CHAPTER 11

NRAO and Radio Astronomy in the Twenty-First Century

Following the inauspicious experience with the 140 Foot Telescope, NRAO apparently learned to manage big projects. The VLA and VLBA were built on schedule and on budget. But the Green Bank Telescope project was funded before the design was complete and was prematurely rushed into construction with unfortunate consequences to the cost and schedule. However, by the beginning of the twenty-first century NRAO was operating the most powerful radio telescopes in the world, the VLA, the VLBA, and the GBT, and had become the acknowledged leader in the evolution of radio astronomy from a technique to an astronomical-based science. As radio telescopes became more sophisticated and computer-aided, observations and reduction became more automated; radio astronomers evolved from experimenters to observers to data analysts. By the turn of the century, the traditional breed of radio astronomers was disappearing. NRAO users often no longer participated in the observing, and with the start of ALMA observations in 2011, often did not even participate in the planning of the observations or the reduction of data.

As the operation of the powerful new NRAO facilities demanded a greater and greater share of the National Science Foundation (NSF) astronomy budget, the university radio observatories were gradually closed, exacerbating the community's long standing love-hate relationship with NRAO. Many university researchers, unable to get sufficient NSF grants to observe with their students at NRAO, turned their attention elsewhere. The pressure for observing time gradually diminished, and the NSF began to discuss the partial divestment of the NRAO, once the NSF poster child.

11.1 New Discoveries and New Problems

Radio astronomy provided the first observations of the cosmos outside the traditional narrow optical window characteristic of all previous astronomical studies extending over many millennia. Today, astronomers study the infrared,

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ultraviolet, X-ray, and gamma-ray portions of the electromagnetic spectrum as well as radio and optical observations, and are beginning to explore the non-electromagnetic Universe of gravity wave and neutrino astronomy. However, radio astronomy was the first of the new astronomies and captured most of the new discoveries. Karl Jansky and Grote Reber started it all in the 1930s, and after WWII, discoveries and recognitions followed, highlighted by Nobel Prizes awarded to eight different radio astronomers.[1]

These exciting new discoveries of the previously unrecognized nonthermal universe were largely outside the main stream of optical astronomy, with its traditional emphasis on solar and stellar astrophysics and other thermal phenomena. For many years, radio astronomy in the US developed separately from the astronomical community, primarily by people with backgrounds in radiophysics rather than astronomy. There was strong support from the federal government, first from the Department of Defense (DOD), in particular the Office of Naval Research (ONR) and the Air Force Office of Scientific Research (AFOSR), and later the NSF. Radio astronomers shared both an appreciation of instrumentation as well as a common feeling of not being fully accepted by the traditional astronomy community. Although competing with each other for limited funds, the real "enemy" was perceived to be the "optical astronomer." US radio astronomers became united in pursuing expensive new facilities, and they felt more at home within the URSI Commission J on Radio Astronomy rather than the American Astronomical Society (AAS) or the International Astronomical Union (IAU) (Sullivan 2009, p. 418).

The middle of the twentieth century saw the construction in the US of many DOD-funded university-based facilities, particularly the very successful Caltech Owens Valley Radio Observatory (Sect. 6.6). Later, the NSF funded the NRAO in Green Bank, the 36 Foot mm wave telescope, the VLA, the VLBA, and the GBT, and, starting in 1971, the Arecibo Observatory, but many other projects, some very promising, died somewhere along the complex funding route. These included the Owens Valley Array (Sect. 7.2), the Associates for Research in Astronomy 100 meter dish (Sect. 9.5), the CAMROC/NEROC 440 foot radome enclosed dish (Sect. 9.5), and the NRAO 25 meter millimeter-wave project (Sect. 10.3).

Due to limited NSF funds for facility operations, the big projects began to eat the ongoing smaller university radio astronomy programs. Those university programs were the breeding ground for the new generation of radio astronomers who designed, built, and operated the large new national facilities, and also provided the opportunity for developing the innovative new techniques and telescopes. The struggle between NRAO and the university-operated radio observatories continued throughout the history of NRAO, beginning in the mid-1950s during the lengthy debates about forming a national radio observatory. However, it was the big VLA and VLBA projects in the 1970s and 1980s that had the biggest impact on the university facilities.

As a result of the greatly improved sensitivity of radio telescopes (Fig. 11.1), radio astronomy was no longer constrained to study radio sources discovered

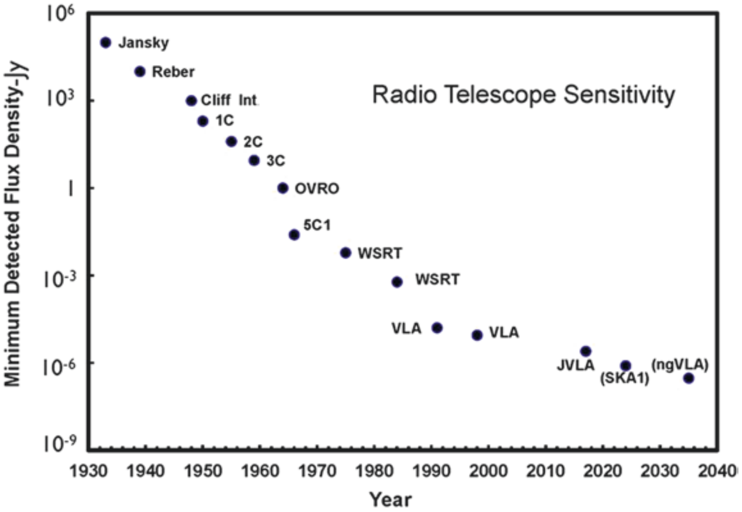

Fig. 11.1 Plot showing the weakest detected radio source as function of time since Jansky's 1933 radio detection of the Milky Way. The points refer in sequence to Jansky, Reber, the Australian Sea Interferometer, the Cambridge 1C, 2C, and 3C surveys, the Owens Valley Interferometer, the Cambridge 5C survey, the Westerbork Synthesis Radio Telescope, and the VLA. The last two points show the expected sensitivities of SKA-1 mid and the ngVLA respectively. In less than 100 years the sensitivity of radio telescopes has improved by a factor of about 100 million. Credit: NRAO/AUI/NSF

by radio surveys, but could study the radio emission from known cosmic objects. This was especially attractive to the large stellar astronomy community who could use observations of the thermal emission to determine the rate at which stars were losing mass. With the introduction of the VLA, astronomers, for the first time, could make images with resolutions comparable to those obtained from the biggest optical telescopes. VLA users studied solar system objects, stars, supernovae, the interstellar medium, galaxies, quasars, and cosmology. Radio observations became a tool for all astronomers, not just those trained in radio astronomy, and NRAO encouraged the growth of this broader user base. However, the VLBA, with its unique angular resolution, had no parallels at other wavelengths, and so had a limited user base, not only because it was perhaps more difficult to use, but also because the science was so different.

