase and into the SPDO era, many Member countries commenced working more strategically with the SPDO to foster links with their industrial partners focusing on technology design and development. These relationships became important for the various R&D consortia that were then forming. This coincided with a greater interest and awareness of SKA from the national funding agencies noted in Chap. 8. Hence there emerged a shift in emphasis from the project primarily engaging with industry to help develop the technologies needed, to an engagement more driven by the desire to show national governments a return on their funding investment.

### *10.2.1 UK*

The Government's STFC took a guiding role in connecting to UK industry with practical advice from the UK university-based SKADS team. This group identified driving technologies that were ripe for commercial procurement such as: broad-band antenna arrays, RF amplifiers optimised for both low noise and RFI robustness, ultra-fast analogue to digital converters (ADC), ultra-fast digital signal processing, high data volume wide-area networks, ultra-precise time and frequency transfer via optical fibres. As a result, various local firms were contracted to provide advanced technologies. (See Box 10.1).

**Box 10.1** ***UK firms that benefited from local contracts for early R&D work***

- Cambridge Consultants (DSP look-ahead study)
- BAE Systems (phased array antenna element study)
- Roke Manor (phased array architecture study)
- EEP (supply of Electromagnetic-tight container to house high-speed digital hardware)
- MC2 (noise measurement)
- RFMOD/LOADPOINT (supply of innovative packaging for semiconductor devices)
- Selex Galileo (design validation and testing of high-speed ADC in technology)
- e2v technologies (high-speed low-power ADC in SiGe and other technologies)
- IBM (study of high-speed low-power integrated CMOS ADC, and supply of advanced DSP hardware).

By mid-2010, SKADS had identified active industrial partnerships with IBM, Intel, SELEX Galileo, BAE Systems, Microsoft, and Altera among others, as well as international connections in Australia, South Africa, Netherlands, and Canada, underlining the growth and importance of global industry linkages.[7]

Subsequent UK industry-specific meetings, mostly driven by the Government-supported Knowledge Transfer Network (KTN) included a briefing meeting held at the Science Museum in London (July 2008); STFC & Sensors & Instrumentation KTN (with UK Trade & Investment) “Research Infrastructures Meet the Buyer” event (Sept 2008); an e-KTN event focused series aimed principally at specific areas of phased array technology; Low noise, High-speed Analogue Electronics (Oct 2008); a Digital Signal Processing meeting (May 2009); System, computing and software workshop (March 2009); and an Antennas and Infrastructure for Phased Arrays meeting (Feb 2009). Under the stewardship of e-KTN’s Manager, Nigel Rix, a focused effort commenced on realising a UK industry cluster to bring together the disparate community of companies in the “SKA technologies” domain and provide a focus for their activity on SKA. Potential benefits anticipated included a knowledge base for members, promotion of the capabilities of the members, assistance with consortia bids for projects, and a general leveraging from the inspirational value of the SKA.[8]

An industry meeting in preparation for the pre-construction phase, held in Manchester in March 2012, heralded the end of e-KTN supported events due funding limitations.[9]

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[7] hba.skao.int/SKAHB-547 *Industrial Linkage and Aspirations*, Crosby, P., Introduction to the session on Industry Engagement at the SKAHistory2019 conference, 2019

[8] hba.skao.int/SKAHB-516 SKA UK Industry Cluster Presentation, Rix, N., SKA Forum, Banff, 2011

[9] hba.skao.int/SKAHB-517 SKA Flyer for industry meeting–March 2012

### *10.2.2 Australasia*

In Australasia, the principal channel for industry engagement was through the re-badged Australian SKA Industry Consortium (ASKAIC), managed by John Humphries of the Global Innovation Centre (GIC), with membership by subscription. GIC maintained regular communications between its membership and the SKA project office, and the Australian and (less frequently) the NZ SKA offices. ASKAIC was effective in mobilising its members to participate successfully in a range of activities including consideration of SKA industry engagement issues and providing advice to government; participation in information exchange with CSIRO and others—including site visits, seminars/workshop, briefings—on technical and policy issues and best practice advice; and championing the SKA. ASKAIC also supported Australian industry capability mapping, and in the pre-site decision era, the Australia/NZ hosting bid. When control of ASKAIC passed from GIC to the Australian Government's SKA office, the welcome decision to abandon subscriptions was made. The membership profile was broadened to include government agencies and research institutes (and any other interested party), thus losing focus in terms of strategic industry engagement with a consequent decline in industry attention and participation.

Practical industry involvement continued with maintenance of the Australian SKA Industry Capability Directory (linked to a capability matching exercise), commercial tenders for design and construction of the Murchison Radio-astronomy Observatory (MRO) Support Facility, sourcing and installation of the ASKAP optical fibre link between Geraldton and the MRO, geotechnical surveys of the MRO, design and installation of foundation pads for each antenna at the MRO, and installation of power and fibre trenches.

At this time, industries showed a keen appetite to establish strategic liaisons with the SKA. Examples included Cisco Systems (secondment of an engineer to the ASKAP team); Raytheon (provision of Systems Engineering training); IBM, Cray, Intel, Dell all offering IT/Computing design support, and other firms provided practical advice, loan of equipment etc. In addition, there were many meetings, interactions, and workshops with a wide range of companies to discuss best practice project management and systems engineering.

A significant procurement occurred during the period of ASKAP's construction, with a contract awarded to the 54th Research Institute of China Electronic Technology Group Corporation (CETC54) for the design, build and commissioning of 36 ASKAP antennas. Responding to an open tender request, the Chinese government's A$ten million offer beat all local offers to the extent that domestic industry could not compete. Patriot Antenna Systems (USA) were contracted to supply a single 12 metre antenna installed at Parkes Observatory for use as an Focal Plane Array (FPA) development testbed; and Puzzle Precision (Australia) were contracted to fabricate and test high-complexity back-end processing boards—a much lauded collaboration with a regional SME that lifted the company's capability and reputation considerably.

### 10.2.3 South Africa

A different approach to industry engagement was taken in South Africa during these formative years of the project and into the SKA pathfinder phase. This was to 'tap into' specific capabilities that existed in local industry, or else develop it in-house. An impressive level of engagement with industry was highlighted by a list of over 50 firms supporting the South Africa SKA effort as outlined by (then) Chief Technologist, Justin Jonas at the Banff SKA Forum meeting in 2011.[10] Ultimately, the design, manufacture, installation, commissioning, and testing of the KAT-7 antennas was subcontracted to BAE Land Systems Dynamics in South Africa. The feed (XDM) and Cryogenic engineering (XDM and KAT-7) were accomplished through a partnership with EMSS Antennas on a cost-plus basis, and this very successful and close partnership continued through to developing and delivering MeerKAT. The SKA had a big impact on EMSS's capability and the growth of the (later) world-renowned FEKO © electro-magnetic simulator product.

Several other firms (Tellumat, ETSE, Foxcom, Miteq, Amplitech, SIA solutions, C$M, BEP, TFD, and Berkeley) were commercially engaged for sub-components and software modules, each a successful collaboration in which SKA South Africa played an active role.

### 10.2.4 Canada

The Canadian approach pre- and post-2009 was to engage and partner with relevant industries early in the process to establish long-term relationships that matched the development timeframe and performance requirements of the SKA. Even at this early point of conceptual design, Canada was actively investigating opportunities for next generation High Performance Computing (mainly with IBM), advanced memory and storage technologies, advanced high-volume data processing technologies, as well as low noise amplifier (LNA) technologies, and integrated receiver system production. Interestingly, NRAO even held concept level discussions with Lockheed Martin concerning the use of airships to deliver dishes to the remote site locations. In October 2009, Canada hosted the SKA focused industry connection/networking conference at University of Calgary, with IBM, government representatives, and other potential industry partners.

Foremost in the Canadian SKA Program 'wish-list' of SKA contributions was dish design prototyping using low-cost, high-performance composites. Work was conducted with Profile Composites, Inc. (Sidney, B.C.) and resulted in a new 10-metre composite dish incorporating significant advancements in design and production of the type of radio reflectors required for the SKA. Associated effort included exploratory discussions with BreconRidge of Ontario, regarding packaging

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[10] hba.skao.int/SKAHB-518 Industry Partnerships in South Africa—Jonas, J., July 2011

of LNA technologies and receiver integration and production. Breconridge also delivered large-scale, high-density correlator hardware for the EVLA correlator and as a result were interested in working on the correlators for the SKA.

### 10.2.5 India

Over 2009–10, the National Centre for Radio Astrophysics (NCRA) initiated the formation of an Indian consortium of industry and research institutes aimed at addressing front line issues regarding software development for large astronomical facilities. This involved development of the architecture for a generic control and monitor system, optimisation tools for telescope scheduling, virtual observatory tools, and graphics processing unit (GPU) computing. To this end, a draft MoU was developed between the consortium partners (Tata Research Development and Design Centre, Persistent Systems Ltd., Centre for Development of Advanced Computing, NCRA and the Inter-University Centre for Astronomy and Astrophysics, IUCAA).

### 10.2.6 The Netherlands

Building on the successful series of Industry Days (see Fig. 10.2) described in the preceding section, ASTRON established an informal industry group (SKA-NL) with over 30 first-tier companies, including IBM. SKA-NL partnered with a Dutch initiative promoted as the "Connecting Industry, Society and Science (CISS) workshop"[11] in Drenthe, during the SKA Forum in June 2010 (See also Sect. 10.10). Supported by several locally based companies—mostly those involved in the LOFAR and/or EMBRACE projects—the meeting offered a platform for the launch of the Dutch SKA Industry Position Paper (NXO, Siemens, IBM, 2010).[12] This document outlined the importance of the project for the Netherlands from an industry perspective and was written in collaboration with an industry group involving multinational companies.

### 10.2.7 Other Countries

Space precludes a detailed description of industry collaboration efforts by all interested nations. However, Italy should be acknowledged for their intense

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[11] hba.skao.int/SKAHB-519 Connecting Industry, Society and Science, ASTRON, 2010

[12] hba.skao.int/SKAHB-548 Dutch Industry Position Paper, NXO, Siemens, IBM, 2010

**Fig. 10.2** Arnold van Ardenne, one of the global leaders of the SKA design work, at the Dutch Industry Day 2004

industrial engagement, and France albeit to a lesser extent. Sweden and Portugal were both industrially very active in the 2010–2020 period, while Germany started to strongly connect with their industry in later years. China showed strong interest in major infrastructure supply (dishes) from around mid-2000s lobbying hard for government factory contracts.

## 10.3 The Dream of COTS (and the Departure from it)

From the fairly intense era of early industry engagement described above, a consistent view emerged among the proponents of the international project that the instrument could only be realised with the direct involvement of industry. Whereas, with earlier large science projects, local (and in some cases international) firms had been contracted to the fulfil the conventional facilities construction and deliver parts of the physical infrastructure using bespoke component parts, it became obvious to most stakeholders that only industry could deliver the necessary production scale and economy for an affordable giant array.

Early concept designs for the SKA even considered the possibility of deploying thousands of cheap satellite TV dishes, of the type commonly seen in both metropolitan and rural communities around the world (personal communication, Peter

Wilkinson to Crosby in 2010). While this approach would certainly have contained the ever-growing project cost projections, it was soon shown that the designs fell short in terms of technical and quality requirements. Nonetheless, aspirations of sourcing mass-produced "commercial-off-the-shelf (COTS)" components from industry remained. As early as 2002, the SKA Newsletter #4, mentioned that a group of astronomers at Jodrell Bank Observatory (including Michael Kramer, Duncan Lorimer, Andrew Lyne, Peter Wilkinson, and Graham Woan) had submitted a concept paper of a ~ 5000 square metre (multi-dish) phased array intended to be a 1:200-scale SKA demonstrator system implying COTS components. In the same newsletter, the Thousand Element Array (THEA) 256 element demonstrator was reported as delivering its first data—again, having been built partly to evaluate mass produced technology for SKA.

Two other components which appeared promising as COTS candidates were the receivers, and high-performance computing systems (HPC). While the former was not strictly a COTS item, the prospect of an order to design and manufacture front-end receivers in their millions would certainly prove commercially attractive (and likely find applications beyond astronomy). The SKA Project Office either consulted, or independently approached, several major computing firms, to investigate whether their existing or planned products could find application with the SKA.

As the conceptual design slowly crystallised through the ISPO era, and proto-scientific goals shaped engineering designs and performance requirements, the instrument specifications became more refined and demanding, lessening ready application of (known) COTS products. For example, the desired frequency coverage began to lend itself to a mix of antenna designs and technologies, not just simple paraboloidal reflectors. Further, the computing requirements (in terms of channels) demanded a huge number of inputs and outputs—substantially beyond any commercially available machine. Power budgets, too, were beginning to be understood, placing further pressure on novel engineering design options.

By 2012, it had become clear that ambitions for a mostly COTS built instrument were unlikely to succeed, but there remained good scope for mass production of certain components (e.g. dipole antennas, receivers, etc.) and this aspiration should stay apparent in dealings with industry.

## 10.4 International SKA Project Office (ISPO) Strategic Initiatives 2004–2008

During the ISPO phase, the subject of industry engagement attracted international attention and began to be investigated largely by International Project Engineer, Peter Hall. He, together with an experienced consulting lawyer, Stephen Kahn, established and led the SKA Industry Liaison Task Force (ILTF) made up of ten representatives from the ISSC which had institutional members from eleven countries at the time, including the USA.

Under its Terms of Reference, the ILTF identified projects which had some similarity to the SKA (principally the Atacama Large Millimetre Array, ALMA, and LOFAR) and which were likely to yield lessons for the SKA in framing its industry engagement and governance, as well as the trade and legal issues associated with very large international collaborations. Even at this early stage, the need to begin looking at procurement issues early in the project was highlighted, yet as later history shows, the topic remained unresolved at the policy level a decade later—though in fairness, the decision to evolve to an Inter-Governmental Organisation (see Chapter 6) did necessitate a re-think of the procurement approach. Importantly, the ILTF addressed the need to identify effective mechanisms for managing both major industry involvement and mutual expectations over long periods of time, including issues around IP management. It is worth noting that IP management was first addressed in the early 2000s with Richard Schilizzi setting up a fledgling IP register.

An interesting exercise of the ILTF was to set out the reasons why companies might wish to be associated with the SKA, an important piece of work for framing future approaches and events to industry around the globe. The main drivers were identified as ranging from short-term financial gain via prototyping contracts in the development phase, through to more indirect motivations such as the wish to develop staff skills in ways not routinely available. This important sentiment remained in the SKA Organisation vernacular, appearing succinctly in subsequent iterations of the SKA Industry Engagement Strategy as[13]:

- The opportunity to grow and hone the creative energies of the best professionals in an imaginative project whose aim is no less than to chart the history of the Universe.
- The ability to develop and perfect leading-edge techniques and products in a very demanding application and to interact with highly technologically sophisticated users.
- The ability to generate and share information with other R&D partners—both institutional and industrial—in a benign and commercially non-threatening environment.
- The visibility flowing from association with an innovative, high profile, international mega-science project; and
- The potential for early involvement contracts with tangible payback in a funded, cutting-edge project spanning a wide range of infrastructure, engineering, and computing disciplines.

The ILTF introduced preliminary considerations about procurement strategy for the SKA, bringing to the fore the major issues (later to be addressed by PrepSKA WP5) concerning public procurement rules, fair competition, *juste-retour*, tender and pricing negotiations, and legal aspects of the defined contracting authority.

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[13] hba.skao.int/SKAHB-555 *Industry Engagement Strategy,* Crosby, P., 2017

The first serious considerations regarding the management of industry interaction were undertaken by the ISPO to address specific collaboration issues then seen as facing the SKA. This included aspects of ownership and transfer of IP, in the context of an international (public) project, what potential legal protections might be afforded, and the implications of an ‘open skies’ telescope access environment (which would naturally limit any ability to guarantee a specific return on a national industrial investment). There was also the question of how external parties (e.g. industry) could become involved with the regional prototypes (known as SKA precursors and pathfinders) without prejudice, particularly when participation might involve contributions of technical know-how that could conceivably end up as part of a future tender specification. Outcomes from ILTF advice included the need for agreements with external collaborators to define tightly the areas of collaboration, set out clearly the background IP of the parties involved, and explicitly note the expected operational lifetime for the agreement. Agreements should also cover the issues of foreground IP, joint IP and licensing.[14]

## 10.5 SPDO Approach and Priorities

In late 2008, following the transition of the ISPO to its new home in the University of Manchester (UK) a new team was recruited under Project Director Richard Schilizzi, and established as the SKA Program Development Office (SPDO) (with the SPDO acronym quickly becoming referred to as “speedo”).

In April 2009, the role of Industry Participation Manager was taken up by Phil Crosby, who was seconded to SPDO for 2 years while researching his PhD on mega-science projects. Crosby’s background in high-technology industry participation brought advantages in support of the PrepSKA WP5 effort (see below and Sect. 4.4), and the development and implementation of an industry engagement strategy for the SKA project.

PrepSKA WP5 was formally titled “Procurement and Industrial Involvement” and when kicked off in April 2008 in Perth, Australia, consisted of an ‘oversight’ group of ten representatives from across the SKA project, led by Corrado Perna, from the Italian National Institute for Astrophysics (INAF), Italy. WP5 contained seven specific tasks, or outcomes, to be met within the stated period of 36 months. These involved; general procurement guidelines, an inventory of relevant member country industries; a cost-benefit analysis of procurement models; and work leading to a draft procurement model. Crosby and Schilizzi broadened and clarified the outcomes assigned to SPDO into four pragmatic objectives relating to industry and global procurement.