Early radio spectroscopy involved the laborious tuning of a single narrow-band instrument over a wide frequency range. With the subsequent enormous increases in sensitivity and the introduction of powerful multi-channel digital spectrometers, the impact to astronomy of the 140 Foot and later the 36 Foot and 12 Meter millimeter-wave telescopes was huge. They opened the new field of astrochemistry, exploring extreme conditions of temperature and pressure not easily duplicated in the laboratory, and the study of cold giant molecular

Fig. 11.2 JVLA radio image of the strong radio galaxy known as Hercules A superimposed on a Hubble Space Telescope optical image. The multi-frequency radio image made at 6 and 8 GHz (5 and 3.75 cm) shows the two-sided radio jet feeding a multiple bubble-like structure extending nearly one million light years from the supermassive black hole located at the center of the parent galaxy, suggesting a history of multiple outbursts. The lighter colored regions along the jet represent synchrotron emission from higher energy electrons and the darker red colors from lower energy electrons in the bubble rings. Credit: W. Cotton and R. Perley (NRAO/AUI/NSF), S. Baum (NASA) and C. O'Dea (RIT), and the Hubble Heritage Team (STScI/AURA)

clouds where new stars are formed. Using the VLA and eventually ALMA, the radio astronomy emphasis has slowly shifted from radio galaxies and quasars (Fig. 11.2) to the problems connected with the formation of stars, protostars, and planetary systems in dense regions obscured to light that can only be studied at radio wavelengths (Fig. 11.3).

11.2 Radio Astronomy and Optical Astronomy

Since their founding in the 1950s, NRAO and its optical counterpart KPNO/NOAO[2] have developed in very different directions. From its beginning, NRAO concentrated on major facilities too costly for a single university, while KPNO/NOAO was founded to provide access to telescopes and clear skies access to astronomers without their own telescope or from eastern universities with cloudy skies.

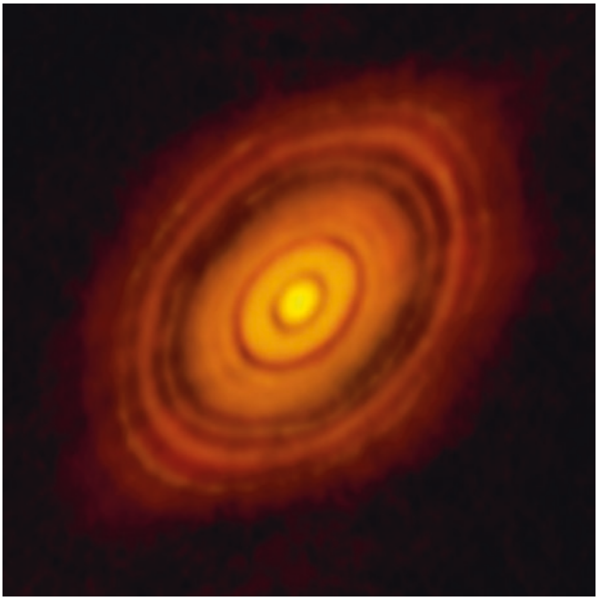

Fig. 11.3 ALMA image of the dusty circumstellar disk surrounding the young Sun-like star HL Tau, located about 450 light-years from the Earth. This image made at 1 mm wavelength (300 GHz) covers an area about the size of our solar system and shows evidence for the early formation of a planetary system. Credit: ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF)

The VLA, VLBA, GBT, and ALMA are all unique facilities, unrivaled anywhere else in the world. By contrast, the national optical astronomy facilities are less competitive. The two 8 meter (315 inch) Gemini telescopes are smaller than the Caltech/University of California 10 meter (394 inch) telescopes. The largest telescope at KPNO, the 4 meter (158 inch) Mayall Telescope, went into operation nearly two decades after the larger 5 m (200 inch) Palomar telescope. As was noted in the minutes of the November 1967 meeting of the AUI Executive Committee, "The Kitt Peak observatory has adopted the policy of acquiring additional small scale observing equipment whenever existing equipment is overloaded, but Dr. Heeschen does not consider this to be a function of NRAO".[3]

There are perhaps three reasons why NRAO and NOAO/KPNO developed along these different paths. For optical telescopes, the sensitivity depends only linearly on telescope diameter, whereas at radio wavelengths the sensitivity depends on the area of the aperture or the square of the diameter (Ekers 1978). Secondly, there are a very large number of stars in the sky with a wide range of astrophysical conditions (e.g., temperature, pressure, element abundance) that can be studied by modern optical spectroscopy using only moderate size telescopes, thus allowing significant research using only modest facilities. The third reason is perhaps more related to the historical and sociological development of radio and optical astronomy rather than to astrophysics. In the US, optical astronomy developed and thrived with support from philanthropists such as Charles Tyson Yerkes, William Johnson McDonald, and James Lick, as well as from the Carnegie and Rockefeller Foundations, and in a some cases state governments (e.g., Arizona, California). The philanthropists, of course, wanted their money to go to big noticeable telescopes. Yet only a privileged few astronomers at Yerkes, McDonald, Lick, Mount Wilson, and Palomar Observatories had access to these giant telescopes in the 60–200 inch class that were required to explore the exciting new developments in galaxy research and cosmology. Others had to be satisfied with using more modest facilities in generally less than ideal locations. Not surprisingly, by the middle of the twentieth century there was increasing tension between the "have" and "have not" optical astronomers, with the former being primarily at the large Mt. Wilson, Mt. Palomar, and Lick observatories which did not encourage competition from NOAO/KPNO.

Unlike optical astronomy which, as result of dramatic improvements in detector technology, has been able to effectively use telescopes as much as 100 years after their initial deployment, the US closed radio telescopes when they became less productive, sometimes when operating funds were no longer available, and in a few cases where acts-of-God led to the closing of otherwise competitive facilities. NRAO closed the 4-element Green Bank Interferometer, the Green Bank 140 Foot Telescope, and the NRAO 12 Meter mm dish[4] so that limited resources could be devoted to newer facilities, the VLA, GBT, and ALMA respectively. Many other, still productive US radio telescopes were closed due to the loss of operating funds.

11.3 NRAO and the US Radio Astronomy Community

Since the first ideas were floated about establishing a national radio astronomy observatory, the "love-hate" relationship between the university-operated radio observatories and national radio astronomy facilities has been the powerful background against which US radio astronomy developed during the latter half of the twentieth century. For the most part, NRAO facilities were used and appreciated by the many radio astronomers located at universities aspiring to do research in the rapidly developing field of radio astronomy, but which had no facilities of their own. Indeed, some schools, such as the Universities of Maryland, Pennsylvania, and Iowa, and Virginia Tech, started new radio astronomy programs and hired new faculty based on the opportunity for their faculty and students to use NRAO telescopes. On the other hand, places such as Caltech, Stanford, Ohio State, and the University of Illinois with ambitious projects of their own, saw NRAO as a direct competitor for limited funds. It was again a case of "haves" and "have-nots." There were many more "have-nots" than "haves," but the "haves" had more clout in Washington.