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[14] hba.skao.int/SKAMEM-80 ISPO Engineering WG-Industrial Liaison Task Force, Hall, P. & Khan, S., 2006

**Table 10.1** *The four objectives relating to industry and global procurement undertaken by the SPDO*

| Objective 1 | Main Tasks |
|---|---|
| Development of global industry engagement strategy (IES) for SKA | • Identify and map out SKA consortium players, and their industry players<br>• Conduct fact-finding missions on member country regional plans, government policies, and industry relationships<br>• Investigate current 'best practice' models for industrial engagement<br>• Develop the SKA industry engagement strategy (IES) for the SKA. |
| Objective 2 | Tasks |
| Support of PrepSKA WP5 activities | • Establish working arrangements with INAF representative (C. Perna).<br>• Conduct collaborative work to research and produce procurement policies, approaches, procedures, applicable to the SKA project.<br>• Assist design and creation of industry database.<br>• Arrange & conduct country/company visits to survey and validate industry capability and procurement models. |
| Objective 3 | Tasks |
| Development of IP strategy for the SKA project | • Research IP environment in regions and develop a draft interim IP management policy for the SKA.<br>• Arrange & conduct country/company visits to discover acceptable models for IP management in mega-science.<br>• Develop practical system to track SKA IP. |
| Objective 4 | Tasks |
| Harmonise approach of 'regions' to development and networking of industry capability for the SKA | • Conduct situational analyses with regional representatives.<br>• Draft agreement for uniform approach to development & application of industry capability.<br>• Document the process for an audit of industry capability. |

The SPDO's core effort during the PrepSKA phase was roughly grouped according to telescope design outputs. (See Chaps. 4 and 5.) The specific WP5 tasks and outcomes were encompassed in four objectives depicted in Table 10.1 below.

The SPDO focused initially on Objectives 1 and 2, the first requiring substantial research and analyses in both public and private sector policies, as well as best-practice models for industry engagement. The latter involved development of a collaborative working arrangement with PrepSKA WP5 leader, Corrado Perna (INAF) together with a Rome-based consultant (Riccardo Colangelo), bringing expertise in European procurement models. Perna coordinated the collaborative processes while the SPDO's Crosby provided specialist experience in global industry participation. Whilst WP5 commenced with a promising suite of documents and initial meetings, (e.g. WP5 Draft Roadmap, work plans and action lists), there was little sustained interest from the WP5 oversight committee. After early concerns by the SPDO about missed milestones, the planned bi-monthly meetings were replaced by periodic progress discussions at INAF in Rome, with the actual document production more effectively executed in Crosby and Perna's respective offices and polished via email exchange.

## 10.6 Broad Industry Engagement Policies and Principles

A vital task within the SPDO to develop an effective industry engagement was to map out the project-industry ecosystem, especially (though not exclusively) among the Member countries. As a first step in understanding the industrial landscape across the SKA project, it was necessary to identify and connect the people nominated from the various SKA Consortia, so they could act as an informal group able to offer local and global advice from their region/country. These Industry Liaison Officers (ILOs) advised on industry engagement matters, government industry policies, national and institutional procurement rules, and international IP management.

The initial nominees became the 'point of contact' for interaction with industry-knowledgeable people from each of the countries involved in the SKA. This meant including business groups, legal and economic advisors, and other relevant associated sources, as well as acting as the local information channel for SPDO discussions. Commencing in September 2009, an SKA Industry Newsletter was produced by the SPDO which contained contributions from the ILOs in actual and potential Member countries, with the first regular updates from the UK, Australia, South Africa and the U.S. (See Table 10.2). Ultimately, Portugal, Spain, New Zealand, and South Korea added ILOs from their respective nations.

Early exchanges across this group revealed that, while central co-ordination of industry engagement was appreciated, not all SKA partners were entirely comfortable with a free exchange of information which sometimes involved contractual matters or commercial relationships. While the key Member countries (including the potential

**Table 10.2** *The initial group of member country Industry Liaison officers*

| | |
|---|---|
| UK | Peter Wilkinson (UMAN), Andy Faulker (UCAM), Sherrie-Lee Samuels (STFC), Penny Goodman (STFC) |
| Australia | Mike Bryson (DIISR), supported by panel from CSIRO, ICRAR, ASKAIC & WA Department of Commerce |
| Canada | Bob Este (UCalgary), Kerry Whelan-Seifried (NRC) |
| China | Feng Wang, Yu Lu (CTI), Suijian Xue (BAO), |
| Germany | Michael Kramer (MPIfR) |
| India | Yashwant Gupta (NCRA) |
| Japan | Noriyuki Kawaguchi (NAOJ), |
| Netherlands | Arnold van Ardenne (ASTRON) |
| South Africa | Willem Esterhuyse (SKA SA), Tshepo Seekoe (DST), Faranah Osman (SKA SA) |
| USA | Lynn Baker (Cornell U) |

site and headquarters host countries) soon found their comfort level in terms of describing industrial arrangements, others declined to openly contribute, perhaps not wanting to jeopardise relationships built over time, or through concerns over breaches of IP or confidentiality. This reluctance lessened over time, but still resulted in a reduced visibility of the industrial relationships landscape of the SKA project.

Nonetheless, as the SPDO became more aware of Member country national industry development policies, favoured suppliers, and procurement sensitivities, this information was used to inform a draft industry participation plan being developed by the SPDO and reviewed by the ILOs. By mid-2010, the first edition of the SKA Industry Engagement Strategy (IES) was released[15], including a description of the project and goals in terms familiar to industry. This included the expectations of industry and principles of engagement, global capability assessment, communication of industry opportunities, and procurement principles and risks. This document continued to be updated and re-released periodically to maintain alignment with project policies and the maturing landscape and served the project into the 2020s.

Along with contributions from the Member countries, the SPDO felt it was important to consult first-hand with other mega-science projects, especially in terms of national engagement, procurement, and industrial participation. Members of the SPDO team had already visited several large infrastructure science/engineering projects to discuss success drivers for mega-science projects, including ALMA, ASKAP, the Australia Telescope Compact Array (ATCA) , Iridium, LIDAR (Antarctica), and the OPAL nuclear reactor in Australia. During 2009, Crosby conducted further investigations at the HIPER high-power laser project, the International Linear Collider, the International Thermonuclear Experimental Reactor (ITER) fusion project, the Large Hadron Collider at CERN, and the LOFAR and MEERKAT telescopes. Interestingly, apart from chance interactions at academic gatherings, there seemed to be few attempts by Member countries themselves to consult local contemporary large-scale projects. Although disappointed in this, reports from SPDO visits were made available to the Member organisations.

## 10.7 Evolution of Project and National Industry Priorities and Initiatives, and Growth of Enabling Organisations

A crucial adjunct to the fieldwork described above, was a series of interviews in 2009 with national government representatives in the SKA Member countries of Australia, China, Italy, Netherlands, New Zealand, South Africa, and the UK. The focus of these meetings was to gain an understanding of policy support and initiatives for new technology development, and how research and development linked between industry, institutes and Universities, and the national science organisations (e.g. STFC, CSIRO, INAF etc.).

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[15] hba.skao.int/SKAHB-554 *SKA Industry Engagement Strategy,* Crosby, P., 2010

An important outcome of this process was the emergence of new or existing industry consortia, in some cases formed specially to address the potential opportunities for industry likely to be generated by the SKA. Mostly these cluster organisations took the form of a loose collection of 'interested' companies, but in some instances, they were much more mature and outward looking, e.g. ASKAIC in Australia, and the UK's KTN. Interestingly, a U.S. industry group emerged in this period under the stewardship of Bill Boas (System Fabric Works). Consisting originally of STADCO, and Cray Computer, it later grew to include in-principle membership from several US high-tech firms but was not sustained following loss of continuing funding for SKA participation in 2011.

The mixture of profiles for such industry groups added to the complexity of the landscape as the SKA became better known, and in some instances became problematic when industry expectations were raised and then failed to be matched by the emerging project budget and schedule. Over time, interest and investment by commercial firms waxed and waned as their appetite adjusted to the inevitable delays towards major procurements, and as consortia activity grew or declined in the Member countries (see Table 10.3).

In the SPDO era, the general (though ultimately incorrect) understanding was that most of the procurement would be 'open market' and that the most of the (then) estimated €1.5 billion budget would be allocated through project contracts. This message was carried through to national industry meetings and project roadshows, inevitably causing dismay when the realities of project schedule, cost, number of interested parties, and funding agency procurement policies emerged. Examples include the telescope control software eagerly pursued by India, and high expectations of orders by regional firms in Western Australia for thousands of mass-produced dipole antennas.

**Table 10.3** SKA Project—Industry participation arrangements in 2012

| Country | Mode of local industry engagement | Type |
|---|---|---|
| Australia/New Zealand[a] | ASKAIC | Formal Consortium |
| Canada[a] | Canadian Industry Cluster | Managed Cohort |
| China | Chinese Gov/Industry Collective | Vendor database |
| Germany/Spain/Portugal | Green Energy Alliance, Industry Consortia | Managed Cohort |
| India | Gov/TATA Consortium | Managed Cohort |
| Italy[a] | SKA Industry Consortium | Formal Consortium |
| Japan | Japanese SKA Industry Consortium | Loose Alliance |
| Netherlands[a] | Dutch industry Alliance | Loose Alliance |
| South Africa | SKA Supplier Data base | Vendor database |
| Spain | Industry Consortia | Managed Cohort |
| UK | SKA Industry Group | Formal Consortium |
| USA | Industry Alliance | Loose Alliance |

[a] Institutes and industries in these countries subscribed to an international MOU for SKA Industry Engagement Collaboration

Table based on a graphic generated by P. Crosby (SKA Project Office) and J. Humphreys (ASKAIC) in 2012

In some sense, this initial expectation that there would be a large, centralised budget and an open international procurement matched the belief that the siting of the project should be determined by scientific grounds alone. And just as there was with the siting decision, there was a price to be paid for greater involvement and interest of the national funding agencies: the realisation that industrial contributions and returns on investment were an important element of the case that needed to be made at the national level for funding the SKA. Funding agencies increasingly made it clear that they were reluctant to commit large sums of money to SKA without at least a strong expectation that a good fraction of what they contributed would be spent in their own region, and the procurement policy and industrial engagement started to reflect that thinking.

## 10.8 Reaching out to Industry

By the end of 2009, the SPDO had a well-established view of the high-level industrial landscape for the SKA project, and effective communication pathways ready to integrate national policies. Personnel in SPDO were in place to address industry enquiries and maintain consistent messaging to stakeholders on the topic. Most importantly, regular contact and consultation was established through scheduled telecons etc.; a move well supported by Member representatives.

With the SPDO located in Manchester, there was a tendency for UK based companies (and in some cases European firms) to want to visit the project office in person and meet with the project specialists. Occasionally this extended to invitations, especially from British organisations, to inspect industry facilities, or speak at technology meetings. Examples of this include a visit by Crosby and Kobus Cloete (SPDO Project Manager) to the BAE Systems radar testing facility on the Isle of Wight to discuss strategic involvement through testing facilities, SPDO support for a major KTN networking event in London, and Crosby speaking about applications of SKA engineering at the Astronomy Technology Centre, Edinburgh.

While in many cases these interactions were welcomed and useful, it did create the perception that UK companies might have an unfair advantage. Although in time this view was dispelled, the perception was partly reinforced when SPDO staff readily attended UK (and European) industry meetings (e.g. the UK Trade Investment KTN gatherings) and gave talks at European radio astronomy and big science events. While this was primarily a result of simple proximity with no intent to favour European markets, Schilizzi did acknowledge the risk early and instructed the project office to maintain a Register of Industry Contacts throughout the SPDO era. The register recorded all such interactions, and the purpose of the meeting or event, so that if a future tender bidder believed that pre-contractual contact with the

SPDO was influential in the contract award, the nature and scope of the visit could be made clear.[16]

Occasionally a special meeting, or series of meetings, was convened to address a particular challenge of the SKA project, an example being the Power Investigation Task Force (PITF) meetings. The agenda for the PITF kick-off meeting in Manchester in October 2009[17] shows broad participation from the project, academia, and industry, with representation from the candidate site countries. Parsons-Brinkerhoff were engaged (by SPDO) to furnish detailed reports (Parsons-Brinkerhoff, 2009)[18] concerning supply/generation technologies, renewable power systems, and trends in a world with carbon trading.

Consultants were also used to advantage where expert opinions and specific data was required, for example during the site evaluation process where advice was sought from Parsons-Brinckerhoff, UK (basic Infrastructure components, power studies), Analysys Mason, UK (long term RFI environment), Kroll Security Group, USA (security), Pinsent Masons, UK (legal services), and KPMG, UK (customs and excise regulations).

The PrepSKA WP 2 meetings on SKA Design[19] offered both good timing and a platform for SPDO to speak on effective industry engagement approaches, and the challenges associated with 'lock-out' and care with pre-contractual collaborations with commercial partners. The WP 2 meetings morphed into annual Engineering meetings with increasing industry attention (see Fig. 10.3). Ostensibly, these meetings were not open to general industry, however certain commercial representatives did attend either through personal invitation or simply showing up. Eventually, due to sustained interest from industry, sessions were added to the agenda to permit some participation.

Industry engagement reappeared on the SSEC meeting agenda in October 2010, with Schilizzi presenting a report on PrepSKA WP5, and the SKA IES. In particular, the SSEC were keen to learn of progress against objectives, particularly the "Towards A Procurement Model for the SKA" document, and a summary of the European Cooperation in Science and Technology (COST) meeting in Rome earlier that year (see below).

This constant tension between a desire to encourage industry involvement while trying to avoid the associated perceptions of favouritism required careful handling at best, and damage control in a few instances when the project technology specialists accidentally included specific supplier specifications in their presentations. Conversely, when the SPDO indicated reluctance to engage with international industry citing the pre-contractual difficulties, it received criticism especially from the

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[16] The register was not maintained after the transition to SKAO in December 2011.

[17] hba.skao.int/SKAHB-520 PITF agenda Oct 2009 v1 0

[18] hba.skao.int/SKAHB-549 *Review of Power Generation Technologies, Trends and Costs.* Parsons-Brinkerhoff. 2009.

[19] The principal objectives of WP2 were to produce an implementation plan for the full SKA and a detailed costed system design for Phase 1.

**Fig. 10.3** The SPDO team at the WP 2 industry event in the Manchester Museum, March 2010

telescope host countries for failing to take advantage of best-practice commercial experience. Schilizzi's response to stakeholders was that the SPDO did not have any funds for industrial contracts for SKA, and until there were additional funds in the pre-construction phase, they would do better to approach the institutes designing and building SKA precursors and pathfinders.

Eventually the SPDO developed a workable solution to this issue through creation of a document called a (non-binding) Statement of Mutual Interest (SoMI). Based on an earlier template from the ILTF, and approved by a succession of legal advisers, the purpose of the SoMI was to:

- Establish a working framework so that certain organisations that had shown a willingness to become strategically engaged with the SKA project could interface in a more structured way with the SPDO on a 'mutual interest' basis.
- Set out the intentions, understandings, and topics that both parties had a shared interest in, and the subject areas that were to be discussed.
- Describe the distinct capabilities and needs of the parties, in order to allow some interchange of ideas and advice around technical innovation and direction, and project management expertise. (Any exchange of confidential information was covered by a separate non-disclosure agreement.)
- Provide limited access for the commercial party to have closer contact with SKA stakeholders, and opportunities for strategic engagement e.g. access to technical specialists.
- Permit access to commercial equipment and testing environments

Importantly, the SoMI was non-binding, contained no legal obligation for either party or any of the participants, and there was to be no exchange of money. Intentionally, only a small number of SoMI's were signed, these were with IBM, Cisco, Selex, Nokia-Siemens, and BAE Systems, as representatives of their various business/technology sectors (see Fig. 10.4). The use of the SoMI instrument proved successful, with much useful advice provided to the SKA project including legal, contractual, technical, access to test facilities, and strategic direction.

By way of example, one of the first positive outcomes from the SoMI arrangement was with BAE Systems. The SPDO team attended a one-day High Technology Project Management and 'lessons learned' workshop arranged with BAE project specialist, Ian Williams, covering key techniques of mega-project management.

An important workshop addressing the non-science benefits of the SKA was held in Rome in 2010 under the auspices of COST. This major event in Rome involved industry aspects of engagement with the project and supported an economics business case approach to governments.[20] In attendance were noted experts from industry, science and technology institutes, business schools, SKA Member country project representatives, and ministry officials. In all, over 16 nations were represented, working together and in break-out themes. The meeting distilled the

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[20] hba.skao.int/SKAHB-521 Extract from the Minutes of the SSEC teleconference on the COST meeting, 10 February 2010,

**Fig. 10.4** Signing of SoMI with BAE Systems at Jodrell Bank (l-r) Richard Schilizzi, SPDO; Les Gregory, BAE; Steve Watts, University of Manchester

major benefits that could be expected from the SKA and other large scale infrastructure research projects, in four key areas: information and communication technology (ICT), renewable energy, global science-industry-government linkages and human capital development.[21] The COST workshop was politically important since it offered evidence that funding agencies and governments took the SKA seriously.[22]

By the time of the SKA preconstruction phase that began in early 2012, the former SPDO had transformed into the new SKA Organisation (SKAO, see Chap. 5). Given the likelihood of significant money being spent relatively soon, a more formal and somewhat more arm's length position regarding industry engagement was adopted, and in early 2012 the SKA Project Office conducted an Industry

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[21] hba.skao.int/SKAHB-140 Report on the Strategic Workshop on the *Benefits of Research Infrastructures beyond Science*: *the Example of the Square Kilometre Array (SKA)* Committee on Science and Technology (COST), 2010

[22] hba.skao.int/SKAHB-535 *Non-astronomy benefits of the Square Kilometre Array (SKA) radio telescope,* Crosby, P & Bowler, J. (2010). COST Workshop Summary, SPDO, version 1.6.

Expression of Interest (EoI) exercise related to the work anticipated to be contracted to industry and managed as described in the 2010 SKA Project Execution Plan (see Chap. 4). During this phase, the SKA Organisation intended to enter into agreements with a small number of consortia that would be responsible for executing large portions of the work, especially at the element level of the SKA. Consortia (industry/ institute collaborations) were invited to bid against work packages described in a detailed Work Breakdown Structure (WBS) /Statement of Work.

The aims of the EoI process were to establish a snapshot of the coverage of the interest to participate/execute the work as defined for the SKA preconstruction Stage 1 WBS and facilitate consortia formation by the gathering and utilisation of the information provided as part of the EoI process.

Following the release of the documents the SKA Project Office clarified that SKA consortia, organisations and industry were all welcome to participate. This latter group initially responded with key questions regarding how they might get paid for their effort, whether industry could lead a work package consortium, and how would IP be controlled. The results of this EoI were made public in a report dated June 2012 titled "*Results of the preconstruction phase stage 1 expression of interest (EoI)*".[23]

## 10.9 The Development of Procurement Policies and Models (PrepSKA WP5 Effort)

Central to the early work for PrepSKA WP5 was the collaboration between Crosby (SPDO) and Corrado Perna (INAF) on the development of a procurement policy and associated papers and guidelines designed to encompass the future specific needs of the SKA project. It also provided a workable framework for global procurement encompassing both central SKA Project Office purchases, and in-kind supply from Member and non-Member countries. A key input for this work was research and examples of actual procurement models from other international mega-science projects.

In accordance with the agreed schedule of deliverables for the PrepSKA project (later slightly modified), it was envisaged that the WP5 effort be staged, with the first reports covering procurement risks and options that could be socialised across the SKA governance committees, as well as a more practical review by those leading the closely associated PrepSKA WP 2 design collaboration. Table 10.4 summarises the PrepSKA WP5 deliverables.

Concentrated PrepSKA WP5 work continued through 2009, resulting in the first deliverable, a guideline for WP 2 procurement released in September 2009.[24]

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[23] hba.skao.int/SKAHB-538 *Results of the Preconstruction phase Stage 1: Expression of Interest (EOI),* Cloete, K. June 2012.

[24] hba.skao.int/SKAHB-550 *Guidelines for Procurement for WP2,* Perna, C., Colangelo, R. & Crosby, P., 2009

**Table 10.4** *PrepSKA WP5 deliverables as originally conceived and approved, and the modified final outcomes*[a]

| Del. no. | Deliverable name (Original) | Deliverable name (Final) |
|---|---|---|
| 5.1 | Guidelines for procurement for WP 2 | Guidelines for procurement for WP 2 |
| 5.2 | Industry inventory | Industry inventory database (beta version created only)<br>Industry capability assessment process model and tool |
| 5.3 | Analysis of procurement models | Analysis of procurement models |
| 5.4 | Risk analysis of the procurement models | Risk analysis of the procurement models |
| 5.5 | Deliver report on procurement models to the SKA forum | Deliver report on procurement models (options) to the SKA forum |
| 5.6 | Deliver options paper for funding agency[b] | Deliver options paper for funding agency (essentially the above report). |
| 5.7 | Incorporate White Paper on final procurement model in the PrepSKA Final Report | Release of white paper on final procurement model, "towards a procurement model for the SKA" |

[a] hba.skao.int/SKAHB-522 PrepSKA WP5 Progress report & Deliverables Update 2010

[b] Although the term "Funding Agency" was used in the original deliverables document, The PrepSKA deliverables were approved by the PrepSKA Board, and conceived during the proposal process

Attention then turned to deliverable 5.2 which ambitiously addressed not only the design of an industry capability database[25] suitable for centralising and storing data from commercial suppliers across the SKA Member countries, but also a model (and ultimately a practical tool) for effectively gathering this data. The thinking behind this expansion of scope was simply that without some formal consistent methodology for gathering global industrial capability field data (and other national intelligence), the proposed database would be ineffective.

The INAF team developed a prototype database, which was then refined through practical testing using data gathered through SPDO's register of industry contacts. Over several iterations, the database did become workable however by 2011 it had become clear that other commercially available systems were easily adaptable to SKA's needs, relieving INAF from having to manage bespoke software with its inherent need for technical support.

## *10.9.1 SKA Global Capability Assessment Tool*

Meanwhile the SPDO proceeded with the crafting of an SKA Global Capability Assessment tool. The model was developed as an initial strategic review process to

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[25] hba.skao.int/SKAHB-539 *Strawman: Industry Capability Database.* Crosby, P., 2009

assess the maturity and industrial capability of each SKA country/region to achieve and sustain contractual supply expectations (especially concerning on-time and on-quality deliveries) and expose any significant trade barriers.[26]. The model did not replace any particular supplier assessment conducted as part of a specific procurement process during the preparatory or execution stage of the SKA project. In particular, the tool was designed to enable:

- identification of any gap(s) between the actual assessment and the expected capability, of SKA Organisation and country/region or key suppliers,
- facilitation of planning to cover the gaps identified during assessment,
- self-assessment by country/region or key suppliers,
- assistance with pre-selection of country/region or key suppliers for the development/construction of the SKA,
- companies to assess/select sub-tier suppliers for the development/construction of the SKA,
- Government agencies to assist in focusing support schemes on industry capability growth.

The output could also inform any decision to: (i) implement strategic foreign exchange contracts ('hedging') ahead of forecast procurements at the broad global scale, and (ii) adopt a decentralised procurement model.

Overall, the model's purpose was to obtain a global view of strengths and weaknesses regarding regional, national, and business processes in relation to practical capability to deliver goods and services to the SKA project. The information derived was intended to provide useful input to procurement planning and help to strategically direct the Request for Quotation / Request for Tender processes and major contract award phases of the project. The tool, tested in both Australia and South Africa, essentially tackled the question—who can reliably and competitively do what? Unfortunately, following transition to the SKA Organisation at the end of 2011, the Global Capability Assessment tool fell by the wayside. In retrospect, the benefits of the model were never properly realised, and more recent observations of the pre-contractual phase indicate that it would have been a useful tool.

Through 2010 and into 2011, the PrepSKA WP5 team of Crosby (SPDO), Perna (INAF), and Riccardo Colengo (procurement consultant) continued research into analogous and best-practice procurement models for mega-science projects,[27] initially focusing on deliverable 5.3 relating to procurement model analyses, based on experience at national and international institutes (e.g. CERN, NASA, ITER).

The report, delivered in January 2010, built on deliverable 5.1 and addressed contracting models, procurement specifications, terms and conditions, quality assurance and risk, and covered approaches to ensure fairness and competitiveness. Importantly, specific experience was included from (then) recent and current

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[26] hba.skao.int/SKAHB-551 *SKA Capability Assessment Model v1.3,* PrepSKA Work Package 5 report, 2011.

[27] hba.skao.int/SKAHB-523 Industry Engagement—Summary of Activities—June 2010

international projects that informed and aided development of practical procurement policy and processes for the SKA. (Crosby, & Perna, 2010).[28]

December 2010 saw the draft release of the PrepSKA WP5 Deliverable 5.4: a Procurement Options and Risk report (Crosby & Perna, 2010).[29] This document presented a summary of the SKA procurement environment and application of the procurement models examined and discussed in the previous report. The project required a good understanding of the procurement rules and legislation applying in the major trading regions of the participating countries, and a summary of such intelligence was included together with realistic options for operating the procurement office, and the associated risks. The paper also offered commentary on approaches to Member contract 'balancing'—a prescient statement given the eventual direction of SKA procurement towards Fair Work Return.

The penultimate output from the PrepSKA WP5 Working Group was intended to be Deliverable 5.5: a report containing an inventory of national policies and SWOT analysis of refined procurement options for the SKA.[30] However, it was decided to combine reports 5.3, 5.4 and (a new) 5.5 into a single document that would eventually mature into a fully developed report integrating the research, findings, and recommendations as a White Paper.[31] Meanwhile the required deliverable defined as "5.5" (in essence, explaining how to define a procurement policy and set up procurement processes to build the SKA) was drafted for discussion during a procurement workshop in late October 2011 in the UK (concurrent with the annual PrepSKA WP 2 meeting).

Feedback from the SKA community contributed significantly to teasing out the most useful areas of advice, and indeed, socialising of draft project policy documents realised many benefits. One example of this was an open meeting of the PrepSKA WP5 group prior to the main programme of the International SKA Forum 2011 (see next section) to review progress with procurement policy. The need for a broad industry capability 'scouting' activity was aired and with positive support, planned to commence later that year.

The final practical deliverable from PrepSKA WP5 (5.7) was a formal document encompassing a compressed version of all the WP5 effort, research, and advice in the form of a White Paper[32] for tabling at the International SKA Forum 2012, and later distributed project -wide. Titled "Toward a procurement model for the SKA", the document's purpose was to enable effective design of the procurement system (policies, strategic sourcing, models, processes, supply chain considerations, and functional structures). Aimed at a general audience, the White Paper included a thorough discussion about work breakdown structures and supply chain design and

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[28] hba.skao.int/SKAHB-533 *SKA Procurement Options and Risks,* Crosby, P & Perna, C. (2010)

[29] hba.skao.int/SKAHB-556 *SKA Procurement Report,* Crosby, P., & Perna, C., 2010

[30] hba.skao.int/SKAHB-524 Detailed workplan for Crosby at SPDO

[31] hba.skao.int/SKAHB-525 Work Package Task Timeline v4 2011

[32] hba.skao.int/SKAHB-552 Toward a Procurement Model for the SKA. Perna, C., Crosby, P. and Colangelo, R., August 2010

management, up to acquisition management. It also included an analysis of options for policies and models for procurement made at a level compatible with the (then) current level of definition of the project. Global, local, and agreed-on procurement models were introduced and discussed and fitted in the framework of the SKA project constraints and the international procurement environment.

The White Paper contents were divided into two parts: Part A covering procurement strategies and the procurement framework, and part B covering options for procurement models for the SKA. The final version of the White Paper was submitted for an independent risk analysis, performed by an external consultant who evaluated the impact and weight of the applicability of the proposed procurement options in the framework of the SKA constraints. This was found to be a very worthwhile task and added polish to the final version.

## 10.10 Strategic Industry Engagement

An annual focal point, especially for external project stakeholders, was the annual International SKA Forums. These were first held in the potential site host nations (Australia and South Africa), later migrating to other Member countries and becoming larger events with more prominent industry attendance.

In June 2010, ASTRON, and its parent organisation, the Dutch Research Council (NWO) hosted ISKAF 2010. As with previous fora, many different meetings and activities were organised in and around the event. The climax of the week was the SKA Forum session itself, attended by scientists, engineers, industrialists, funding agencies and government, including many presentations from the broader SKA community. A trade exhibition was held with around 30 companies and organisations represented. Maria van der Hoeven, the Dutch Minister of Economic Affairs boosted local and international industry interest with the announcement of a new €2.1 M financial investment in ASTRON’s SKA technology program. This was specifically for the Aperture Array Verification Program (AAVP) led by ASTRON, setting a pattern of national government announcements riding on the SKA’s industrial opportunities.

ISKAF 2010 included the Connecting Industry, Science and Society (CISS) workshop, organised by local group Sensor Universe. The event focused on exploring cooperation between science and industry to foster industry-scientist interaction from an early stage, with an outcome being the Dutch Industry position paper on SKA, jointly produced by NXP, Siemens and IBM. The document described the importance of SKA to the Netherlands from an industry perspective, making a clear statement to the Netherlands Government and outlining the value of the SKA project to Dutch industry.

The following year, progress with development of SKA procurement guides and industry engagement models again featured at the SSEC meetings, with a study of options for IP management tabled.[33] The International SKA Forum 2011 was held in Banff, Canada, and hosted by the National Research Council (NRC). This annual event once again brought together representatives from science, national agencies, industry, and other stakeholders to review and discuss progress following the release of the pre-construction phase Project Execution Plan (PEP).[34]

Reflecting a fresh emphasis on industrial participation, the organisers of the various regional and national industry clusters each gave an overview of their profile, structure, and anticipated benefits. Speakers from Australia, South Africa, Italy, UK, The Netherlands, and Canada each described how their clusters were growing in maturity and cohesiveness as they gained involvement in the SKA project. Delegates at the mid-week Forum Day in Banff were treated to stimulating keynote presentations from R&D executives from IBM and Boeing, each expressing the opportunities and challenges associated with large, complex, high-technology projects of the scale of the SKA. The upbeat mood for the commercial and scientific opportunities associated with the SKA was palpable, with industry expectations possibly peaking at this event.

The Industry and Engineering session at the Banff meeting was organised by the SPDO and was the largest to date at any International SKA Forum. Over 50 companies joined a similar number of science and institutional delegates to conduct a 'deep dive' into the industrialisation aspects of the SKA project. After several scene-setting talks by SPDO staff and from Cisco, participants were offered a choice of

**Fig. 10.5** Wayne Goss (IBM, left) as Master of Ceremonies for the Industry and Engineering meeting at SKA2011 in Banff, Canada

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[33] hba.skao.int/SKAHB-515 Extracts on Industry Engagement from the Minutes of ISSC and SSEC meetings from 2003 to 2011

[34] hba.skao.int/SKAHB-526 Industry Meetings agenda, SKA Forum, Banff 2011

**Fig. 10.6** PrepSKA WP5 group at SKA2011, Banff, Canada. Left to right: Corrado Perna (INAF), David Luchetti (Australian Government), Peter Dewdney (SPDO), Riccardo Colengo (INAF Consultant), Simon Haynes (STFC), Simon Berry (STFC), Rob Millenaar (SPDO), Maaike Damen (NWO), obscured, Miriam Roelofs (NWO), Patricia Vogel (NWO), Phil Crosby (SPDO)

seven break-out sessions, each focusing on a particular technical domain and led by senior personnel from industry (see Fig. 10.5). The expert groups each reported back to the Forum with comments on future directions for their technologies and offering feedback concerning the value industry could bring in terms of R&D, strategic participation, supply, programmatics and experience (see Fig. 10.6).

As with other SKA-related events, the International SKA Forum 2011 afforded an opportunity for several industry-related announcements. Cisco became the fourth international company to sign the Statement of Mutual Interest (SoMI) arrangement with the SPDO, thus opening the way for specific interactions concerning advanced digital signal transport technologies. Also John Humphreys from GIC, the secretariat of the ASKAIC, proposed a global ‘cluster of clusters’ industry network to support the SKA project[35] but this did not materialise.

The SPDO remained very active in this period in terms of industry events and building the project profile with presentations at many SKA meetings, including industry gatherings for the KTN in London, and at the Solar Flair event in Durham, UK, where the Boeing subsidiary, Spectrolab Inc., featured—heralding a fast-growing interest in the power supply aspects of the SKA. This meeting gave excellent exposure to a wide range of solar power experts and companies and led to important renewable energy contacts later in Germany. Meanwhile the Power Investigation Task Force (PITF) met in Oxford, where a speaker from Prudent Energy presented Vanadium Redox Battery technology as a practical option for a solar array energy storage system, together with some sobering data on the realities of the required scale of a renewable power infrastructure for the SKA.

Throughout the period 2010–2012, the SPDO continued to meet and talk to industry players regarding the project requirements, including a visit to the Selex Galileo Edinburgh facility to inspect radio frequency design and fabrication capability, meetings with IBM UK to discuss project management applications in their suite of software, and discussions with Circadian Power (UK) to get industrial perspectives on concentrated solar power technologies. Similarly, the challenges in relation to high-performance computing were addressed by Data Direct Networks (DDN) who outlined their Storage Fusion Architecture for balanced, high-performance storage systems. UK member support for the project was boosted by university visits and meetings between Manchester and Cambridge personnel and many high-technology companies.

PrepSKA WP 2 events were also highly valued and well attended by the key engineering staff in the various participating countries, their consortia groups, and attendant industry representatives. As the PrepSKA work gained pace and Conceptual Design Reviews and other technical evaluations were undertaken, the need for effective communications with industry about future procurement became ever more paramount, as evidenced by the inclusion of the WP5 team at WP2 meetings, and serious interest shown by representatives from the SoMI) partners (Fig. 10.7). These events allowed companies to understand the status of the project and the anticipated work programmes, as well as giving opportunities to meet the domain experts from the SPDO and network with other companies interested in the project.[36]

While the Member countries each managed their domestic relationships with industry with varying effort and success, there remained a small number of multinational companies that invested substantial resources both in-country, and transnationally, in keeping close to the SKA project and its key protagonists. Examples of these included Boeing (initially, although later largely withdrew),

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[35] hba.skao.int/SKAHB-527 Industry Consortium MoU, Humphreys, J, 2011

[36] hba.skao.int/SKAHB-553 *Square Kilometre Array—Pre-Construction Phase*. Rix, N., 2012

**Fig. 10.7** SPDO personnel and SoMI partners at the PrepSKA WP 2 meeting, Manchester, Oct 2011 (l to r): Phil Crosby (SPDO), Peter Matthewson (BAE Systems), Richard Schilizzi (SPDO), Tony Kinghorn (Selex-Galileo), Gerlinde Bedoe (NSN), Ian Kennedy (CISCO), (inset) Jan Blommaart (IBM)

Cisco, and IBM which proactively remained engaged with the SKA. (See Box 10.2).[37]

**Box 10.2 The IBM story**

American computing giant IBM was particularly supportive of the SKA from the project's early conception days based in The Netherlands. Leading IBM's involvement was Bruce Elmegreen from IBM's Watson's Research Laboratories in New York, a noted astrophysicist and development engineer. Elemgreen (along with US colleagues Henry Brandt, Tom Liebsch, and Jan Blommaart in Holland) maintained close and regular contact with the SKA project through the SPDO years and beyond, providing valuable industry

(continued)

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[37] hba.skao.int/SKAHB-530 Interview Bruce Elmegreen with Phil Crosby, April 2020

**Box 10.2** (continued)
advice on large-scale computing as well as keynote talks at the annual International SKA Forums,[38] [39] and at the important COST meeting in Rome.

IBM contributed valuable strategic input concerning the trajectory of computing technology, including cost per computation, the outlook for Moore's Law, storage and memory, and technology roadmaps in relation to processing hardware, processing speed, and power consumption. Unlike CISCO which also contributed crucial design intelligence but looked for more immediate design 'down-selects', the IBM team worked on a 10+ year timescale, fully expecting delays and a later partitioning of the project into SKA Phase 1 (with its cost cap) and SKA Phase 2. Moreover, involvement with the Dutch LOFAR instrument (which employed an IBM Blue Gene machine) helped IBM define the need for future exascale streaming analysis (a.k.a. computing-on-the-fly) that would ultimately underpin the SKA as an ICT machine.

Nonetheless, IBM were very careful to adopt a firm position of working with the SKA project but remaining at arm's length in terms of detailed design input or proximity to the SKA Leadership. As Elmegreen noted in a 2020 interview, *"If we gave you so much technology input to your design, we would not be allowed to bid … because we would have an unfair advantage. Following procurement, another company could complain*". Elmegreen added, *"Maybe that hurt us, but we had no choice. [However] we always felt that we were listened to, we always felt welcome"*. There's little doubt that this finely tuned engagement worked well at the time, and will pay off in the longer term, with IBM continuing to brief the SKA team with new developments in the realm of exascale high-performance computing.