This dichotomy came to a head with the NRAO/Caltech controversy, first over the VLA (Chap. 7) and then the VLBA (Chap. 8). In the end, even the "haves," sensing the growing competition from abroad, combined with their strong interest in having the best possible facilities for their research, supported funding for NRAO, even if it might be at the expense of their own facility. For example, as discussed in Sect. 7.4, MIT's Bernie Burke provided critical support in getting the VLA funded, even at the expense of the proposed MIT-Harvard CAMROC 440 foot dish. Similarly, as related in Sect. 8.7, Marshall Cohen and others at Caltech supported and helped design the VLBA, knowing that it would lead to the loss of funding for the Caltech/JPL VLBI correlator, then the leading instrument of its kind in the world.

The 1969 amendment to the 1970 Military Authorization Act, introduced by Washington Senator Mike Mansfield, limited the use of Defense Department funds to research that included "a direct and apparent relationship to a specific military function." The Mansfield Amendment had an immediate and long lasting impact on the future funding of US radio astronomy, and ultimately on all US astronomy. Although the amendment formally applied only to the 1970 DOD Authorization Bill, both military and civilian funding agencies were apparently unclear on the interpretation. Military laboratories were fearful of risking their military programs, so did not contest the amendment. The NSF was faced with absorbing new university-led activities previously supported by DOD, with an uncertain level of funding to support these new activities. The NSF struggled for years to keep a balance between operating the university radio astronomy observatories and NRAO. Nevertheless, with continued budget challenges resulting from the need to operate the powerful new instruments being constructed, NSF support of still-productive university radio observatories gradually declined, and with time so did the support for NRAO facilities. Some of the unique US radio telescopes that lost NSF funding included the University of Maryland Clark Lake decameter array, the Stanford 5 element array, the Owens Valley Interferometer and 130 foot antenna, the University of Arizona Radio Observatory, and the Caltech Sub-Millimeter Observatory. As discussed in Sect. 10.4, threatened with closure in 2007, the Berkley-Illinois-Maryland Millimeter Array at Hat Creek and the Caltech OVRO Millimeter Array combined to form CARMA, the Combined Array for Millimeter Astronomy, but it too was closed for lack of operating funds in 2015.

11.4 Conflict and Collaboration

David Munns (2013) has characterized the development of radio astronomy as the result of friendly collaborations by scientists united by a common culture, an appreciation of technical matters, and a need to deal with a perceived common "enemy," optical astronomers. While collaborations have been important in some areas such as VLBI (Kellermann and Cohen 1988; Kellermann and Moran 2001), the intense competition between Australian and UK radio astronomers and between Cambridge and Manchester radio astronomers in the 1950s and 1960s (Sect. 2.1) (Edge and Mulkay 1976) reflects an alternative interpretation, as does the continuing tension between NRAO and some US university-based radio observatories.

For example, the deferral by Doc Ewen and Ed Purcell to the Dutch and Australian H I teams to simultaneously publish their H I discovery is described by Munns (2013) and Sullivan (2009, p. 414) as evidence of the cooperative culture of radio astronomy. Only after their success did Ewen and Purcell offer to wait for a joint publication, knowing full well that they were the first and that they would be so recognized, as indeed they have been. It is perhaps reflective of the sense of competition and priority, that when Jan Oort wrote to Grote Reber in 1945 asking his advice on building a radio telescope, he only mentioned his interest in the distribution of interstellar gas in the Galaxy. Oort, of course, was already aware of the possibility of detecting the 21-cm line, and that was clearly much of his motivation.[5] But he apparently held that close to his chest.

As described in Chap. 7, VLBI, especially earth-to-space VLBI, has perhaps been the poster child for a technically complex, and successful scientific cooperation among individual scientists, institutions, and countries, including some of the earliest serious scientific collaborations between the US and the Soviet Union. Perhaps these collaborations were successful because they were not driven by a political desire to collaborate or build bridges between countries and political systems, but because the science required it. The first VLBI experiments came about following friendly, but nevertheless intense, competition between Canadian and US radio astronomers who can (and still do) argue about who was first, depending on one's definition of success and what constitutes VLBI.

As discussed by DeVorkin (2000), Harwit (2015), Sullivan (2009) and others, much of the early support for radio astronomy, particularly in the US, came from military interests. With the end of the Cold War and the reduced threat of a major war between super-powers, the political forces have moved in the direction of international collaboration in the construction of expensive new scientific research instruments. Radio astronomy, with its long history of international collaborations, has been well poised to exploit these opportunities. The European VLBI Network (Sect. 8.5) has been successfully driven by a combination of scientific goals, European unity, and competition with the US. ALMA (Sect. 10.7), with a price tag in excess of 1 billion US dollars, is the most recent example of a successful large global collaboration involving countries from four continents. The Square Kilometre Array (Sect. 11.7) is a very ambitious multi-billion Euro international program that has been challenged by the international aspect, differing views on the technical implementation, and national ambitions.

11.5 THE NATIONAL RADIO QUIET ZONE AND RADIO FREQUENCY SPECTRUM MANAGEMENT[6]

Since its earliest years, radio astronomy has needed to deal with interference from both intended radio broadcast and communication transmissions as well as from unintended radio noise, generated, for example, by automobile ignitions, radars, or computers. As early as the 1930s, Karl Jansky reported radio interference from passing motor boats and from nearby medical diathermy machines. Grote Reber could only observe at night at 160 MHz, due to daytime interference from automobiles. Reber recognized the sensitivity limitations imposed by radar and the FM broadcast services, and was probably the first person to urge the creation of protected bands to study the astrophysical lines which he predicted might be observed in emission or in absorption. With the increasing use of the radio spectrum for a wide variety of communication and data transfer applications, the competition for frequency allocations has become intense. Radio frequency spectrum management has developed an extensive, often contentious, bureaucracy, with a rich collection of national and international agencies, committees, and acronyms.

Radio waves do not respect international borders, and since 1906 the allocation of the radio spectrum has been guided by the International Telecommunications Union (ITU), now a specialized agency of the United Nations. The 1927 Washington Conference established the International Radio Consultative Committee (CCIR) to coordinate technical studies and to develop international standards which are reviewed every three to five years at a World Radiocommunication Conference[7] (WRC). National administrations enable their own frequency allocations, generally, but not always, respecting the ITU/WRC guidelines.[8] Within the US, radio frequencies are assigned by the Federal Communications Commission (FCC) for non-federal government use and, for federal use, by the National Telecommunications and Information Administration (NTIA) based on input from the government Interdepartmental Radio Advisory Committee (IRAC).

In the early 1950s both URSI and the IAU discussed the need to protect some frequencies for radio astronomy. Although URSI passed a 1950 resolution asking that frequencies be reserved for radio astronomy, it was not initially adopted by the CCIR. In 1957, URSI set up the Sub-Commission on Radio Frequency Allocation for Radio Astronomy under the leadership of NRAO's John Findlay to prepare for the 1959 Geneva Administrative Radio Conference. With input from Findlay's committee, as well as from the IAU, the CCIR recommended that (1) radio telescopes should be located at sites as free as possible from interference, (2) governments should protect frequencies used for radio astronomy in their countries, and (3) that there should be complete international protection from interference in the bands around the 327 MHz deuterium frequency, the 1420 MHz H I frequency, and the 1667 MHz hydroxyl (OH) frequency, as well as seven bands between 40 MHz (7.5 m) and 1 GHz (30 cm) reserved for continuum observations.

At the WRC meeting later that year in Geneva, radio astronomers made the case to reserve frequencies for passive radio astronomy. Jan Oort represented the IAU and Lloyd Berkner represented URSI as non-voting delegates. John Findlay was part of the official US delegation, which was dominated by commercial interests and so provided less than enthusiastic support for radio astronomy (Sullivan 1959). Following long and contentious negotiations, for the first time, largely due to the pressures from the Dutch delegation, the Radio Astronomy Service was recognized as a legitimate user of the radio spectrum. The 1959 WRC recommended that multiple bands covering about one percent of the radio spectrum be allocated for radio astronomy, with special protection in the 1420 to 1427 MHz hydrogen band (Findlay 1960, 1991). In 1992, the ITU also defined the level of harmful interference not be exceeded in the radio astronomy bands, but with the great improvements in the sensitivity of radio telescopes since that time, these approved levels were no longer adequate to protect radio astronomy from harmful interference.

After the 1959 WRC, following a recommendation from the US President's Science Advisory Committee, the National Academy of Sciences (NAS) held a series of meetings to begin a dialog between radio astronomers and the government. This resulted in the creation of the NAS Committee on Radio Frequencies (CORF) to represent the US radio astronomy community in reacting to FCC "Proposals of Proposed Rule Making." Starting with John Findlay and Hein Hvatum, CORF has nearly always included someone from NRAO to provide advice on proposed new threats to radio astronomy such as satellite broadcasting and communications, airport radars, and most recently the pervasive automobile collision control radars. In addition to CORF, the NSF Astronomy Division, like other government agencies and military branches, includes at least one person expert in spectrum management issues to protect from threats to each agencies' use of the spectrum. On the international front, the Inter-Union Committee on the Allocation of Frequencies (IUCAF) was set up in 1960 by the three international scientific unions, URSI, the IAU, and COSPAR,[9] to coordinate the requirements for the protection of radio astronomy, and to convey these priorities to the national and international bodies responsible for frequency allocations. Both CORF and IUCAF have paid particular attention to the protection of frequencies corresponding to especially interesting spectral lines.

In Sect. 3.4 we described the establishment of the West Virginia Radio Astronomy Zoning Act which was passed by the West Virginia legislature to protect NRAO from unintended radio noise. This was followed on 19 November 1958 by the FCC establishment of The National Radio Quiet Zone (NRQZ) to provide protection from radio transmissions that might cause harmful interference to NRAO and to the US Naval Station at Sugar Grove (Sect. 9.3). It is centered around Sugar Grove, West Virginia, and covers an area of approximately 13,000 square miles in Virginia and West Virginia. All applications for fixed radio transmissions located within the NRQZ are reviewed for potential interference to either the Green Bank or the Sugar Grove facilities before being licensed by either the FCC or NTIA. The combination of the regulatory protection afforded by the NRQZ, the low population density, and the geographic protection provided by the surrounding mountains have been crucial in keeping Green Bank radio astronomy observations relatively free from radio frequency interference (RFI).

However, with the increasing demands on the radio spectrum from commercial, government, personal, and military activities, RFI has become an even greater problem than ever for radio astronomy. Moreover, the proliferation of satellite-based transmissions, high-powered radio and TV broadcasts, and equally high-power global communications satellites, has left no place on earth immune from RFI. At the same time, radio astronomers are no longer content with observing around a few protected spectral line frequencies or within the narrow bands allocated for continuum observations. Spectroscopic observations are subject to redshifts due to the expansion of the Universe. The region just below 1.4 GHz is of particular interest for observing atomic hydrogen in distant galaxies, but this is an especially crowded part of the radio spectrum. Continuum observations are even more difficult. The JVLA, for example, now covers the entire spectrum between 1 and 50 GHz. A typical continuum observation may cover several GHz of bandwidth, but the protected radio astronomy bands are typically only a few tens of MHz wide and do not provide meaningful protection.

On the other hand, there are only a few radio observatories left in the US, and to a lesser extent in the world, and they do not each observe in all of the protected bands all of the time. Modern radio astronomy needs only local protection around each observatory, and only in those bands and for those times that they are being used. Fortunately, above a few hundred MHz, radio propagation is limited to about one hundred miles, so selective protection is possible. Except for a few bands containing important spectral lines such as the 1420–1427 MHz band or the 1.6 GHz OH band, the protected radio astronomy bands have become no more than bargaining chips. However, fearing that the powerful commercial interests will gobble up anything put on the table, CORF, IUCAF, and the radio astronomy community, have been reluctant to offer up these narrow protected bands in return for local, time-sensitive, protection over much larger bands. While it seems inevitable that the current paradigm for radio spectrum management will be replaced by a shared use of the spectrum policy, it remains to be seen who gets what share.[10]

11.6 THE TRANSITION TO "BIG SCIENCE"

Following the early work of Karl Jansky and Grote Reber, radio astronomy in the United States has been largely supported by federal or state funds with little contribution from universities, industry, or private supporters. There were few obstacles to pursuing new initiatives, and few formalities to inhibit creative ideas. As described in Sect. 8.1, the NRAO VLBI program was initially funded by the NRAO Director with no formal proposal or committee review, and has developed into a global industry and one of NRAO's major facilities (Sects. 8.8 and 8.9). The 36 Foot millimeter wave (Sect. 10.2) telescope was initially funded on the basis of a few paragraphs added to NRAO's 1964 budget request, although based on what was known at the time, there were only a few objects in the sky known to be strong enough to be detected with the proposed telescope. No one anticipated the explosion in millimeter wave spectroscopy that would result in an international billion dollar ALMA program (Sect. 10.7).