A point of tension observed by both multi-national and Member country industrial stakeholders (including IBM) was the 'make or buy' choice that would inevitably arise in the procurement era. While industry acknowledged the inspirational nature of the engineering challenge as outlined in the SKA IES,[40] many would-be suppliers were quick to point out the cost advantages of (COTS) technology, as against the largely academia-based push for bespoke solutions. IBM's Bruce Elmegreen characterised the SKA project as an almost perfect customer for something big and great, with excellent potential for discovery, and clear opportunities in adjacent markets, thereby making it an excellent candidate for collaboration with IBM's product development team. It is interesting to note that IBM even postulated the commissioning of an intercontinental cable for SKA data traffic, with revenue

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[38] hba.skao.int/SKAHB-558 *SKA and Industry: Cutting Edge Technology and the Cost Challenge*. Elmegreen, B., Presentation at the SKA Forum, Cape Town, February 2009

[39] hba.skao.int/SKAHB-559 *SKA—Impact of the Global ICT*. Elmegreen, B., SKA Forum, Assen, June 2010

[40] hba.skao.int/SKAHB-554 SKA Industry Engagement Strategy, Crosby, P., 2010

potential through leasing to other mega-scale data customers—just one idea among many imagined by industry excited by the inspirational nature of the SKA.

## 10.11 Ongoing Industry Engagement 2012

Following the establishment of the SKA Organisation (SKAO) at the end of 2011, the new SKA Project Office replacing the SPDO continued to interact with industry. Staff established contact with industry representatives to explore capability and technology pathways more broadly related to space science, with examples including Ciena Inc. (US), Orbit Communications (Israel), Vega Space (Telespazio VEGA, UK), as well as exploring new cryo-cooling technologies with engineers from Honeywell (US). Meanwhile, Crosby (by this time returned to Australia) facilitated meetings between top-level SKAO management and large-scale industrial project management (infrastructure) experts from Fluor Ltd., and Worley Parsons, in order to lift understanding around mega-scale infrastructure project management.

The SKAO Project Office continued to build its 'knowledge-bank' of mega-project management through high-level interactions with experienced multi-national firms and agencies. In March 2012, the International Centre for Complex Project Management (ICCPM) held its first Complex Project Management Roundtable in Australia. Crosby (SPDO) and Simon Berry (STFC) joined around 40 other mega-project experts from across the spectrum of government and the private sector, including aerospace firms such as BAE Systems and Thales. David Pitchford, Executive Director of the UK's Major Projects Authority, gave the keynote address and specifically addressed SKA in his speech. The closing remarks were given by Kim Gilles, Vice President Boeing Australia, who recognised the value of lessons learned through projects analogous to the SKA.

Both SKA precursors (ASKAP and MeerKAT) continued to engage with industry to support site engineering work, and electronics fabrication. In South Africa, contracts were put in place for the radio frequency chain, dishes, and receiver support. Tenders were announced for antenna positioners, and partners evaluated for the digitiser, timing and frequency reference, and science processing. ACTOM (Pty) Ltd, the largest manufacturer and distributor of electromechanical equipment in Africa, won contracts for providing major power distribution components.

In Australia, workshops held in Perth on SKA Power and SKA Networking attracted over 20 firms to review the known SKA requirements and Project Execution Plan phase work. ICRAR ICT established a number of industry collaborations including agreements with Data Direct Networks and ThoughtWorks. Fremantle-based (WA) company, Poseidon Scientific Instruments was awarded a A$1.3 M contract to help deliver a key SKA precursor located at the Murchison Radioastronomy Observatory (MRO).

In Europe, the VIA-SKA project (Viability study of the Spanish industrial participation in the SKA), produced a first survey of the capacities of Spanish industry in 2012. More than 40 companies showed their specific interest in areas ranging from design and manufacturing of antennas and aperture arrays to data processing and signal transport and synchronisation.

Discussions in Portugal, Spain, Germany and the Netherlands on sustainable energy options for the SKA led to an initiative to organise a two-day seminar in June 2012, with a focus on applications to the SKA.

In Canada, the University of Calgary hosted an industry workshop in April 2012, with the purpose of communicating the processes and timelines of the SKA pre-construction phase. The aim was to foster international linkages and the national collaborations between Canadian industry and government and university research and development laboratories for Canadian participation in the pre-construction phase of the SKA, as well as establish a Canadian SKA Industry Consortium similar to industry organisations established in other participating countries.

In March, UKTI KTN hosted a meeting for UK companies to learn about the overall structure of the SKA pre-construction phase. Nearly 60 organisations were represented—from major international companies to small- and medium-sized companies and specialist firms. An aspect that became clear at this gathering was the increasing credibility of the SKA project and its non-core benefits in terms of commercial participation, in some cases stimulating investment in technology design generally.

In September 2011, BAE Systems recognised Crosby and Georgina Harris (SPDO) for their collaborative efforts in early industry engagement with the SKA through the announcement of a BAE SYSTEMS Chairman's Award (Figs. 10.8 and 10.9).

**Fig. 10.8** 2011 Award ceremony at BAE Systems, Portsmouth, UK where Phil Crosby and Georgina Harris shared the Chairman's Award for work on the SKA with BAE Staff

BAE SYSTEMS

chairman's awards

SUPPORTING OUR TOTAL PERFORMANCE CULTURE

Capturing the imagination - the SKA SoMI

BENEFIT

An ultra-sensitive radio telescope that will combine signals from thousands of antennas spread across a continent to explore the formation of the universe.

TEAM

Eileen Fehily, Peter Matthewson, Terry Soame, Phil Crosby, Georgina Harris, Laurie Burgess

BAE SYSTEMS MARITIME BRONZE CHAIRMAN'S AWARDS

**Fig. 10.9** BAE Systems notice of the award presentation, which was for collaboration during the concept phase of the SKA mega-project

## 10.12 Effectiveness of Approaches to Industry

In the years prior to 2009, approaches to, and interactions with, industry from the major western SKA Members were essentially ad-hoc and opportunistic, relying mainly on past and ongoing relationships between members of the science and engineering teams and known, trusted suppliers. Many of these companies had worked successfully before with the scientific agencies and institutes, and in some cases collaborated in joint developments. By and large, such arrangements were appropriate and could often exploit contractual efficiencies through "preferred supplier" status, pre-approved schedules of components and/or labour, extensions of term contracts, or simply exploit goodwill. In South Africa and India especially, there was a preference for drawing on trusted (and in the case of EMSS Antennas in South Africa, co-located) suppliers, whereas in China the research teams looked mostly to government factories (e.g. CETC-54) for any large scale procurements.

From early 2010, thinking within SPDO on industrial participation had matured to the point that the first (virtual) gathering of ILOs, and the release of the first iteration of the SKA IES document[41] took place. The IES was the first formal guide for both SKA Member countries, as well as actual and potential industrial collaborators. This document covered the goals of industry engagement, expectations of both the project and industry, principles of engagement, capability assessment, and risk management. It also offered a framework for global industrial engagement strategies and remained an important framing document throughout the SPDO era and beyond, being updated at least annually.

Under the stewardship of nominated (ILOs), national industry groups and consortia formed (and re-formed) as the tone, scope, and timescales of the project developed. While the larger firms tended to stay interested and closely monitored progress through attendance at meetings and workshops, smaller suppliers with fewer resources tended to come and go, with many moving to a ‘watching brief’ status once the realities of budget and schedule (i.e. slippage) became obvious. One important avenue of sustained connection to the SKA development program was participation in the technical design consortia, although only a few of these arrangements enjoyed remunerated contracts—most were either in-kind contributions or simply goodwill involvement gambling on being better positioned to win a profitable contract during the construction phase.

Notwithstanding such arrangements, there were certainly missed opportunities. Promising early relationships with firms such as Communications Engineering Australia (now CEA Technologies Pty Ltd)—experts in array design with a real interest in beamforming—went undeveloped after the key CSIRO contact left Australia. Similarly, potentially seminal relationships with both Raytheon and Boeing cooled when engagement beyond the SKA ILOs was not exploited or sustained. The eventual withdrawal of the National Science Foundation also impacted on US companies interest. On the other hand, for some early motivated technology companies, the timescales between conceptual design and profitable supply contracts were simply too long. Peter Elford from Cisco captured this sentiment in the open forum at the Banff International SKA Forum (2011) when he stated: “Right now, the SKA may seem like a project to the scientists and engineers, but to industry it’s just a conversation”. Possibly the one big lesson from this experience is not to over-sell the project opportunities to industry too early.

Another probable missed opportunity was the lack of use, post-2012, of the Capability Assessment Tool[42] (about which more below) crafted by the SPDO in 2010 and field tested both in Australia and South Africa.[43] This device, in the hands

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[41] hba.skao.int/SKAHB-554 SKA Industry Engagement Strategy, Crosby, P., 2010

[42] hba.skao.int/SKAHB-551 Industry Capability Assessment Model, Crosby, P. 2007

[43] hba.skao.int/SKAHB-552 Capability Assessment Model, Crosby, P., 2003

of a trained assessor, offered a mature process to guide the consistent assessment of the SKA Consortia Member countries in terms of industry capability, as well as a common model to identify regions/countries/organisations that have (or could have) capability to achieve sustainable on-time and on-quality delivery.

## 10.13 Industry Engagement: The Journey to SKA Procurement

There are many positives to the industry engagement effort through the ISPO and SPDO eras, with several contributing a lasting legacy to the SKA project going forward from 2012:

- The early work of developing productive relationships with known and trusted industry players set an excellent foundation that both inspired many collaborations with industry and gave confidence to governments to support the project at the national level in the Member countries.
- Many benefits flowed from personal and professional relationships as a result of plentiful opportunities to interact with industry. The encouragement given to industry to attend and speak at briefings, international project meetings, high-level fora, and Member-organised national gatherings, engendered a spirit of cooperation and sharing of ideas.
- The ambitious science goals of the SKA served as a catalyst for truly innovative thinking by industry. Presented with the challenge of a highly demanding application, industry responded with thought-provoking and creative concepts fostered by a sophisticated project team. Many of these solutions will no doubt emerge in adjacent products and technology.

Nonetheless, there are also many lessons to be gleaned from the experience, including:

- The dangers of misunderstanding the expectations of industry. While the larger ‘primes’ (e.g. BAE systems, Cisco, etc.) are well used to R & D phases lasting many years, encompassing both dead-ends and breakthroughs, the majority of industry partners envision a shorter timescale between initial interactions and commercial contracts. In retrospect, the initial projections for the early contractual and procurement phases were not only optimistic, but prone to continual slippage. This resulted in much disenchantment within early industry associations. At the time of transition from SPDO to SKAO, the project mantra was that procurement was only a year or two away, whereas history has shown it commenced in earnest a decade later.
- While the physical interactions between the project and industry were useful and positive, little of the advice and feedback from industry was heeded in terms of

adopting an industrial project management environment that would have meshed better with industry and provided a ‘drumbeat’ for the project. Too often, offers of support from industry went unanswered, (e.g. project tools and training from Boeing, and battery storage solutions from Prudent Energy) and at times the project participants (both SPDO and the partner institutes) seemed reluctant to accept external input.

- In hindsight, the overall structure and process of shaping and executing the industry engagement function (largely under PrepSKA WP5) was inefficient and constrained by traditional and formal framework for scientific project funding. Committee oversight, work allocation and milestone reporting could have benefitted by a lighter touch, and the process of international collaboration was often clumsy and probably resulted in too many meetings and documents produced without a clear audience or user - either in the project or in the funding agencies. Much of what constituted “output” from WP5 was never revisited post-2012 for reasons that are not entirely clear.

The initial idea of adopting and integrating mainly COTS components to fulfil the vision of a massive, yet affordable, instrument was a seductive one, but could never be properly reconciled with the scientists’ desire to push the capabilities as far as possible. It was never wholeheartedly embraced through the concept development era, evidenced through reluctance by many of the international design teams to willingly take up offers by industry to collaborate. This attitude can isolate institutional design teams from taking advantage of commercial product development leading to increased costs from inevitable re-design.

Notwithstanding the less successful outcomes from early industry engagement processes, the underlying experience, enduring relationships, and other benefits of stakeholder association with such an aspirational project will no doubt pay off in time. The original ‘open procurement’ stance did not prevail into the early construction phase; the project protagonists reasoning that the specialist nature of cutting-edge science infrastructure requires that contractual risk should be minimised through ‘directed’ procurement, ideally via alliance-style contracting. To this end, the (European Commission supported) GO-SKA policy guidance project (November 2011—January 2015) addressed procurement through to the construction phase and endorsed the approach of undertaking work through a mixture of direct procurement and in-kind contributions from the Members. Accordingly, this adopted procurement policy was reflected in the 2016 Prospectus (for the SKA Organisation) and the 2020 version for the SKA Observatory.

While the overall effort could no doubt have been more effective on a global scale, the complex task of matching of industry with the critical capabilities, technologies, and challenges of the SKA will likely be delivered through arrangements that will unfold during procurement, construction, and commissioning.

# Chapter 11
# Concluding Remarks

## 11.1 Introduction

The major elements of SKA development in its first two decades from 1990–2012 have been explored in some detail in the preceding chapters. Here we attempt to draw back from the details of the historical narrative and sketch the broad issues that occupied the attention of the SKA project, particularly in what we have called the "Transition Era" from 2006 to 2012 (see Fig. 4.1). By 2006, the global radio astronomy community was convinced it was in a position to take on a project of the scale of the SKA and accomplish the goal of constructing the world's largest radio telescope. This conviction was based on the work already carried out on the project nationally and internationally, as well as previous experience in the community in building large telescopes like the VLA and global collaborations for Very Long Baseline Interferometry (VLBI). Recognition of the SKA as a potential "project of pan-European relevance" by the European Strategy Forum for Research Infrastructures[1] (ESFRI) in 2006 was one of the first steps. But there was much still to learn about how to implement a global project and problems to overcome before the SKA was accepted as one of the landmark astronomical observatories for the twenty-first Century.

For much of the time in the Transition Era, considerable uncertainty remained as to whether the SKA would gain sufficient support from the community and funding agencies to become a reality. It was also a time when it had to weather a number of severe storms including the withdrawal of a major partner.[2] Several potentially existential issues faced the project including (i) achieving recognition of the SKA as a high priority project in "roadmaps" generated by the wider astronomy community in Europe and the USA as well as recognition by funding agencies and

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[1] ESFRI, see Sect. 4.3.2.2.1

[2] The USA, see Sect. 4.5.3.

R. T. Schilizzi et al., *The Square Kilometre Array*, Historical & Cultural Astronomy,
https://doi.org/10.1007/978-3-031-51374-9_11

governments,[3] (ii) establishing a long-term governance structure centred on a legal entity to create a stable environment for the project,[4] and (iii) choosing a site for the telescope in an increasingly tense competition that had been politicised and elevated to President/Prime Minister level in the shortlisted candidate countries. In parallel with resolving these issues, the preparatory phase, PrepSKA, contract with the European Commission[5] expected the project to deliver a costed telescope design and a signature-ready document to start construction by 2011.

Projects of all sizes, and large projects in particular, have their own tempos dictated by internal and external—national and international—influences, many of which are unpredictable. No two projects are alike, and the authors do not plan to set out here a list of prescriptions for the mega-science development process for other projects in similar phases of development.[6] Nor will we compare the SKA to other individual science mega-projects in order to draw conclusions about better practice that might have been adopted. Rather, in the first part of this chapter we will attempt to sketch the characteristics of the SKA during its phase as an early-stage mega-project in the hope that other projects and mega-project scholars will draw benefit from seeing how this particular endeavour navigated its way towards becoming a reality. In the second part of the chapter we will also reflect on specific issues and decisions that were taken in the SKA project collaboration over the course of the two decades we cover in this book, and then make some general observations.

We start by sketching what defines a mega-project and in particular a science mega-project before going on the describe the challenges faced by the SKA in working at this level.

## 11.2 Mega-Project Characteristics

Mega-projects are usually defined as large-scale complex ventures, typically having (multi-)billion-dollar budgets, timeframes measured in decades, and attracting a high level of public and political attention. Mega-projects are often (although not always) transformational, and can have social, economic, scientific, and technological impact. "Mega" also implies the size of the task involved in developing, planning,

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[3] hba.skao.int/SKASUP11-1, *International profile raising for the SKA, 1993–2012*

[4] Note that the SKA was governed for 18 years from 1993–2011 by means of Memoranda of Understanding and Agreement among the research institutes and universities working on the SKA around the world (see Chaps. 3 and 4).

[5] See Sect. 4.4.

[6] See hba.skao.int/SKAHB-531 for a report from the OECD Global Science Forum on *Establishing Large International Research Infrastructures: Issues and Options*, 2010. The report discusses infrastructures that are based on formal agreements between governments, agencies, or research institutions from more than one global region.

and managing projects of this magnitude. The risks are substantial and cost overruns are common.[7]

As (Flyvbjerg, 2014) notes, *"megaprojects are not just magnified versions of smaller projects but are a completely different breed of project in terms of their level of aspiration, lead times, complexity, and stakeholder involvement. Consequently, they are also a very different type of project to manage."*

Mega-projects appear across a range of national and international endeavours including infrastructure, water and energy, defence, information technology and software systems, many fields of science, aerospace projects, industrial processing plants, mining, transport, and large strategic corporate initiatives and upgrade programs to increase the capability of already existing mega-projects. Global mega-projects carry additional areas of complexity in terms of collaboration, logistics and funding compared with national megaprojects.

Mega-projects are constantly growing in scale and cost (Flyvbjerg et al., 2003).[8,9] Budgets of 50–100 billion dollars or euros are now relatively common, and costs above 100 billion dollars not unknown, e.g. the International Space Station, the F-35 Joint Strike Fighter and the UK's high-speed rail project. A conservative estimate in 2014 by Flyvbjerg (2014) for the global megaproject market was 6–9 trillion dollars per year, or approximately 8% of total global gross domestic product. Funding for mega-projects most often comes from central governments, often appropriated through domestic agency budgets. Philanthropy is also a funding source, and not unusual especially in the USA. Foreign aid is occasionally a source in association with capacity building for developing nations.

### 11.2.1 Science Mega-Projects

As discussed in Chap. 1 (De Solla Price, 1983) recognised the important role played by the transition in project scale from individual researcher to institute to national facility and, finally, to international facility, each step removing a resource limitation ceiling. He coined the terms 'little science' and 'big science' to describe the two

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[7] The first decade or so of the new millennium was one of enlightenment regarding the rise of projects on the scale of the SKA, LHC, ALMA etc. Major project practitioners and scholars (e.g. Nassim Taleb, Bent Flyvbjerg, David Dombkins, Jeffrey Pinto, Graham Winch, Terry Williams, and others) and relevant knowledge organisations (e.g. The International Centre for Complex Project Management) were fast gaining credibility with audiences looking for innovative approaches to better manage very large projects for success. (Flyvbjerg et al., 2003)

[8] There have also been many mega-projects in the very distant past that were major undertakings at the time. A small sample are briefly mentioned in slides 27–38 in hba.skao.int/SKAHB-532 *The SKA: A modern equivalent of the Antikythera Mechanism?,* Schilizzi, R. T., 2012.

[9] In the mid-1980s a world-renowned theoretical physicist, Subrahmanyan Chandrasekhar, gave an inspiring talk at the Very Large Array radio observatory in New Mexico, USA. In his introduction he described the VLA as the modern scientific equivalent of the great medieval cathedrals. "This is where scientists come to look up to the stars and begin to understand the nature of our universe."

extremes (De Solla Price, 1963). Institutional facilities are built to enable research on a scale which no individual can afford; national facilities are built to enable research on a scale which no single institute can afford; and likewise international facilities are built to enable research on a scale which no single nation can afford.

Science mega-projects are at the top end of international facilities and have five distinguishing characteristics (Crosby, 2012a)[10]: (i) Typical budgets are in the range of 1 to 10 billion euros, with space science and high energy physics occupying the high end of the scale; (ii) Funding is usually derived from national (government) sources, although philanthropic contributions to funding also occur, especially when encouraged by tax incentives. For the most part, the funding for global projects remains under the control of the national funding sources rather than unencumbered cash contributions to a central project office, and is usually made in the form of in-kind contributions to the design efforts and *juste retour* (fair work return) contracts in the construction phase; (iii) Almost by definition science mega-projects are daring cutting-edge enterprises that leapfrog existing technological capability to deliver new knowledge and understanding. In contrast, *"Commercial enterprises are understandably more risk averse in terms of direct financial return to themselves but may well think in terms of issues like building capability. A government research group on the other hand, should arguably have wider and longer-term measures of impact."*[11] (iv) Science mega-projects are complex[12] to manage and almost always involve international collaborations between scientific institutions, universities, and industry; and (v) A key difference with institutional infrastructure mega-projects is that the users, who are in a sense customers, are members of the research community and are distinct from the financier(s).

Delving deeper into science mega-project management, Crosby[13] pointed out that the innovative character of these projects requires that many new technologies and components need to be developed in parallel by academic and industry partners, and this adds to the complexity. A substantial preparatory phase before the beginning of construction is necessary to deliver a competent understanding of technical scope

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[10] See also *Predictive Indicators of Success in Science & Engineering Projects—Application to the SKA Initiative*, Crosby, P., 2012, PhD Thesis, Curtin University, Perth, Australia, https://www.google.com/search?client=firefox-b-d&q=PhD+thesis+Philip+Crosby+Curtin+University

[11] Quote from John O'Sullivan, recognised as the inventor of WiFi, CSIRO Division of Radiophysics and later senior research engineer in CISCO. Email communication from O'Sullivan to Ron Ekers, 6 February 2023.

[12] Whilst there is no universally accepted definition for Complex Project Management, the International Centre for Complex Project Management (ICCPM) define complex projects are those that (i) are characterised by uncertainty, ambiguity, multiple dynamic interfaces, and significant political or external influences; and/or (ii) usually run over a period which exceeds the technology cycle time of the technologies involved; and/or (iii) can be defined by effect, but not by solution. Point iii) means complex projects can be defined by the effect of complexity on their management but not by the solution to the initial goal.

[13] *Predictive Indicators of Success in Science & Engineering Projects—Application to the SKA Initiative*, Crosby, P., 2012, PhD Thesis, Curtin University, Perth, Australia, https://www.google.com/search?client=firefox-b-d&q=PhD+thesis+Philip+Crosby+Curtin+University

and associated risks. This is sometimes undertaken by academic institutes, often under rather blurry funding arrangements that can complicate later claims that the work done qualifies as in-kind support for the project. Central project authority is aspired to for obvious project management reasons. However, without central financial control on an international scale, major participants naturally maintain their highest allegiance to their own institute or department and the national/regional funders. For SKA in the Preparatory and Pre-Construction phases, this necessitated a different approach to project control, best described as "centrally managed best efforts".

Crosby also noted that technical project reviews in science mega-projects are also seen in a different light to their industrial equivalents, being less procedural and action oriented, more collegiate and allowing more freedom in terms of options for corrective action especially in the project shaping phase—a characteristic that can sometimes lead to "scope-creep". In the SKA, this was a consequence of the centrally managed best-efforts basis of project management (see Sect. 6.2.2.6 and hba.skao.int/SKASUP6-3). Science technical project review panels for sub-system elements are usually dominated by specialists—people with domain knowledge—from the project stakeholders, in most cases individuals with experience in other major projects. With stakeholders from around the world, SKA had access to a wide range of, often divergent, views. In contrast, industrial style reviews include a higher proportion of external experts from other types of major projects and industry, and this was seen as bringing worthwhile value from 'the outside world'. The SKA benefitted from this approach for its International Engineering Advisory Committee (IEAC) formed in 2007 (see Sect. 6.2.2.3) and for the SKA Concept System Design Review in 2010 (see Sect. 4.5.2). The latter had a major positive effect on project direction and focus at a critical time in the project.

Crosby's PhD research undertaken concurrently with the final years of the period under review in this book included the SKA as a case example. It produced a practical output from the developed theory in the form of an audit (or review) tool, the Checklist for HIgh technology ProjectS (CHiPS).[14] This has been used since then to complement reviews of the type discussed above, or as an independent assessment tool to verify key project indicators for any or all project stages.

Project termination in mega-science is rare although "descopes" are quite routinely used as a coarse instrument to contain cost.[15] This occurred for the SKA in 2014–15 as a result of the imposition of a cap on the budget for capital expenditures by the SKA Organisation's Board of Directors (see Sect. 8.7). A feature of institutional science mega-projects with relatively weak central project authority is a perceived lack of consequences for the collaborative teams in cases of

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[14] hba.skao.int/SKAHB-534_*The Checklist for HIgh technology ProjectS (CHiPS)*, Crosby, P., 2012

[15] *Predictive Indicators of Success in Science & Engineering Projects—Application to the SKA Initiative*, Crosby, P., 2012, PhD Thesis, Curtin University, Perth, Australia, https://www.google.com/search?client=firefox-b-d&q=PhD+thesis+Philip+Crosby+Curtin+University

non-conformance on, for example, unfulfilled delivery promises. Prior to the project entering the centrally controlled construction phase with its contract-based activities, any sanctions on individual institutes for poor performance or delivery are measured more in terms of loss of reputation than any legal or financial penalty. This is an essential difference with industry-based models for mega-projects which should be recognised.

## 11.3 The SKA as a Science Mega-Project

The initial 1990 concept of the SKA as a radio telescope with a collecting area of one million square metres and one hundred times the sensitivity of the then current state-of-the-art, the US Very Large Array (VLA) (see Sects. 2.4 and 5.5.5) implied a mega-scale project scale even without the label of "mega-project" . The first recorded mention of a link between a large radio telescope like the SKA and mega-science was in May 1993 following a talk given by Ron Ekers on the large telescope ideas circulating in the radio astronomy community at the European Space Agency meeting on Frontiers of Astronomy. Françoise Praderie (then Scientific Head, OECD Mega-Science Forum, MSF) contacted Ekers with the suggestion that SKA could be considered by the MSF.[16] This led to the OECD-sponsored activities on radio astronomy and large telescopes described in Sect. 3.2.5.2 during the period from 1996 to 2004. It also led to the involvement in the SKA of the two international scientific unions most relevant for radio astronomy, the International Union of Radio Science (URSI)[17] in 1993 and the International Astronomical Union (IAU) in 2004. Two years later, the European Strategy Forum for Research Infrastructures (ESFRI, see Sect. 4.3.2.2.1) included SKA as a potential pan-European research infrastructure in the roadmap compiled in 2006. By this time, it was clear that SKA ticked the boxes for a science mega-project—large price tag, long time-scale for completion, innovative science, cutting-edge concept, global, and complex project management. The ESFRI action paved the way for SKA to obtain Preparatory Phase funding from the European Commission in 2007, a crucial step on the path to the successful transition to the SKA Organisation in late-2011.

One characteristic that distinguishes the SKA from other science mega-projects is its "grassroots" origin.[18] As described in Chap. 2, it began life in 1993 as a global community-driven mega-scale project[19] that did not originate in an existing

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[16] hba.skao.int/SKAHB-125 Letter from Françoise Praderie to Ron Ekers, 7 June 1993. See also Sect. 3.2.5.2.

[17] URSI was the host organization for The Large Telescope Working Group established in August 1993, described in Sect. 2.5. The IAU established the Working Group for Future Large Scale Facilities in August 2004, described in Sect. 3.2.5.1. Françoise Praderie pointed out that this was probably the first use of these international scientific unions to coordinate the collaboration in a global project (priv. Comm. to Ekers, 2003).

[18] This was first pointed out to Schilizzi in 2017 by Nuno Gil (University of Manchester).

organisation or institution or government. One of its major activities during the period we describe in the book was to create a host organisation since no suitable candidate existed in the astronomical world that could accommodate a global project like the SKA (see Chaps. 3 and 4). Key to the SKA's early development was the involvement of a small number of institute directors and senior staff who actively sought funding.[20] The URSI Large Telescope WG[21] built up the science and engineering case over time, and, as funds became available, relatively light forms of governance (MoUs) were created by the institute directors to coordinate activities. The SKA remained a collaboration governed by MoUs or MoAs for 18 years until December 2011 when a legal entity was established for the first time to manage the activities.

### 11.3.1 Innovative Concept

As set out in the SKA Science Case in May 1998,[22] the aim was to build "the world's premier astronomical imaging instrument. No other existing or planned instrument in any wavelength regime can provide simultaneously: angular resolution better than the Hubble Space Telescope ($< 0.1$ arcsec), field of view significantly larger than the full moon ($\sim 1$ square degree), spectral coverage of more than 50% ($\nu/\Delta\nu < 2$), spectral resolution sufficient for kinematic studies ($\nu/\mathrm{d}\nu > 10^4$), and all at a sensitivity about 100 times the VLA."

The authors of this book note that what is under construction by the SKA Observatory at the time of writing is the first 10% phase of the final telescope which already has a budget and global scope justifying the "mega" designation.

### 11.3.2 Complex Project Management

The unavoidably wide range of stakeholders makes the SKA a complex project to manage. There are multiple nations involved[23] and multiple players within those nations including large and small research groups in research institutes and universities, government departments and funding agencies, and large and small industrial organisations. In the telescope site candidate countries, Australia and South Africa,

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[19] This terminology was not in common usage in the astronomy community at the time.

[20] See Sect. 3.2.

[21] See Sect. 2.5.

[22] hba.skao.int/SKAHB-124 *Square Kilometer Array Radio Telescope, The Science Case*, Robert Braun and the URSI Large Telescope Working Group, May 1998.

[23] See Chap. 4.

radio spectrum management agencies as well as indigenous and farming communities involved in land-use agreements were additional stakeholders.

At an operational level, such a wide range of stakeholders created many challenges and tensions in managing the SKA, as we have discussed in this book. Examples are the different funding cycles in the countries and regions involved, different prior investment histories in radio astronomy leading to differences in experience and maturity level of relevant technology development, different scientific priorities impacting the scientific requirements on the telescope design, different policies towards industry engagement and *juste retour* on investment, different cultural approaches to science and decision-making at all levels and different science-government interaction cultures. And finally, at a geo-political level, government-level relationships between nations were important. Indeed, mega-projects like SKA are highly relevant to relations at the level of science minister to science minister. Whether the SKA made it up to the next level politically depended on its visibility nationally; it was certainly the case in Australia, South Africa and China and subsequently in the UK. On the other hand, international relations between nations that are on less than friendly terms can lead to restrictions being placed on exchange of information on state-of-the-art technology or cross-border supply of the technology itself—and in a project with such long timescales, who is on friendly terms with whom may itself change. In a global project like the SKA, these differences needed to be understood and managed for a successful collaboration. In all of this, we emphasise open and transparent communication across the project was a key element of success.

As we have noted in earlier chapters, over the 18-year collaboration phase from 1993 to 2011, central project management in the SKA evolved considerably. It took place on four levels: (i) overall project oversight and major decision-making initially (1993–2005) carried out by the scientific steering committees and later in conjunction with the funding agency groups[24] and the SKA Founding Board; (ii) coordination of the global effort on the science case and engineering design by the SKA community; (iii) coordination of the three PrepSKA "policy" work packages (governance, procurement & industry engagement and funding) by the funding agencies from 2008–2011; and (iv) coordination of telescope site characterisation by the SKA Project Office in 2004–6 and 2008–2011. In addition, the individual partner institutes were responsible for the management of technical design work-packages.

With no single nation or organisation occupying a dominant position in the SKA project through expertise, magnitude of funding or legal position, an additional layer of management complexity was added compared to the top-down centrally funded and managed projects more common in government and industry. Issues of governance, funding strategy and site decision strategy had to be resolved by "sufficient consensus" within the International SKA Steering Committee (ISSC) and SKA

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[24] The funding agencies and governments represented in the Funding Agencies Working Group and the Agencies SKA Group regarded their role in SKA as advisory until the Founding Board was established in April 2011. Nevertheless, their advice was always heeded by the ISSC and SSEC.

Science and Engineering Committee (SSEC) in conjunction with the Agencies SKA Group (ASG) as discussed in Chaps. 3 and 4. This was successfully carried out for the most part. A balance was found between the scientist-driven aspects of the program and strong agency engagement while avoiding the suggestion that the Funding Agency involvement in the SKA was in any way a formal endorsement of the project[25] until the time came to make such a commitment.

As far as oversight of the SKA technical work-packages was concerned, there was a further difference with industrial project development. The latter mostly relies on expert contractors to produce the required physical systems and components to a given set of specifications. In contrast, much of the instrumentation for the SKA was designed and fabricated in-house in the research institutes, drawing on combinations of co-located specialist skills. A notable characteristic of many of the SKA team members, at least in the early stages of the project, was the ability to bridge the science-engineering gap, with scientists well-informed in relation to the engineering challenges (often contributing to the technical design), and many of the engineering staff adept at understanding the science challenges in terms of practical design of experiments and equipment. This characteristic is common to successful science mega-projects and provides the most innovative technology development path.

However, in collaborative enterprises, questions of “authority” on design issues can lead to tensions within the project. In a collaboration without a dominant partner, design authority is gained primarily by domain expertise and track record. Design authority was the role to which the central SKA Project Office - both International SKA Project Office (ISPO) and SKA Program Development Office (SPDO) - aspired but its achievement took longer than expected at the outset.

The role of the SKA Project Office in the development of the SKA design began slowly in 2004 in the early days of the ISPO and initially continued the annual review of technology progress in the institutes by the International Engineering Management Team under Peter Hall’s leadership. In 2005 the ISPO led the Tiger Team developing the Reference Design (see Chaps. 3 and 6), and in 2007 a similar Tiger Team developing the Preliminary Specifications for the SKA[26] (see Memo 100 and Sect. 6.2.1.4). In both cases, the Tiger Teams were composed primarily of members from the institutes involved in design work. The new SPDO began to grow in numbers in early-2008 with PrepSKA and institute funding and a mandate to carry out the overall project management and coordination (see Sects. 4.4.2.1 and 6.2.2.4).

It took time to recruit the SPDO staff and for them to achieve a comparable level of expertise, if not experience, to the institute-based engineers. It was difficult to attract leading specialists from the partner institutes, particularly those with system engineering talent, to the central office. Only the relatively unencumbered were prepared to take the gamble of moving to a project not yet funded for construction

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[25] See Sect. 4.4.2.3 and Box 4.7.

[26] hba.skao.int/SKAMEM-100 *Preliminary Specifications for the Square Kilometre Array,* Richard Schilizzi et al., SKA Memo 100, December 2007

and no guaranteed long-term future. Many were not interested in moving from the current exciting hands-on activities to a long-term paper design activity. Consequently, it took additional time for SPDO staff to be recognised by the community as the design authority in practice. The SPDO adopted a mode of operation of consulting widely with the community before making decisions, paying attention to the individual concerns of the partner institutes as much as possible in order to move the project forward—the centrally managed best-efforts approach. By the time the SKA Project Execution Plan was generated in 2010, it was judged an opportune moment to formally designate the future SKA Project Office as the "Design Authority" in the forthcoming pre-construction when design consortia would formally report to the Project Office.

One of the issues faced in the SKA at the start of the PrepSKA project in 2008 was the substantial lack of experience in the radio astronomy community of projects larger than could be handled by individual institutes. Only their involvement in ALMA was comparable. The education (and self-learning) of the community about the ramifications of SKA as a science mega-project took some time. One example was the necessity to communicate conflicts in resource priorities between national projects and the international project. The system engineering approach advocated by the SPDO and adopted in 2009 helped the engineers in the institutes come to terms with the distributed nature of the design work and enabled a more coherent approach to the overall design process (see Sect. 6.2.2.2).

Complex Project Management (CPM) as a recognised phenomenon with distinct behaviours, was still in its infancy at the time PrepSKA commenced in 2008 (Geraldi et al., 2011) (Crosby, 2012b). However, CPM as a discipline was not on the radar of the SKA leadership throughout PrepSKA. The focus there was on delivering the required outcomes by 2011 while at the same time resolving the existential questions about the SKA mentioned in the Introduction to this chapter. The issues of uncertainty and dynamic and socio-political complexity then being introduced into CPM were not unknown to the SKA; they had been part of the project management framework from the start. In any case, it is doubtful that the management resources required for CPM would have been regarded as having higher priority than staff to fill the technical domain specialist positions to interact with the institute engineers. The fifteen staff able to be funded in the SPDO[27] were well below the original estimate of requirements (28) made in 2006 (see Chap. 9). Both early and later SKA project teams had fundamental project management skills and experience, but true CPM (at the level of the Large Hadron Collider project at CERN) was not part of their toolkits. It is probably fair to say that management of the design process of a global science mega-science project is much more straightforward to establish within an already well-established organisation like CERN or the European Space Agency (ESA) . In 2011, the SKA was just on the point of establishing a stable project environment.

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[27] In 2011, there were an additional four seconded part-time staff members in the SPDO.