Since those early years of the 1930s through the 1950s and the golden years of discovery of the 1960s, the landscape has changed. Whether for building a new instrument, an individual research grant, or for observing time, proposals are expected to give the expected results in some detail, almost obviating the need for the proposed activity. Risky but high potential payoff projects are difficult to get through the success-oriented peer review system. Some researchers have learned to play the system by proposing projects that are already nearly done, and using the new resources to attack more speculative projects.[11] Proposals to the NSF, even for modest research grants, need to supply a detailed technical description, a budget, a discussion of the "Broader Impact" to society,[12] as well as the expected scientific results. Indeed, even before submitting a proposal to the NSF, one has to be familiar with the 181 page NSF "Proposal & Award Policies and Procedure Guide" as well as other instructional material.

Combined with the increasing cost and complexity of radio telescopes, the modern administration of science provides fewer opportunities for individual initiative or opportunity to make new discoveries. The early pioneers were able to develop a new idea, build their own equipment, observe, and interpret the results. There were few, if any previous papers that had to be read, understood, and cited. Single or two or three author papers were common. By contrast, modern radio astronomy programs often involve large teams of scientists, engineers, and software experts, sometime located in different countries. The four-level peer review filter of facility or instrument proposal, research grant proposal, telescope time preproposal, and journal referees often represents a significant challenge to new research ideas, new facilities, or publishing new ideas. At the same time, the responsibilities of reviewing proposals for grants, telescope time, and journal reviewing represent a significant burden on the community.

While it is tempting to look back on those early years with rose-colored glasses, it is sobering to recall that Karl Jansky (Sect. 1.1), George Southworth (Sect. 2.1), and John Bolton (Sect. 6.6), to name a few, were constrained from pursuing their radio astronomy interests by the more immediate needs of their employer. Grote Reber had to deal with an editor who delayed publication of his pioneering paper because the editor did not have the background to understand and appreciate it (Sect. 1.3). The personal sacrifices of people like Lovell, Bowen, Hachenberg, and Heeschen in taking on the challenges and risks of building the Jodrell Bank, Parkes, Effelsberg, and VLA telescopes respectively should not be minimized.

The early ideas of Menzel and Berkner that led to the formation of NRAO reflected a departure from the individualism of the pioneering radio astronomers such as Reber, Ryle, Lovell, Pawsey, Bolton, Wild, Mills, and Christiansen. The NRAO founders had envisioned a facility where university scientists would bring their own instrumentation to install and use on the large NRAO telescopes. To an extent this happened during the early years in Green Bank with the 300 Foot and then 140 Foot Telescopes as well as the 36 Foot millimeter antenna on Kitt Peak. All this changed with the VLA. As Dave Heeschen (1991) noted,

> Most radio astronomy in those days was done by radio physicists and engineers who invented, built, and then used their own instruments. New telescopes usually came about either because someone had a bright idea, developed it and then did whatever radio astronomy he could with it, or because someone asked a particular scientific question and then designed an instrument to answer it. These both proved very fruitful ways to proceed, especially, when the practitioners were as talented and clever as those of the 50's and 60's. The VLA did not come about this way, however. Our motives and goals were quite different. We set out from the beginning to build a flexible, general-purpose instrument for a broad scientific purpose, to be used by a lot of people other than, or in addition to, the designers. Many people considered that approach inappropriate, unimaginative, undesirable, overly expensive, and unneeded, and we had to cope with these criticisms for 10 or 15 years.

Obtaining government funding for big science projects remains challenging. At best there is a long series of hurdles that must be passed; at any point a project can be killed. At a 1963 Green Bank meeting to discuss options for building a large steerable radio telescope, Dave Heeschen listed the "filters" that any project must pass through as (a) the NSF, (b) the Office of Science and Technology, (c) the Bureau of the Budget, (d) the President's Science Advisory Committee, (e) Congress, and (f) the President. Of these, Heeschen considered the NSF, even with its multiple reviews "the easiest" and the Bureau of the Budget "the toughest."[13]

From the earliest years, NRAO pioneered the use of digital data and computer aided analysis. When John Bolton visited Green Bank in late 1964 he wrote back to Taffy Bowen in Australia,

> Green Bank is now very impressive as far as facilities are concerned, very depressing as far as surroundings and social life are concerned, has a large working staff who are expending a lot of energy but, considering the resources, is not overproductive. It is probably over-automated and over-digitized. If you make your observation by writing a set of instructions for a telescope operator to carry out, then write a set of instructions for a computer to extract some data from the results, then it is rather unlikely that you are going to find anything other than what you are looking for.[14]

Ironically, it was John Bolton who led the effort at Parkes to transition from analyzing chart recordings to the use of computer analysis of digitized telescope output. But his 1964 warning would be prophetic. At first, radio astronomers wrote their own programs to reduce the burden of manual data analysis. With time, the software became sufficiently sophisticated that it was written by others, often teams of people rather than a single individual, and increasingly the software teams included more people trained in computer science than in physics or astronomy. Observers were able to use these software packages to reduce their data, but were increasingly ignorant about how they worked. Indeed, with rare exceptions, no one person understood everything. NRAO was satisfying its expected role to provide easy-to-use facilities for students and scientists not trained in radio astronomy techniques. Multi-wavelength astronomy became the norm, and NRAO was expected to produce so-called "science-ready-data-products." Astronomers are no longer radio, optical, or X-ray astronomers. Instead, they are galactic or extragalactic astronomers, or they perhaps concentrate on planetary astronomy or exoplanets—and are equally familiar, or perhaps unfamiliar, as the case may be, with techniques at all wavelengths. The ambitious goal of providing science-ready-data-products for data of increasing complexity and sophistication remains a challenge.

Bolton's warning about computers inhibiting discoveries is debatable. Certainly many of the scientific areas of contemporary radio astronomy would not be possible without modern high-speed digital computers. This certainly includes essentially all interferometric arrays such as the VLA, ALMA, IRAM (NOEMA), the Westerbork telescope, Murchison Widefield Array (MWA), and the Australia Telescope Compact Array, and especially VLBI; but also most single-dish studies, including pulsar searching and timing, spectroscopy, and mapping of extended structures, would not be possible without modern digital data analysis. Further, there has been an explosion in the volume of data associated with many radio astronomy programs. Sophisticated computer clusters have replaced laptops, and multi-person software development teams have replaced individual programmers.

At the 1997 dedication of the Jansky Memorial monument at the former Bell Labs Holmdel site, Paul Vanden Bout pointedly summarized the situation.