**Table 11.1** Governance entities for the SKA

| Project Era | Year | Governance entity | Rules and procedures |
|---|---|---|---|
| Grassroots era | 1993–1996 | Large Telescope Working Group | Terms of Reference |
| | 1996–1999 | Institute directors | Memorandum of Agreement |
| | 2000–2007 | International SKA Steering Committee | Memorandum of Agreement |
| Transition era | 2006–2008 | Funding Agencies Working Group | Informal agreement |
| | 2008–2011 | SKA Science & Engineering Committee | Memorandum of Agreement |
| | 2008–2012 | PrepSKA Board | Contract with European Commission |
| | 2009–2011 | Agencies SKA Group | Informal agreement |
| | 2011 | Founding Board | Letter of Intent |
| Pre-construction era | 2011–2021 | SKA Organisation | Articles of Association |

### *11.3.3 Governance*

It is obvious that a governance framework is critical to any science project once it involves collaboration among scientists and engineers in more than a small number of institutes. The ability to revise or change the governance to suit the development phase of the project is also critical. In each major transition that SKA went through (see Chaps. 3 and 4), experience showed that finding a governance structure that ensured mutual advantage for all parties was a key factor underpinning continuing success in the collaboration. Understanding the agendas of the potential member parties in the collaboration was key to 'sealing the deal' in each transition. The sequence of changes in governance entities from the Large Telescope Working Group in 1993 to the SKA Organisation's Board of Directors in 2011 is shown in Table 11.1 (See also Fig. 4.1).

Interesting to note is that the SKA leadership did not regard the global governance aspects from 1993 to 2011 as being particularly challenging in practice, with the exception of the tri-partite governance in operation during the PrepSKA contract period from 2008–2011. The three governance entities in the PrepSKA era were: the SKA Science and Engineering Committee, the Agencies for SKA Group, and the PrepSKA Board, an arrangement that proved onerous at times for the SPDO.[28] Years of successful experience in running collaborative global VLBI networks indicated that well-tested governance structures existed in radio astronomy which could be, and were, adopted for the SKA in its collaboration phase up to 2011. In the

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[28] See Sect. 4.4.2.

pre-construction era that followed, it seemed natural that the approach taken in most European inter-governmental research organisations, including the European Southern Observatory (ESO), of a Board with one government representative with voting rights and one scientist per country, would serve for the SKA. and so it did.

### *11.3.4 Industry Engagement*

While it had been obvious to the SKA project from its grassroots days that engaging industry was going to be essential in the design, prototyping and construction phases, there was also an expectation among some in the radio astronomy community that industry involvement—and lobbying—would put additional pressure on governments to provide funding for the SKA. Later, in the transition era from 2006–2012, there was also explicit encouragement from the funding agencies in all countries except the USA to involve local industry in order to facilitate associated industrial spin-off to adjacent markets and ensure national benefits from government investment in the project. In the USA, the approach is less political; the National Science Foundation funds basic research purely on research quality and it is assumed that US industry captures the benefits without making this an explicit requirement. This meant that the SKA project had to target individual companies in the US like IBM and others (see Chap. 10). But this effort was hindered by the lack of experience among US astronomers with the industrial strategies used in other countries.

Early engagement with industry was only partially effective as discussed in Chap. 10. It did allow the development of productive relationships with industry players setting a foundation that both inspired many collaborations with industry and gave confidence to the funding agencies to support the project at the national level. The ambitious science goals of the SKA served as a catalyst for innovative thinking by industry. However, one consequence of engaging industry in the design phase was that protection of intellectual property at institute level became an issue. In some cases, the design progress was impeded by Non-Disclosure Agreements binding some of the participants in design meetings. Inability to obtain protected industrial production methods had a profound effect on cost estimates for dishes, a dominant cost component of the SKA (see Sect. 6.4.6).

The dangers of the radio astronomy community not understanding the different cultures, expectations, and modes of operation of industry were ever present. While the larger companies were well used to R&D phases lasting many years and saw involvement in a state-of-the-art project like the SKA as a means to enhance their capability,[29] the majority of smaller companies envisioned a shorter timescale between initial interactions and commercial contracts. In retrospect, the initial projections for the early contractual, and procurement, phases were not only optimistic,

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[29] See the quote referred to in Footnote 11 from John O'Sullivan in Sect. 11.2.1.

but subject to continual slippage. This resulted in much disenchantment in the smaller companies.

Having a well-considered procurement approach was recognised in the PrepSKA study to be strategically important to the successful completion of the SKA project and would underpin productive and open relationships with suppliers. Prior to 2012, there was no need to implement a formal procurement function, but thought was applied to how procurement might best be implemented and managed through the work of PrepSKA Work Package 5 (WP5, see Sect. 4.4.1 and Chap. 10). As well as producing much in the way of procurement guidelines and preferred approaches, WP5 endorsed the early establishment of a procurement office structure with resources, processes, roles and responsibilities, and information management systems in place. There was also encouragement from WP5 for the SKA leadership to obtain a full understanding of global supplier capability information, and implementation of appropriate contractual instruments with terms and conditions directly referencing and supporting project goals.

### *11.3.5 Project Plans: Costs and Timelines*

Both cost and timescale were severely underestimated in practice in the SKA, a situation not uncommon in mega-projects.[30,31] Many project plans were made for the SKA over the years. They were necessary to provide focus for the project but were less than accurate predictions of the course of events.[32] Even with well-developed cost planning tools and techniques, experience with mega-projects, especially those with a large software component, shows cost uncertainties of +100% are not

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[30] On cost and timescale underestimation, Bent Flyvbjerg remarked in 2014 that "*Evidence shows that megaprojects are highly risky endeavours. Cost overruns, time delays, and benefit shortfalls have remained high and constant for the 70-year period for which comparable data exist. Nine out of ten megaprojects have cost overruns.*" https://www.pmi.org/-/media/pmi/documents/public/pdf/research/research-summaries/flyvbjerg_megaprojects.pdf, (Flyvbjerg, 2014)

[31] The tendency to understate has always pervaded the institutional high-tech project world, as evidenced in a quotation from scientist Robert Hanbury Brown FRS, inventor of intensity interferometry, in 1987: *"In my experience most major programs of scientific research would never have got started if the people who proposed them had not greatly underestimated the cost, time and amount of work involved"* (Robertson, 1992, p. 132)

[32] Another apt quote here is "*Plans are worthless, but planning is everything"*, Dwight D. Eisenhower, 1957 November 15, in the New York Times, *President Draws Planning Moral: Recalls Army Days to Show Value of Preparedness in Time of Crisis,* by William M. Blair (https://quoteinvestigator.com)

unknown.[33,34] There was much activity and thought given to project costing throughout the Transition Era from 2006 to 2012, where possible using ALMA as a "reference class" radio telescope for the SKA, but little of this activity influenced the publicly announced 'big numbers' for which the SKA could be built. A mantra of a "one and half billion Euro" instrument (for SKA Phase 2, the full SKA) prevailed throughout the Transition Era until the first industry-led analysis of the dish costs (the major cost driver for the telescope) made in 2011–12 showed that early estimates of these costs used in the submission to the US Decadal Review Panel in 2009 were an underestimate by a factor of four to five.[35] This led to estimates of the total cost for the full SKA being most likely a factor of three too low (see discussion in Sect. 4.4.3.3.1, and 4.5.3.5).

In retrospect, the project was not at a sufficient technical readiness level to make a detailed cost estimate in 2009 as the system-wide Conceptual Design Review had not been held by then and would not be held until a year later. This points to one of the complexities inherent in a global project, that of the project not having control of the timing of major review cycles in the different countries in terms of technical readiness to comply with proposal requirements on budgets. The conclusion here is that the SKA project was naïve to give as much credence as it did to the early cost estimates until there was much better access to the details of the design and the assumptions made. The conundrum is that to obtain accurate costs, irrevocable design decisions needed to be made, cutting off options.

Preliminary cost estimates based on scaling and rough models are in most cases only known to within a factor of two or more. This should be translated into a contingency allocation (see Sect. 6.4.6). But the reality is that very few projects include contingency in their initial estimates as it is not required until formal funding requests are made.

The timeline for SKA has proven to be equally optimistic and governed to some extent in the pre-2006 period by what was the "acceptable" horizon for completion (as seen by the astronomical community). As noted in Sect. 4.6.1, a relatively short projected time to potential funding and, beyond that, to start of construction is almost universally found embedded in large project plans and is a well-known sociological phenomenon.[36] The National Audit Office report clearly links over-optimism with the nature of complexity. Truly complex projects are quite different to merely

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[33] hba.skao.int/SKAHB-536 *Costing the SKA: a commentary,* Peter Hall, presentation at the WP2 Kick-off Meeting, November 2008

[34] *Predictive Indicators of Success in Science & Engineering Projects—Application to the SKA Initiative*, Crosby, P., 2012, PhD Thesis, Curtin University, Perth, Australia, https://www.google.com/search?client=firefox-b-d&q=PhD+thesis+Philip+Crosby+Curtin+University

[35] The dish cost estimates were based on a simple scaling from the ASKAP dishes without taking full account of the differences in specifications compared to the SKA dish requirements as well as making speculative assumptions about volume reduction in costs and the use of other fabrication techniques, see Sect. 6.4.6).

[36] hba.skao.int/SKAHB-537 *Over-optimism in government projects,* Report by the UK National Audit Office, December 2013

complicated ones. Their behaviour is non-linear, hard to predict and inevitably flawed. To try to predict outcomes by time or cost is not sensible without a multiplier for contingency.

However, an initial project timescale with a distant milestone for funding approval runs the risk of the wider community turning its attention to shorter-term projects with more immediate scientific and reputational returns. A shorter timescale to funding approval gives institutes and individual colleagues the feeling it would be useful to engage with the project sooner rather than later in order to get an inside edge on technology development and so influence design decisions or access to the telescope when operational. It also makes logical sense to quote a technically limited timescale when there are so many unknowns, like political decision-making, outside the project's ability to manage.

This situation began to change for the SKA when the project started to appear in national and European roadmaps in 2006. Other external influences on the timeline came into play at that time including competing projects like the European ELT, and the PrepSKA deliverable of an Implementation Plan for the Pre-Construction Phase[37] starting in 2012.

### *11.3.6 Measuring Success*

Measuring success in any mega-project, as a general class, is ill-defined. Industrial-style reviews focus on measuring progress against rigidly defined critical success factors, with schedule, cost, and scope (or performance) ranked uppermost. The first two of these factors are frequently given less weight in mega-science, and scientific performance itself may be impacted in the light of construction funds available. Project success factors may differ from national success factors such as industrial return or national prestige. The SKA is no exception to this observation.[38]

Success factors were not explicitly defined for the SKA in the 2006–2012 period. In hindsight, there was a straightforward meta-goal at the outset—to resolve the existential issues noted in the Introduction to this chapter and to ensure the project was well on the way to successful completion by the end of the period. To re-iterate, these were: (i) recognition of the SKA as a high priority project in "roadmaps" generated by the wider astronomy community as well as recognition by funding agencies and governments, (ii) establish a long-term governance structure centred on a legal entity to create a stable environment for the project,[39] (iii) select the best site

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[37] See Sect. 4.6

[38] See Sect. 4.4.3.3.1 on cost estimates and 4.6.1 on schedules, timelines and project plans.

[39] Note that the SKA was governed for 18 years from 1993–2011 by means of Memoranda of Understanding and Agreement among the research institutes and universities working on the SKA around the world (see Chaps. 3 and 4).

to host the telescope, and (iv) deliver the PrepSKA outcomes of a costed telescope design and a signature-ready document to start construction.

All these goals were achieved with the exception of the PrepSKA outcomes defined in iv) above which were adjusted to match project progress and became the preparation of an implementation plan and business plan for the Pre-Construction Phase. Nevertheless, widely accepted PrepSKA progress on the overall design of the SKA telescopes enabled a baseline design to be defined in 2013,[40] which has broadly held into the construction phase.

Ultimately, success for the SKA was seen as the fulfilment of the common vision held by partners at all levels in the project to build the world's largest radio telescope. At the time of writing, the first major step towards achieving this vision, SKA Phase 1 construction, is well on its way.

### *11.3.7 Project Resilience*

Project resilience is defined formally as the building of inherent robustness during project shaping and was shown by Crosby's study (Crosby, 2012c) to raise the chances of mega-project success. Resilience appeared to be strengthened through key practical factors such as the early setting of project mission and success definitions and clear and consistent structures and processes for reporting and decision-making. For SKA the shared common vision from the outset in 1993 was to complete the construction of the world's largest radio telescope. This was not only the ultimate measure of success but also a major factor in project resilience that carried the project and its community through the inevitable ups and downs of an undertaking of this scale.[41]

Also important for project resilience was the feeling in the SKA scientific community, throughout the 2006–2012 period, that the funding agencies and governments in most countries were broadly supportive of the SKA endeavour (see Chap. 4, Box 4.7). The global adoption of the project generated resilience and was a key factor when striving for a treaty level organisation. This resilience was key to the project remaining coherent and able to adapt in the wake of the US decision not to continue its participation in the project in 2010,[42] as well as at the time of the telescope site decision in 2012.[43]

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[40] hba.skao.int/SKAHB-206 *SKA1 System Baseline Design*, Dewdney, P. E., et al., SKA Document SKA-TEL-SKO-DD-001, 2013-03-12

[41] See Sect. 11.1, this chapter.

[42] See Sect. 4.5.3

[43] See Sect. 8.6.3

### 11.3.8 Motivations for Participating in a Project like the SKA

The primary motivation for a project like the SKA comes from the scientists and engineers who create and develop the concept because they want to have the opportunity to do ground-breaking research and make new discoveries with innovative instrumentation. National and regional level motivations follow on from this primary drive. In the case of SKA, the scientist motivations were not uniform at personal and institute level. Many sub-disciplines exist and there are many directions in which to take innovative engineering. The scale of a mega-science project such as the SKA requires international funding and involvement of multiple scientific groups. Different emphases on what constituted the most important science almost inevitably drove the project scope beyond a "simple" experiment to solve a particular scientific question—detecting neutral hydrogen in the distant parts of the universe—and into the realm of an observatory with an instrumental capability to accommodate many different types of investigations.[44] Perhaps this would not have occurred had there been a dominant partner in the SKA, but that was not the case for a project "born global" .

Institutes and university astronomy departments with a long history of radio astronomy research as well as telescope design and construction were natural partners for a project like the SKA. The prospect of playing a leading role in initiating and then designing and building a global telescope was a strong motivation for the senior radio astronomers in charge of institutes, observatories and university departments around the world,[45] in particular in Australia, Canada, China, India, the Netherlands, and the USA, and somewhat later in the UK. Elsewhere, there was more interest in the scientific opportunities provided by the SKA than in the design aspects of the telescope itself.

There was an additional motivation at scientist level in China, South Africa and New Zealand. The SKA was seen as an entry point into state-of-the-art radio astronomy and membership of a global community for themselves and their institutes.

The national and regional motivations for the SKA beyond the excellent science case were covered in Chaps. 3 and 4.[46] Chief among them were the national prestige accruing from international recognition of the country/region playing a significant role in a global science project, developing a new research infrastructure, accruing

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[44] As discussed in Chap. 1.

[45] Russia has never been a major player in the SKA despite its historical interest and research on the Square Kilometre Telescope concept described in Sct. 2.4.1.4. This may have been the result of the breakup of the USSR in the early-1990s. In any case, the concept developed by Yuri Pariiskii and colleagues was not envisaged as a global telescope.

[46] See also hba.skao.int/SKAHB-140, Report on the Strategic Workshop on the *Benefits of Research Infrastructures beyond Science*: *the Example of the Square Kilometre Array (SKA)* Committee on Science and Technology (COST), 2010, and *The SKA Approach to Sustainable Research*, Berry, S. T., 2021, in The Economics of Big Science: Essays by Leading Scientists and Policymakers | SpringerLink

knowledge and industrial return on investment, maintaining a competitive position with respect to other observatories/institutes, and developing science and engineering talent in the country via education and training opportunities provided by the SKA to build human capacity and stimulate technological innovation. For all countries involved, both large and small, there was an underlying argument for participation, the mutual benefit of membership in an international partnership that has the prospect of expanding the national base of state-of-the-art astronomical techniques and technological approaches to complex problems. In addition, international partnerships like the SKA can enhance global and transcultural collaboration in communicating advances in knowledge to the general public.

There were arguments specific to each country as well. For Australia and the Netherlands, maintaining their positions as leaders in the historical development of world class radio astronomy despite being "small" countries in terms of population was important. For Australia and South Africa their excellent sites for hosting the SKA telescope combined with far better access to the astronomically-rich southern hemisphere sky compared to a northern hemisphere site were drivers of the strong political support received in both countries. In the post-apartheid era, South Africa prioritised astronomy as a means of attracting young people into science and engineering and providing them with exciting and challenging projects, particularly the expensive, multi-national science infrastructure projects. Having such a project located in South Africa was seen as creating a centre of science and engineering that could stimulate technology in local industry and science and technology in universities.

For most of the bigger countries involved in the SKA, a different mix of motivational factors came into play. In Europe as a whole and in the individual countries, the science had to be seen to be excellent by the wider astronomy community. However, an additional motivation for the European Commission was that the SKA was seen as a potential enhancement of the European Research Area,[47] a single, borderless market for research, innovation and technology across the European Union, able to increase Europe's impact and prestige on the global stage. In more developed countries the sociological and educational impacts are relatively less important, but the economic payoff from industrial contracts is interesting to all. In contrast, for US funding agencies like the National Science Foundation, national prestige and industrial return were not a direct concern; the economic value of industrial involvement is assumed to flow naturally without making this explicit. Funds are provided to high priority science projects as judged by peers in the science community. Philosophical labels for the SKA like "born global" while attractive to the radio astronomy community in the US, were not relevant to the US funders.