> Large facilities require large teams to keep them going. We have moved very far from the days of Jansky and Reber where a lone individual made a big contribution..... [Users] treat these facilities as vending machines. They put in a proposal, decide whether they want their M&Ms with or without peanuts. They pull the right lever and out comes data. Preferably calibrated data. It's all too much for those of us who grew up thinking real radio astronomy was done with a chart recorder. So we sit around and lament this. On the other hand, I've noticed that the people who complain the loudest, are the very people who are lobbying for the big new telescopes. I guess that means that we recognize that it is inevitable that we should seize the future and get on with it. After all, if this is what it takes to make the field go, then we ought to do it. There will be surprises and discoveries.[15]

11.7 The Square Kilometre Array (SKA)

Discussions about building a radio telescope with a very large collecting area go back at least to the early design of the Benelux Cross (Sect. 7.1) that had a collecting area of 600,000 square meters (Christiansen and Högbom 1961). Barney Oliver's Cyclops concept of one thousand 100 meter dishes (Oliver and Billingham 1973) had a geometric collecting area of about 10 million square meters. Later, Govind Swarup (1981, 1991) proposed the Giant Equatorial Radio Telescope (GERT) with more than 100,000 square meters of collecting area, while in the USSR, Yuri Parijskij (1992) discussed radio telescopes "with a collecting area of about 1 million square meters." A half a century ago, Grote Reber actually built an array in Tasmania with about a square kilometer of collecting area (Reber 1968). Reber's 2.1 MHz (144 m) array contained 192 half-wave east-west dipoles arranged in a 1075 meter (3526 foot) diameter circle. By properly phasing the elements, he could steer the 8 degree wide beam anywhere along the meridian. Reber's array had, and still has, the largest collecting area of any radio telescope ever built.[16]

First Years The start of the modern discussions directed toward building a next generation radio telescope, with an effective collecting area of one million square meters or one square kilometer, is generally considered to be Peter Wilkinson's (1991) paper on the "Hydrogen Array," which he discussed at a symposium held in Socorro, New Mexico, on the occasion of the tenth anniversary of the VLA dedication. Even earlier, Dutch radio astronomers, led by Robert Braun, were discussing a Square Kilometre Array Interferometer (SKAI) (Noordam 2013). In 1993 and 1994, URSI and the IAU set up the Large Telescope Working Group and the Future Large Scale Facilities Working Group, respectively, to coordinate discussion and planning among groups considering large scale radio and optical telescope projects. It was soon realized that the description of a "Square Kilometre Array Interferometer" was redundant and the term Square Kilometre Array or SKA was adopted. By agreement, the British spelling "kilometre" was adopted rather than the American spelling "kilometer."

The early strawman SKA concept consisted of a condensed nearly filled array for high sensitivity to low surface brightness complemented by three sparsely filled arms to improve the angular resolution. There was no shortage of ideas about how to implement the SKA, but most turned out to be unrealistic. The most straightforward approach considered was to build an array of parabolic dishes, much like the VLA or the Westerbork Synthesis Radio Telescope (WSRT), but with a much larger number of elements, perhaps taking advantage of Swarup's GMRT SMART concept (Sect. 6.6) to reduce costs. The Dutch proposal for a so-called "aperture array" of a very large number of simple antenna elements appeared very attractive. By properly combining the signals from the different elements, it would be possible to create multiple beams in the sky, and, moreover, to generate nulls in the response in the direction of interference. Australian radio astronomers suggested a field of Luneberg lenses[17] or parabolic cylinders. Canada proposed to build an array of 200 meter Large Adaptive Reflectors, each illuminated by feeds and receivers suspended from a tethered floating aerostat. China proposed to build some ten Arecibo-like spherical reflectors.

The challenge with all of these approaches was to keep the cost down to a level that could be realistically funded. An early cost estimate suggested that the aperture array could be built for \$100–\$200 million, but further development work indicated that the true cost of the SKA could be much higher. As the estimates of the construction costs continued to grow, there was agreement to revisit the specifications. Noting that the original requirement of a million square meters of collecting area was based on the 1991 assumption that the system temperature was likely to be about 50 K, the requirement was restated that the ratio of collecting area divided by system temperature (A/T) would be 20,000 m^2/deg. With anticipated system temperatures of 20 K, the required collecting area to meet the new specification was reduced to 400,000 square meters but the name "Square Kilometre Array" was nevertheless retained.

Although the SKA started out as the "Hydrogen Array," it was clear that with the planned sensitivity of the SKA it would impact almost every area of astronomy. Successive publications advertised the growing science case (Taylor and Braun 1999; Carilli and Rawlings 2004), culminating in the massive, two-volume, 1996-page book edited by Tyler Bourke (2015). Complementing the science publications, Hall (2005) and Smolders and Haarlem (1999) updated the status of the engineering design.

In his foreword to Peter Hall's book, Richard Schilizzi reported that

> The current schedule for the SKA foresees a decision on the SKA site in 2006, a decision on the design concept in 2009, construction of the first phase (international pathfinder) from 2010 to 2013, and construction of the full array from 2014 to 2020. The cost is estimated to be about 1000 M€.

International Organization Starting in 1999, an informal group of scientists from the US, the Netherlands, Australia, and Canada began to meet to develop plans for building the SKA. As there was no existing international structure to accommodate a multi-national project, one had to be created. At the IAU General Assembly in 2000 in Manchester, representatives from nine countries interested in the SKA signed a Memorandum of Understanding establishing the International SKA Steering Committee (ISSC) to provide broad oversight to the project. Ron Ekers (Fig. 11.4) from Australia, who had been the key person in getting the SKA program off the ground and in generating interest from the various national funding agencies, was elected as the first Chair of the ISSC. Four years later the ISSC created the International SKA Project Office (ISPO), with Richard Schilizzi (Netherlands) as ISPO Director, and a year later Peter Hall (Australia) became the Project Engineer. In 2008, a new Memorandum of Agreement created the SKA Science and Engineering

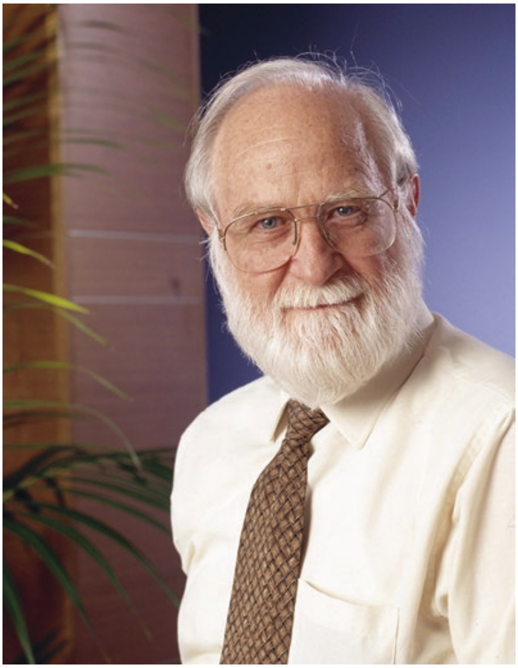

Fig. 11.4 Ron Ekers was as strong advocate for building the SKA as an international collaborative activity. He became the first Chair of the International SKA Steering Committee (ISSC). Credit: CSIRO Radiophysics photo archives

Committee (SSEC) and SKA Project Development Office (SPDO) replacing the ISSC and ISPO respectively, with Schilizzi continuing as SPDO Director.

The ISSC/SSEC met twice a year to review progress on the planning, costing, and siting of the SKA. Initially the Committee consisted of 18 members but was later expanded to 24 to accommodate the growing global interest in the SKA. One-third of the membership represented Europe, one-third the US, and one-third the rest of the world, reflecting the anticipated cost sharing. The ISSC/SSEC received input from international Science, Engineering, and Site Selection Advisory Committees, while the ISPO/SPDO was supported by a number of Working Groups and Task Forces within the ISPO.

The US SKA Consortium Recognizing the growing interest in the SKA, both internationally and within the United States, NRAO organized a meeting in Green Bank in 1998 to discuss how the US might participate in planning for the SKA. A few months later, a small group met at MIT and agreed to form the US SKA Consortium (USSKAC) to coordinate US participation in the SKA. Jackie Hewitt from MIT was elected as the Consortium Chair and Jill Tarter from the SETI Institute as the Vice Chair. Hewitt soon stepped down as Chair due to her other responsibilities, and was replaced by Tarter, then Yervant Terzian followed by James (Jim) Cordes, both from Cornell, and finally Patricia (Trish) Henning from the University of New Mexico.

The initial USSKAC membership consisted of Caltech, Cornell University, MIT/Haystack, NRL, the University of California, Berkeley, Ohio State University, and the SETI Institute. NRAO did not join originally due to some uncertainty about whether joining such an organization was allowed under the NRAO-NSF Cooperative agreement. Instead, Rick Fisher and one of the authors (Kellermann) were appointed as At-Large members of the USSKAC. In October 1999 AUI became a formal member of the USSKAC, and Fisher and Kellermann then continued as the AUI/NRAO representatives. Nevertheless, due to NSF concerns about NRAO's responsibilities to ALMA and the EVLA program, as well as community desire to keep the US SKA development within the university community, NRAO did not play a leadership role in the USSKAC activities, reflecting the continuing tensions between NRAO and the university groups.

The US SKA Technology Development Program (TDP), funded by the NSF and totaling about \$13.5 million, supported the USSKAC between 2000 and 2011. The TDP was administered by Cornell with Jim Cordes as the PI. The USSKAC developed an antenna concept, investigated possible feeds, receivers, and backends, and studied the array configuration and RFI mitigation. In addition to the funded programs at Caltech, Cornell/NAIC, MIT/Haystack, the SETI institute, and the Universities of California and Illinois, in-kind support of technology development was provided by JPL, NRL, NRAO, and the University of New Mexico. For about a decade, the USSKAC met twice a year to review the progress with the TDP and to adopt a US position for the various issues being considered by the ISSC/SSEC. In addition to supporting technical developments within the US, the TDP also provided the funds to hold the semi-annual USSKAC meetings as well as to send six (then eight) representatives to the ISSC/SSEC meetings.

As one of its goals, the USSKAC developed a "strawman design" to build the SKA as an array of 4400 twelve meter diameter dishes known as a *Large-N Small-D* array. The antenna elements were configured to include 2,320 antennas within a 35 km diameter, and 160 stations, each containing nine antennas spread across North America, with baselines up to 3,500 km. Unlike the strawman proposals developed in other countries, the US concept included the full costs of instrumentation, site development, program management, software, etc., and was optimistically estimated to cost \$1.41 billion. The US also included an operations plan based on VLA operations that included an operations budget of \$61.5 million per year.[18]

Management and Funding From the beginning the SKA was planned as an international project, with the US, Europe, and the "rest-of-the-world" each contributing one-third of the costs. Owing to the anticipated NSF commitments to ALMA, Large Synoptic Survey Telescope (LSST), and Daniel K. Inoue Solar Telescope (DKIST), as well as to a large (24–30 m) optical telescope, it was understood by all that the NSF would not be able to contribute to SKA construction on the same time scale anticipated by other countries, but that a phased contribution seemed feasible, possibly with a US emphasis on the higher frequencies in a possible second phase of construction. Both NASA and the Department of Energy were approached, but showed little or no interest. The US Department of State expressed interest, but offered no money.

Financial support for SKA technical development came partly from the US TDP, as well as from other national sources, but the driving support came from the European Commission funding for the Square Kilometre Array Design Studies (SKADS, 2004 to 2009) led by Arnold Van Ardenne from the Netherlands and the Preparatory Phase for the SKA (PrepSKA, 2008 to 2012) program led by Phillip Diamond from the UK. PrepSKA was organized into seven Work Packages covering Management, SKA Design, Site Studies, Governance, Procurement, Funding, and Implementation. As the planning proceeded, there was a wide range of opinion on the SKA technology, the siting, and the organizational structure, leading to escalation in both the scope and cost of SKA.

Concerned that, due to other priorities, the national funding agencies could not meet the growing cost of the SKA on the ambitious time scale planned by the ISPO, the ISSC decided to split SKA construction into three phases. Phase 1, or SKA-1, would comprise only five to ten percent of the full SKA, and probably cost 15 to 20 percent of the full SKA, which was to be completed in Phase 2. It was clear that no single technology could cover the entire frequency range, so in 2005, the SKA was divided into SKA-Low, below a few hundred MHz, and SKA-Mid, up to a few GHz, using an aperture array and dish array respectively. A vaguely defined Phase 3 covering the higher frequencies, up to few tens of GHz, primarily financed by the US, was part of the longer term planning.

Reflecting the broad international interests and with the encouragement of ISSC members, in 2005 representatives of the various national funding agencies began to hold their own meetings, and in 2006 they formed the Informal Funding Agencies Group (IFAG). From the NSF, Wayne van Citters, Vernon Pankonin, and Jim Ulvestad participated at various times in IFAG meetings. Pankonin, in particular, was an active participant in many of the committees and working groups. In 2009, the funding agencies further formalized their role and created the Agencies SKA Group (ASG).

The ISPO Director reported to the ISSC/SSEC Chair, the Chair of the IFAG/FAWG, and the Chair of PrepSKA Board, each with their own goals and ambitions. This created an organizational challenge, not only for the ISPO Director, but for the broader project management issues as well. Management by committee, in this case multiple committees, was reminiscent of the committee management of the Green Bank 140 foot Telescope (Sect. 4.4), with the added challenge of international membership, each with their own agenda.

Open Skies The concept of Open Skies was widely accepted by the international radio astronomy community. Most of the world's major radio telescopes, including Westerbork and the Australia Telescope Compact Array, as well as the European VLBI Network and all of the NSF-funded radio observatories in the US, welcomed proposals from all scientists independent of their national affiliation. The ISSC naturally assumed that an Open Skies policy would carry over to the SKA, so was surprised that the national funding agencies expressed strong reservations. In 2007, the SSEC presented a resolution to the FAWG for an Open Skies concept for the SKA which read,

> Recognizing that open access to all qualified scientists, independent of institutional, national, or regional affiliation will give the best scientific returns, the ISSC believes that the allocation of SKA observing time or access to data obtained with the SKA should be based solely on merit, without regard to quotas, financial, or in-kind contributions to the construction or operation of the SKA.[19]

However, the IFAG responded that they could not sell this to their governments, who would ask what they were getting in return for spending tax money if their scientists did not have priority access to the SKA. While this same question is often asked of NRAO, as a matter of national policy, the Open Skies concept has remained in effect in the US for essentially all federally funded science projects.