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[47] The ambition of the European Research Area is to help countries be more effective together by strongly aligning their research policies and programs and enabling the free circulation of researchers and knowledge, https://research-and-innovation.ec.europa.eu/strategy/strategy-2020-2024/our-digital-future/european-research-area_en

## 11.4 Reflections on Specific Issues

### *11.4.1 Project Politics and Funding, 2006–2012*

It was important for the project politics and funding of the SKA as a whole that the project leaders in the candidate hosts for the telescope site, Australia and South Africa, could access high government levels not easily available to their counterparts in other countries and enable governmental support early in the project's life. This high-level access provided a significant impetus to the SKA in the other countries making it visible in a way that might not have been otherwise possible.[48]

### *11.4.2 Key Science Projects: Who Requires them?*

It seems a requirement for aspiring large science projects that Key Science Projects (KSPs) are identified. But who drives that requirement and where does it come from—governments, funding agencies, the astronomy community? And do KSPs generated by committee consensus actually constrain the scientific ambition of the large projects? Is sufficient recognition given to the historical fact that, in astronomy, most discoveries made by new telescopes are in fields that were not included in the project proposal at the time of funding so are not going to be covered by the KSPs?

*Governments:* as noted above in Sect. 11.3.8, governments are mostly interested in global mega-projects for their impact on the economy, human capacity building, public perceptions, international visibility and science diplomacy.[49] Governments will prefer simple descriptions of the scientific value, while at the same time wanting there to be potential for big and unanticipated discoveries.

*Funding Agencies:* are the interface between the government and the scientific communities they support. They need KSPs as evidence of focus in the project and ability to keep the project scope under control. KSPs also simplify the communication process with governments. They may have to advise the government on the relative value of competing projects and provide feedback to the scientific community on how best to promote their projects to the government, industry and public.

*Astronomy community:* Being able to set out KSPs that answer key questions in the field is seen by project leaders as being a way to get scientific community support which, in turn, is seen as demonstrating maturity and an essential element in the funding process. Unified community support is also needed to prevent fragmentation and competition between competing projects in the same sub-discipline.

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[48] hba.skao.int/SKAHB-540 Michael Garrett, 2019, transcript of comment in the discussion on Project Politics and Funding at the SKAHistory2019 conference.

[49] hba.skao.int/SKAHB-140 *The COST Strategic Workshop on the Benefits of Research Infrastructures beyond Science: the Example of the Square Kilometre Array (SKA)*, held in Rome in March 2010 is an example of governmental level interest.

Occasionally two separate fields, e.g., optical and radio astronomy, can work together with a common set of KSPs to enhance prospects for funding, as happened in Australia in the 2000s. In this case, astronomy was competing for funds with other disciplines such as medicine and biology and astronomy leaders in Australia did not want the astronomy submission fragmented.

Scientists more deeply involved in the project will understand that the KSPs are only a subset of all the science drivers. However, the engineering community strongly prefer a well-focused set of KSPs which can be translated to design specifications as part of a system engineering approach.

Finally, KSPs are a core part of project promotion to the wider community. They help make a project like the SKA easily recognisable to young scientists and to the general public. In this sense, outreach has political value and can influence governments if the public is perceived to be interested and supportive.[50]

To answer the questions posed in the first paragraph of this section: (i) it is clear that KSPs are required by the astronomy community, funding agencies, and governments, for different but complementary reasons; (ii) it is arguable for valid project profile and engineering reasons that KSPs do constrain the scientific vision of the SKA, and (iii) in view of the past history of unforeseen major discoveries resulting from telescopes with the potential for discovery, there is general recognition[51] of the exploration of the unknown as a valid scientific driver for a telescope. However, the translation of this recognition into concrete plans of action for design teams is not straightforward (see discussion in Sect. 6.2.2.8).

### *11.4.3 Technology Innovation and the SKA*

From the earliest days of the project,[52] it was understood that the concept of a square kilometre of collecting area at a reasonable cost would require an innovative design solution. The cost/m$^2$ for different designs was considered a key metric since the cost of the antennas themselves would be the largest contributor to total construction costs. International meetings of the world's top radio astronomers and engineers generated many innovative proposals to build the SKA. Historical precedent in the VLA and the Australia Telescope Compact Array (ATCA) had shown that some innovative changes had been successfully implemented throughout the design and construction phases. In both cases this involved substantial risks[53] and was instrumental in creating the landmark instruments they became.

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[50] See comment in Sect. 3.2.6.3 on the public interest in astronomy noted by the then Australian Prime Minister, John Howard, in connection with early (1998) discussions on the SKA.

[51] This does not include the proposal review system in the USA. See Sect. 4.5.3.4.

[52] See Sect. 2.4.

[53] See hba.skao.int/SKASUP11-2, *SKA and innovation, examples of risk taking in earlier radio telescopes*

Three stages of innovation in antenna design can be discerned for the SKA: (1) 1990–2005, (2) 2006–2010, and (3) 2011–2021. Stage 1 included dense aperture arrays with all-sky electronic multi-beaming capability, Luneberg lenses to enable simultaneous all-sky multi-beaming at higher frequencies, long focal length reflectors with airborne focus (Large Aperture Radio-telescope, LAR), the deformable surface reflector implemented in FAST in China, cylindrical paraboloids (later implemented as CHIME[54]), focal plane arrays[55] (also called phased array feeds, PAFs) to enlarge the field of view for a given collecting area, large number—small diameter (LNSD) dish arrays with relatively cheap elements, and active dipole arrays at low frequencies (later implemented in LOFAR and the Murchison Wide-field Array, MWA) (see Sect. 6.2.1.2, Table 6.2).

Stage 2 began in November 2005 when the International SKA Steering Committee (ISSC) decided (see Sect. 7.3.7.1) that an array of large diameter dishes would not provide the desired image quality for the SKA. This automatically meant that the LAR and FAST-like concepts were no longer in the competition to be part of the SKA design. Following the first encounter with the funding agencies, at Heathrow Airport in June 2005, an antenna technology down-select was carried out to demonstrate project maturity to the funding agencies. In the process, Luneberg lenses were also eliminated and a reference design including the Large N-small D (LNSD) array, mid-frequency "dense" aperture arrays, and wide-band, low-frequency sparse aperture arrays based on dipoles took centre stage for the next 5 years. The LNSD array component included both wide-band single-pixel feeds and PAFs at the dish focus, the so-called dishes + "smart" feeds.

Stage 3 can be described as the phase when the SKA design confronted reality (see Chap. 6), starting with the Concept Design Review in early-2010 and made manifest with the Project Execution Plan (PEP) later in the year. The project perceived an opportunity for continued funding in the next decade as long as a workable plan for the first 10% phase of the SKA was generated by early-2011. This was the timescale needed if the SKA were to complete PrepSKA in December 2011 with the ingredients in place for the pre-construction phase including the establishment of a legal entity.

In the PEP, the project took what can be described as a risk-averse approach using known technologies—the LNSD dish array with narrow band-width single pixel feeds and low frequency dipole aperture arrays. It also assigned the innovative higher-risk solutions—wide-band single pixel feed, phased array feed and dense aperture array concepts—to a new Advanced Instrumentation Program (AIP). At the time when the PEP decisions were made neither the PAFs nor the wideband single pixel feeds had competitive noise performance. However, they would now, at the time of writing, be competitive due to further technology developments, but that could not have been known in 2011. It is interesting to note that it was recognised in

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[54] Canadian Hydrogen Intensity Mapping Experiment

[55] hba.skao.int/SKAHB-542 *The Development of Focal Plane Arrays in Radio Astronomy,* Ron Ekers, and John O'Sullivan, 14 November 2022, presentation at PAFAR meeting in Sydney

2007[56] that discoveries of transient radio sources would be better facilitated by optimising a different metric for the telescope design which had a stronger dependence on field of view (see Sect. 6.4.7). However due to the complexity of implementing this metric, it was ignored in technology decisions. Since 2012, most of the discoveries of new transients have been made with SKA precursors and pathfinders with a large field of view. In contrast, the dense aperture arrays did not receive the required continuing funding in the post-2011 period and research on this approach slowly petered out. At the time of writing, it is unclear whether any of the AIP concepts will reach fulfilment in the final design for SKA Phase 2 despite there being an Observatory Development Program in place in the SKA Observatory.

Was this decision correct in retrospect? There is no clear answer. As the 2010s decade proceeded, PAFs were implemented successfully on the ASKAP antennas in Australia which themselves included an innovative three-axis feed rotation arrangement at the focus to enable simple wide-field imaging and excellent polarisation calibration (see Sect. 6.4.4.1). Single pixel, wide-band feeds have been implemented on a small number of telescopes, but the wide bandwidth presents a difficult signal processing challenge. A further consideration is that in 2011 there was a window of opportunity for pre-construction funding, as well as engagement and enthusiasm from the governments and funding agencies to carry the project forward. These factors could easily have disappeared or dissipated if there was perceived to be a substantial technology risk remaining.

In summary, the desire for innovation in the SKA was slowly replaced with increasing emphasis on conventional solutions which reduced risk and had predictable time scales and costs. The adoption of such solutions appears inevitable in global big science projects since risks cannot be shared easily over an international community, and the large committees needed to manage such facilities are necessarily risk averse.[57]

**Reflections on technology development in large radio astronomy projects**

In 2009, Rick Fisher (National Radio Astronomy Observatory, USA) and colleagues[58] submitted a white paper to the US Decadal Review (ASTRO2010) Committee on Large Instrument Development for Radio Astronomy. The abstract, quoted below, noted that the desire for an all-purpose solution and continued R&D into the construction phase led to higher risks, cost overruns, schedule delays, and project de-scoping, and made a plea not to put all the radio astronomy R&D “eggs” in one basket. Without referring to the SKA directly, they also made several other relevant observations for a project with the ambitions of the SKA.

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[56] hba.skao.int/SKAMEM-109 *Survey metrics*, Jim Cordes, October 2007

[57] Francis Crick “Committees are necessarily conservative and risk averse.”

[58] hba.skao.int/SKAHB-541 *Large Instrument Development for Radio Astronomy*, Rick Fisher et al. (14 co-authors), 2009. Fisher is a senior engineer at the National Radio Astronomy Observatory in the USA and a leading world-figure in the radio astronomy science and engineering community.

> This white paper offers cautionary observations about the planning and development of new, large radio astronomy instruments. Complexity is a strong cost driver so every effort should be made to assign differing science requirements to different instruments and probably different sites. The appeal of shared resources is generally not realized in practice and can often be counterproductive. Instrument optimization is much more difficult with longer lists of requirements, and the development process is longer and less efficient. More complex instruments are necessarily further behind the technology state-of-the-art because of longer development times. Including technology R&D in the construction phase of projects is a growing trend that leads to higher risks, cost overruns, schedule delays, and project de-scoping. There are no technology breakthroughs just over the horizon that will suddenly bring down the cost of collecting area. Advances come largely through careful attention to detail in the adoption of new technology provided by industry and the commercial market. Radio astronomy instrumentation has a very bright future, but a vigorous long-term R&D program not tied directly to specific projects needs to be restored, fostered, and preserved.

In a talk given by Ekers in connection with the award of the Grote Reber Prize at the URSI General Assembly in Beijing in 2012, he reflected on how changing technologies had enabled continuing innovation in radio astronomy and how to accommodate the differing timescales of change in both science and technology.

The time scale for science topics to evolve, and even go in and out of fashion can be much less than the lifetimes of major physical elements of the telescopes themselves such as antenna structures and site layout and infrastructure (typically 50 years). Hence it is no surprise that telescopes are not known for the science they were originally built to study, but instead for new unanticipated discoveries which, for a new instrument, emerge on much shorter time scales (see also Chaps. 1 and 5). Flexibility to upgrade may be more important than desired functionality at the outset to solve particular scientific questions[59] (Wilkinson et al., 2004), (Kellermann & Bouton, 2023). Due to the influence of rapid technology development, particularly digital technology which progresses on a faster time scale (Moore's Law) than software developments, it is necessary to continually innovate and take risks to push the boundaries of instrument performance. For large projects, however, this has to be balanced with the reality noted by Fisher and colleagues that more complex instruments with longer lists of requirements and are necessarily further behind the technology state-of-the-art because of longer development times. A facet of the SKA design approach was to produce a constrained maximisation of discovery space by retaining flexibility wherever possible (see Sect. 6.1). But we note that instruments designed to be general purpose are not necessarily more complex. It is possible to design simple robust systems which are sufficiently flexible to enable innovative upgrades. In radio astronomy this has generally been true of the large parabolic dishes.

In Chap. 1 (Sects. 1.2, 1.3 and hba.skao.int/SKASUP1-1), we noted that Livingston curve analyses of high energy physics accelerator performance and radio astronomy sensitivity as a function of time showed that there had been an

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[59] See also Sect. 5.3.7

exponential increase in performance for 60 years but that is now flattening out. There are probably two reasons for this: i) no fundamentally new technology has yet emerged[60] which can maintain the exponential envelope; and ii) when international collaboration is required to provide the financial and skilled human resources for a mega-project, an inevitable delay is introduced. For global science mega-projects there will be limitations set by government priorities in each participating country on the total funding provided and in the rate the funding is made available. As noted in Sect. 1.5, global science mega-projects are particularly complex to deliver, especially in cases where no single partner is dominant as is the case for SKA. This complexity increases as some power of the number of different stakeholders. Delays would be inevitable even if fundamentally new technology was to be implemented. Our conclusion is that for large multi-national projects, it is not feasible to maintain rapid technological innovation as is the case with simpler organisational structures.[61]

SKA Phase 1 is under construction. The coming years could provide an opportunity for changes in technology to emerge that enable new parameter space in sensitivity and survey speed to be explored and show the way for a future expansion towards SKA Phase 2, the full SKA originally envisaged. See further discussion in Sect. 11.4.6.

### *11.4.4 Timing of the Engagement with the Funding Agencies*

There was disagreement in the ISSC in 2005 about the timing of the first approach to the funding agencies in the SKA countries (see Sect. 3.4.1). While some were not inclined to expose the project to outside political influences before the major decisions on technology and site had been made on scientific grounds, the majority decided to take up an invitation to provide a position paper on the SKA ahead of these decisions.

The funding agencies had other issues on their minds. In Europe, with other pressures on funding including ALMA and the era of extremely large optical telescopes coming along, it was difficult to see how the SKA was going to be afforded. According to Richard Wade (Science and Technology Facilities Council, UK), co-chair of the group of funding agencies discussing the large telescope projects in 2005, the main problem they saw with the SKA at that time was how they could make it happen. In retrospect in 2019,[62] Wade's view overall was:

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[60] Radio astronomy has now reached the fundamental physical limits on receiver noise and bandwidth. Collecting area is not subject to the same fundamental physical limits, but an exponential increase in collecting area using current technology is not feasible for a general-purpose instrument.

[61] The authors acknowledge discussions with John Womersley on these ideas.

[62] hba.skao.int/SKAHB-543 *Did we engage with the Funding Agencies too early?*, Richard Wade, April 2019, SKAHistory2019 Conference (Transcription)

> You can never engage with the funding agencies too early. And [with] something as important as site selection, if you don't engage with the funding agencies then you might as well pack up and go away.

The SKA project engaged with the funding agencies at the opportune time. It was ready for external scrutiny, building on 12 years of global collaboration in which a case for ground-breaking science had been generated, significant progress on the telescope design had been made, a well-established governance structure was in place, and an agreed formal site selection process was in progress.

### *11.4.5 Impact of Site Short-Listing vs Definitive Decision in 2006*

The ISSC began the process of selecting a single site for the SKA in 2001.[63] Its approach was straightforward and followed the example of ALMA: find the best site to optimise the science, free of political interference, and sort out other issues including politics and funding later. With the goal of starting SKA construction in 2010 in mind,[64] it was also thought essential to complete site selection by 2005 or 2006 to allow the project to focus on the telescope design knowing where it would be located and taking any design requirements imposed by the site location and infrastructure into account. The selection process was well advanced at the time of the ISSC's first encounter with the funding agencies at Heathrow Airport in June 2005, with multiple responses to a call for proposals expected at the end of 2005 and an outright decision on one site planned for mid-2006.

The funding agencies had other ideas about the process[65] and preferred an approach that created a short-list of two or more sites meeting agreed minimum requirements. The final down-select would include other factors such as the willingness of the potential hosts to make significant contributions called host country premiums. Creating a competition via the down-select process carried with it the prospect of higher host nation contributions to the project than might otherwise have been expected. Although not articulated at the time, this approach was consistent with ameliorating the funding agencies' concerns about how to fund the SKA in the crowded project environment then in prospect in 2006 (see Sect. 11.4.4 above). Support of the funders[66] was needed for both site selection approaches, the difference being the timing of that involvement.

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[63] See Sect. 7.3.1

[64] See Sect. 4.6.1

[65] hba.skao.int/SKAHB-543 *Did we engage with the Funding Agencies too early?*, Richard Wade, April 2019, SKAHistory2019 Conference (Transcription)

[66] hba.skao.int/SKAHB-543 *Did we engage with the Funding Agencies too early?*, Richard Wade, April 2019, SKAHistory2019 Conference (Transcription)

In retrospect, following the funders' advice to include a short-list stage was the best decision for the ISSC to take despite the (unanticipated) 6 years it took before the final site decision was made. As made clear at the Heathrow Airport meeting, the project as a whole was not sufficiently well supported by funders around the world at that time and, without that broad support, an outright selection of the site may not have been the best way to proceed. More important than persisting with outright selection of the site was for the ISSC to make sure the SKA was included on national and regional (European) roadmaps of future projects so that funding agencies and governments around the world had a formal basis for engagement with the SKA and, with that, a basis to proceed with a site decision.

It is interesting to speculate whether the post-Heathrow ISSC proposal in August 2005 to rank all four sites followed by the "softer" approach of "round-table discussion" would have led to a different outcome for the site selection than the hard competition via the short-list approach adopted. One such outcome of the ISSC approach might have been a compromise between the top-ranked sites, Australia and South Africa, whereby a mutually acceptable sharing of the developments was achieved. With Australia in the pole position in 2007–8, they would have been in the stronger position to fashion the compromise more to their liking, but also would have been less inclined to accept that a compromise was necessary; we shall never know.

As far as the final site selection was concerned, the competition in its later stages did trigger some unhelpful animosity between countries that had had good relations previously, as related in Sect. 8.6.3. One further negative consequence of the competitive relations between Australia and South Africa engendered by the governmental/funding agency entry into the site selection process was the decision in Australia to make the post-2006 internal deliberations on their site proposals confidential. This prevented the normal process of community consultation and comment. This was not the case in South Africa.

### Consequences of an outright site decision in 2006

Had the definitive site decision been made in 2006, it is most likely Australia—New Zealand would have been selected ahead of Southern Africa.[67] The former was seen at the time by the ISSC and the International SKA Site Advisory Committee as having the better credentials to host the SKA[68] although both were acceptable sites.

It is interesting to reflect on what might have happened to the project in that case. The political impetus and profile of the project would have been much lower. Negotiating a host country premium would have been off the table. Without the high political profile and lobbying associated with the competition, the likelihood of substantial funding for the project may have been jeopardised.[69] There would have

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[67] See Sect. 8.1

[68] See Sect. 7.3.8.3

been strong arguments in favour of locating the project headquarters in Australia in addition to the telescope. This may have led to the perception of SKA being more of a national rather than global project, possibly resulting in less interest from other potential partners in making major funding contributions. A predominantly Australian SKA with some European involvement was one likely scenario. Were the site decision to have gone to Australia in 2006, the development of radio astronomy in South Africa may have been less vigorous despite MeerKAT. In addition, the intangible benefits for science and training/education in Africa of having a high profile global scientific infrastructure on the continent would have been foregone.

Finally, it is interesting to note that despite their being a central issue in the funders' minds in 2006, host country premiums played no part in the site decision outcome in 2012. No negotiations took place on premiums due, no doubt, to their being regarded as a step too far in an already fraught site decision process in which the priority was to hold the project together. However, as time went on, it was recognised that, during discussions on overall contribution levels, there were other assets and past investment at the telescope host sites which, when made available, would constitute an additional financial contribution. This was not an active part of the main discussion on the contribution.[70]

**Was the dual-site outcome in 2012 inevitable?**

In retrospect, the answer to this question is yes, from the moment the SKA Site Advisory Committee (SSAC) submitted its recommendation to the SKA Organisation in early-2012.

The outcome was not expected despite having been discussed briefly at several meetings of the SSEC and Agencies SKA Group/Founding Board as well as by the Science Working Group[71] in the previous 4 years and was included as an option, in somewhat ambiguous terms, in the SSAC mandate. This stated that analysis and evaluation of the site proposals from Australia/New Zealand and Southern Africa was to be "open to a variety of site selection solutions, if the data and information provided to the SSAC support them".[72] However, as we describe in Sect. 8.6.1, the SSAC did not consider any alternative solutions for the SKA project in the belief it was charged to make a firm recommendation on which site to choose from the two proposals, not to work out a grand compromise acceptable to all parties.[73]

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[69] hba.skao.int/SKAHB-540, Discussion on Project Politics and Funding at the SKAHistory2019 conference. This includes a comment by Michael Garrett on the positive benefit of the site competition in raising the SKA profile in other countries, 2019.

[70] Simon Berry and Phil Diamond, private communication, August 2023

[71] hba.skao.int/SKAHB-499 *The Science Implications of an SKA "Win-Win" Siting,* SKA Science Working Group, Supporting Paper for the 3rd Meeting of the SSEC, October 2009. See also Sect. 5.9.9.

[72] hba.skao.int/SKAHB-463 SSAC Terms of Reference, Attachment 2—Report and Recommendation of the SKA Site Advisory Committee (SSAC), February 2012

[73] hba.skao.int/SKAHB-489 Reflections on the SSAC and its work, Jim Moran, email to Richard Schilizzi, 12 April 2021

Four factors underpinned the dual-site decision made by the Members of the SKAO Organisation. (1) The SSAC had determined that the SKA could be sited in either Australia/New Zealand or in Southern Africa. It was their detailed analysis of the selection factors that "favoured" Southern Africa. Australia had been expected to win decisively but that was clearly not the case. Neither was Southern Africa's case so strong that it was seen as the decisive winner; (2) The Site Options Working Group (SOWG)[74] established by the SKAO Board of Directors had concluded that a dual-site implementation with the two sites hosting different technologies operating at different frequencies, was capable of delivering the SKA Phase 2 science case. There was no scientific, technical, significant cost or operational disadvantage compared with a single-site implementation for doing so; (3) The SOWG further concluded that for SKA Phase 1, distinct advantages arose from incorporating the MeerKAT and ASKAP precursors and related infrastructure into the SKA in terms of increased scientific capability and the availability to the SKA project of an estimated total investment in excess of €300 M in the precursors; and (4) The SKAO Board of Directors and Members were conscious of the overriding concern to keep the project together and maximise its financial viability in the longer term through continuation of the current Organisation membership, and ensuring its global character remained attractive to future members.[75]

One might argue that South Africa had more to lose from the dual-site decision than Australia in view of the original SSAC recommendation. However, indications are that the recommendation came as a surprise to South Africa as well as Australia and that the dual-site decision was eventually an acceptable outcome to South Africa (see Sect. 8.6.3.3). It is interesting to note that the South African SKA leadership recognised early on that a split site was a possibility,[76] even though it was not regarded as a good idea.[77] At that time, it was important to avoid an "also-ran" outcome from the site short-listing in 2006; their aim was to be one of the short-listed sites. It is interesting to note that, at the time of writing, both sites are relieved that they only have one telescope technology, the mid-frequency or low-frequency array, assigned to them. This has avoided the difficulties, unforeseen at the time, related to having two quite different sets of construction issues to solve at the same time on the same site. It is now clear that the dual-site outcome can be defined as a classic moment of project peripety when the future trajectory suddenly seems clear and possible.

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[74] See Sect. 8.6.3.2

[75] hba.skao.int/SKAHB-503 *Statement from the Chair*, John Womersley, Supporting paper for the 2nd meeting of SKAO Members.

[76] hba.skao.int/SKAHB-442 *Memorandum on the Request for Proposals for a Site for the Square Kilometre Array*, Bernie Fanaroff, 9 May 2004. See Sect. 3 in this document.

[77] Justin Jonas, private communication to Richard Schilizzi, 19 June 2017.

### 11.4.6 *The Influence of the Precursors and Pathfinders on the SKA*

The SKA-specific Precursors and Pathfinders—ASKAP, MeerKAT, MWA, LOFAR and FAST—were designed and built for a variety of reasons: to demonstrate technologies of interest to the main SKA project, provide a fallback in case the site decision did not go their way, or to provide a means of maintaining and growing the radio astronomy community nationally and globally while the SKA was in its long design and construction phase. National prestige considerations were important in all cases.

In Australia, ASKAP was originally a 10-element array demonstrating the phased array feeds technology in an array of telescopes and the potential of the remote, RFI-quiet site in Western Australia. It grew into a 36-element array when additional money was found from government to provide innovative observing opportunities for the local astronomy community and a state-of-the-art telescope as a fallback position in case the SKA was not built in Australia.

In South Africa, the MeerKAT project was more than an engineering prototype. It proved South Africa could assemble a team of highly qualified engineers, astronomers and commercial enterprises to build a state-of-the-art radio telescope that would, at the same time, act as a beacon for young scientists from the African continent. A key aspect of the approach was also to build up relationships in the global radio astronomy community and benefit from external expertise in designing, building and operating MeerKAT. South Africa was keen to show it was much more than just a developing-world host country for an international facility, receiving access to the telescope or financial contributions to a development program for astronomy in that country in return for a telescope site. Continental, national and institutional pride was involved. It is probably fair to say that the site fallback argument carried more weight there than in Australia.

In The Netherlands, the development of LOFAR was driven by George Miley's assessment of the state of radio astronomy in the country in 1997.[78] He argued that maintaining and growing the radio astronomy community by building a telescope that explored new parameter space and offered new science opportunities on the relatively short term was a better strategy for the long-term health of the community than contributing all the Dutch resources to the main SKA project.

After entering the SKA collaboration with a very innovative big dish concept, China remained enthusiastic to explore this option themselves even though the down-select had excluded the big dish options. It is interesting to note that there are plans to expand FAST to the multiple element array first proposed as KARST (Kilometre-square Area Radio Synthesis Telescope) in the 1990s. This would approach the original sensitivity conceived for the full SKA.

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[78] See Sect. 3.2.6.1.

The SKA precursor instruments in both Australia and South Africa were much larger than necessary for the SKA from an engineering demonstrator perspective for the reasons outlined above. However, the larger than necessary scale has had benefits. The resulting telescopes are powerful instruments on the world stage and have shown themselves capable of ground-breaking research and hence attractive to the community. Their size also means that their instrumentation and software systems provide a more useful guide to future design directions for the SKA while enabling innovative design changes on shorter time scales and at lower costs than possible during the SKA construction project.

Would the SKA have made faster progress if the precursors on the sites had been restricted to engineering prototypes? Yes, engineering resources would have been freed up in principle, particularly as the timescales for completing the precursors and pathfinders were considerably underestimated. However, even if all the national resources had been put at the disposal of the SKA in its design and pre-construction phases rather than towards developing the precursors and pathfinders into working state-of-the-art telescopes, it is hard to quantify how much faster overall SKA progress would have been. Moreover, it is unlikely there would have been the same build-up of the user community that has occurred as MeerKAT, ASKAP, MWA, LOFAR, and FAST have come into operation.

There is little doubt that the top-level hardware design of a project the size of SKA Phase 1 had to be frozen at a relatively early stage from which point onwards further innovation was no longer possible without delaying the project. In contrast, the SKA software design was much less well developed for a substantial fraction of the Pre-Construction Phase and is now strongly influenced by principles developed by the precursors. It may be that precursor and pathfinder upgrades and enhancements will be a major segment of the planned Observatory Development Program (ODP) coordinated by SKA Observatory and lead to innovations that are implemented for SKA Phase 2 while the role of SKA Phase 1 will be as the workhorse for regular astronomy. One area of innovation could be exploiting Artificial Intelligence in future software development at the individual institutes involved in the SKA Regional Centre Network (SRCNet) which will eventually handle the SKA data products. Perhaps the SRCNet can serve as an example for a future network of instrumentation innovation centres. And perhaps, totally unexpected developments such as a quantum formulation of imaging theory in radio astronomy may impact the way we carry out our science in some fundamental way.

A deeper analysis of the influence of the precursors and pathfinders is beyond the scope of this book but would certainly be worthwhile.

## 11.5 General Observations from the SKA Experience

- Science mega-projects need to incorporate the ambitions of both the science community that drive the science goals and the engineering community that provide the underlying practical reality. Ideally, they will include some key (rare) individuals who live in both communities.
- Although a grassroots initiative may be the starting point of a science mega-project, as was the case for the SKA, spokespersons with established reputations are very important, particularly in the early years. The SKA had several of these people including Ron Ekers, Govind Swarup, Harvey Butcher and Ken Kellermann.
- Although the initial aspirations expressed by an international cross-section of scientists are essential, at some stage the profile of the project must grab the attention of government institutions and relevant global forums. In SKA's case, government buy-in had quite different motivations in Australia, Europe and South Africa. When and how this buy-in is accomplished is a matter of tactics, strategy, and luck.
- To enable the achievement of transformational science goals, initial key objectives must include efforts to overcome traditional technical approaches either by innovation or by smart adoption of newly available technologies. Even if these goals are not ultimately achieved, the interest created by well targeted efforts will generate excitement and interest from a broad community (and governments).
- It is likely that initial schedules and budget estimates will be optimistic.
- As the project proceeds, it will be necessary to make irrevocable design decisions, so that the project as a whole can maintain technical credibility and a believable timescale. This is a very sensitive stage in any project in which there are multiple potential technical approaches, and addressing this issue requires a nuanced decision-making process.
- The SKA has demonstrated that a global mega-project can succeed even without a single dominant national or international entity providing leadership and majority funding. In fact, a widely supported mega-project provides resilience against withdrawal of a single partner.
- As a global project, the SKA was seen as an entry point for participation in a state-of-the-art project by scientists from countries that did not have long-established facilities in the field. This lent support from a wider international base and from governments seeking a means to increase their country's exposure to leading science, especially the prospect of joining an international treaty organisation at a reasonable cost.
- New science mega-projects are likely to require a new site. The SKA's experience in selecting the telescope site provides many lessons, but the option of a dual-site, dual nation solution may be unique to the SKA. It was also an unexpected option resulting from the requirement to use two technologies to cover the SKA frequency range. There is no doubt that competition among the partners to host a mega-project is a means to raise its profile.

- Project management techniques which are typically applicable to projects with a single sponsor are unlikely to be adequate for a global mega-project without a dominant partner because textbook project management methods cannot fully allow for the inherent political considerations and sometimes unquantifiable risk. Funding agencies must be willing to accept substantial risk contingencies in cost and timescale in return for the advantages of participation in a global project.
- The SKA experience shows that with sufficient vision, tenacity, creativity and technical ingenuity, the many barriers to implementing a global science project can all be successfully overcome.

## 11.6 The Future

In 2019, at the meeting on the history of the SKA shortly after the signing ceremony for the Convention leading to the establishment of the SKA Observatory as an Inter-Governmental Organisation, Martin Gallagher[79](formerly an ASG member from Australia) raised the question of whether the SKA project was likely to move towards an ESO-like Observatory for radio astronomy. His arguments were that, initially, the SKA story was one of building a giant telescope, the largest in the world, to carry out ground-breaking research. Since then, partly as a consequence of the dual-site decision, the SKA has evolved to a concept with multiple sites, multiple instruments, a separate headquarters,[80] and perhaps the prospect of a longer-term life as a scientific enterprise with an even broader scope of research than originally conceived. An Observatory of this size would be able to influence a scientific discipline and build capacity in the science, technology, engineering and mathematics (STEM) areas over many decades.

Events have gone in this direction with the ratification of the SKA Convention in early-2021 and start of Phase 1 construction in mid-2021. The SKA project has already created a rich legacy for radio astronomy with the precursors and pathfinders. In the process it has regenerated a vibrant radio astronomy community eager to harvest the scientific results and change our view of the universe, as well as to prepare for the second phase of the telescope to fulfil the original vision set out decades before. And perhaps even loftier goals?

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[79] hba.skao.int/SKAHB-545 Martin Gallagher, 2019, Transcription of comments in the discussion on Project Politics and Funding at the SKA2019History Conference.

[80] *One global observatory, two telescopes, three sites*, https://www.skao.int/en/about-us/skao

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# Appendices

## Appendix A. Instructions to Readers Concerning Online Access to Reference Documents

All unpublished documents and material referred to in the text of this book or via footnotes are held by the SKA Observatory Archive and are subject to standard copyright controls. Further information on copyright is available for the reader when accessing individual documents.

Documents are labelled with one of three category descriptors: (i) "hba.skao.int/SKAHB-nn" for unpublished minutes of meetings, supporting papers, authors' personal papers and other documents, (ii) "hba.skao.int/SKAMEM-nn" for documents in the SKA memo series published in the interval 2001 to 2015; and (iii) "hba.skao.int/SKANEWS-nn" for the SKA Newsletters published in the interval 2000 to 2012. "nn" is the document number. A fourth category of document held in the SKA Observatory archive is supplementary material of relevance to an individual chapter. Its descriptor is "hba.skao.int/SKASUPx-nn" where "x" is the chapter number and "nn" is the document number as before. Some references to supplementary material are in the main text rather than in footnotes.

Access to the documents is provided by clicking on the link to the category descriptor in the footnote or main text. Some of the reference documents are held by the SKA Observatory Archive in a "restricted access" area. Specific permission to view these "restricted access" documents can be requested at hba.skao.int.

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https://doi.org/10.1007/978-3-031-51374-9

# Appendix B. On-Line Supplementary Material Held in the SKA Observatory Archives

(hba.skao.int/SKASUPx-nn nomenclature: x is the chapter number, nn is the document number within the chapter)

Supplements can be accessed via hba.skao.int/SKASUPx-nn

| Document | Title |
|---|---|
| hba.skao.int/SKASUP1-1 | Exponential Growth and the Livingston Curves |
| hba.skao.int/SKASUP2-1 | Other Large Radio Telescope Concepts and Constructions, 1957–1990 |
| hba.skao.int/SKASUP2-2 | (i) The Royal Astronomical Society—Royal Society Study Group on UK Priorities for Astronomy for 1990-2000, and<br>(ii)The Wilkinson Note and its transcription |
| hba.skao.int/SKASUP3-1 | Video of the signing ceremony for the August 2000 Memorandum of Agreement on the International SKA Steering Committee (ISSC) |
| hba.skao.int/SKASUP4-1 | US Decadal Survey 2000 Prioritised Initiatives |
| hba.skao.int/SKASUP4-2 | SKA pathfinders |
| hba.skao.int/SKASUP4-3 | Participating Organisations in PrepSKA |
| hba.skao.int/SKASUP4-4 | PrepSKA Work Packages |
| hba.skao.int/SKASUP4-5 | Members of the ISSC, SSEC, Funding Agency groups, Founding Board and PrepSKA Board |
| hba.skao.int/SKASUP4-6 | Breakdown of SKA cost estimates from the submission to the US ASTRO2010 Decadal Survey Committee |
| hba.skao.int/SKASUP4-7 | High-level SKA timeline and schedule elements from the Project Execution Plan |
| hba.skao.int/SKASUP4-8 | Members of the Review Panel for the Project Execution Plan, March 2011 |
| hba.skao.int/SKASUP4-9 | SKA Organisation: Signatories, Members and Directors, 19 Dec 2011 |
| hba.skao.int/SKASUP5-1 | The Oort Workshop 1997: Scientific Drivers for the next generation radio telescope |
| hba.skao.int/SKASUP6-1 | WP2 Description of Work as a Matrix of Tasks and Programs |
| hba.skao.int/SKASUP6-2 | SPDO staff members, Liaison Engineers, and Working Group Chairs |
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| hba.skao.int/SKASUP6-10 | Detailed Version: Cost Estimates for Dishes |
| hba.skao.int/SKASUP6-11 | Detailed Version: Principles of Phased Array Feeds (PAFs) |

(continued)

| Document | Title |
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| hba.skao.int/SKASUP6-12 | Detailed Version: Development of PAFs at the Dominion Radio Astronomy Observatory (DRAO, Canada) and the University of Calgary |
| hba.skao.int/SKASUP6-13 | Further developments on PAFs for the SKA after 2013 |
| hba.skao.int/SKASUP6-14 | CSIRO Collaboration with Canadian Institutes on ASKAP |
| hba.skao.int/SKASUP6-15 | Computing Challenges: CSIRO collaboration with South Africa |
| hba.skao.int/SKASUP6-16 | Detailed Version: the SKA1 Survey Telescope post 2012 |
| hba.skao.int/SKASUP6-17 | Basic Technology of Aperture Arrays at Low- and Mid-frequencies |
| hba.skao.int/SKASUP6-18 | Detailed Version: SKA-low Array Elements |
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