Prototypes, Precursors, and Pathfinders Trying to demonstrate the merits of their proposed technology, a number of countries set out to build what were variously called SKA prototypes, precursors, or pathfinders. Others, seeing an opportunity to exploit the growing visibility of SKA, declared already planned or ongoing new facilities as SKA pathfinders.

The US *Large-N Small-D* concept grew out of the series of SETI Workshops held between 1997 and 1999 (Ekers et al. 2002) which led to the plan for the Allen Telescope Array (ATA) as an SKA Pathfinder for SETI as well as for radio astronomy. However, as a result of over-optimistic cost estimates, only 42 of the originally planned 350 six meter hydroformed dishes were built at the University of California's Hat Creek Observatory. China was able to build the Five-hundred-meter Aperture Spherical Telescope (FAST), which has the largest collecting area of any filled aperture radio telescope in the world[20] LOFAR[21] in the Netherlands and the MWA[22] in Western Australia, PAPER/HERA,[23] and the LWA[24] have all demonstrated the aperture-array technology at meter wavelengths. The Australia SKA Pathfinder (ASKAP)[25] is a novel array of 36 parabolic dishes, each containing a focal plane array. Perhaps the most impressive SKA Pathfinder is the South African MeerKat array of 64 antennas each 13.5 m in diameter which rivals the VLA in sensitivity.

Siting the SKA The competition for siting the SKA was intense and for nearly eight years drove much of the SKA discussion and planning. Australia, South

Africa, and Argentina each proposed sites with very low population densities and free of locally generated RFI. China proposed a site in the karst region in southern China in order to accommodate their proposed array of large spherical reflectors. The proposed US SKA Consortium *Large-N Small-D* concept was located in the US desert southwest and centered near the VLA, but with elements located throughout North America.

In 2004, the ISSC called for proposals to host the SKA. Due to a lack of resources, and perhaps lack of interest, the USSKAC, in spite of all its earlier work, did not respond with a formal proposal.[26] After careful review, the ISSC reduced the potential sites to Western Australia and the Karoo area of South Africa. The Chinese plan contained too few elements for satisfactory imaging and had high cloud cover, while the proposed Argentina site between two mountain ranges was too small to accommodate the planned configuration, and was located too close to the geomagnetic equator with corresponding ionospheric instabilities.

In 2011, both Australia and South Africa submitted extensively documented proposals to host the SKA and vigorously promoted the merits of their sites in the political as well as the scientific arena. Vernon Pankonin (NSF) chaired the SKA Siting Group (SSG) charged with overseeing the confrontational process. Following RFI tests at the two sites, extensive review by the SPDO, the SSEC, as well as by an external international SKA Site Advisory Committee (SSAC) chaired by James Moran from Harvard, the SKA was faced with a problem. Both Australian and South African radio astronomers had already invested huge resources in developing their sites, in getting their governments on board, and in preparing their proposals. Concerned that if the SKA were built in only one of these countries, the other country might drop out of the program, the new SKA Organization Board, after considering input from yet another advisory committee, the SKA Site Options Working Group (SSOWG), recommended a two-site solution. SKA-1 would include a mid-frequency array of dishes in South Africa, while Australia would host the low frequency aperture array as well as a survey telescope patterned after ASKAP.

Choosing the location of the SPDO and later the SKA Organization Headquarters was equally contentious. Cornell, Dwingeloo, and Manchester each put in a bid to host the SPDO. NRAO had submitted a Letter of Intent but withdrew, recognizing that the PrepSKA funding was not going to be spent in the US. In 2007, Manchester narrowly beat out Dwingeloo to host the SPDO, largely due to concerns that Dwingeloo was too far from an international airport. At this time, the SPDO optimistically anticipated that Phase I construction would begin by 2012. Manchester again narrowly defeated Dwingeloo and Bonn in 2011 to host the SKA Project Office during the preconstruction era, and UK funding enabled the construction of an elaborate £3.34 million headquarters building at Jodrell Bank. In a later competition to host the SKA permanent headquarters, the selection advisory panel[27] gave a close nod to Padua, Italy over Manchester, but the UK flexed its political muscle, and following a not too subtle threat to withdraw from the project, the SKA Global Headquarters ended up at Jodrell Bank (*Nature* editorial 2015).

The SKA Sans the US The first USSKAC TDP was funded following a favorable endorsement from the 2000 Decade Review, *Astronomy and Astrophysics in the New Millennium* (McKee and Taylor 2001), which suggested $22 million for SKA technology development among the top half of its recommendations for Moderate Initiatives, and specifically called attention to the significant nature of the international SKA collaboration. The 2005 report of the NSF Radio, Millimeter and Submillimeter Planning Group, chaired by Martha Haynes from Cornell, stated 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".[28] In 2008, the AUI committee on Future Prospects for US Radio, Millimeter, and Submillimeter Astronomy, chaired by Richard McCray from the University of Colorado, gave further endorsement to "Develop the technologies for the era of Square Kilometer Array science, Develop, test, prototype, and implement the technologies required to achieve SKA-class science, [and] Review and assess the progress of the international SKA effort on a continuing basis."[29]

Encouraged by these earlier endorsements and the growing worldwide attention to the SKA, the USSKAC and the international SKA partners were optimistic that the SKA would get a green light from the 2010 Decade Review, *New Worlds New Horizons* (Blandford 2010). However, NRAO, the USSKAC, and the SPDO apparently sent mixed messages to the Blandford Committee. Knowing that the NSF was already committed to other large construction projects, NRAO led a proposal for a $40 million plan for technology development only for a North America Array (NAmA) that could lead up to construction of the high frequency component of the SKA with construction not starting until sometime after 2020. The proposed NAmA[30] had ten times the collecting area of the VLA with baselines comparable to those of the VLBA spread throughout the US. Meanwhile the SPDO and the SSEC were discussing a much earlier start of SKA construction and were not considering any sites in the US.

The National Academy's report (Blandford 2010) gave a strong endorsement to the scientific opportunities presented by the SKA as well as to the international nature of the project. But the Blandford Committee was concerned about the short time scale being discussed by the SKA project, and by the 1.7 billion Euro construction cost which they calculated to be underestimated by a factor of five or six.[31] As a result, the Committee's report did not include any recommendation for funding for either the SKA or the NAmA, which effectively eliminated any possibility of significant US participation in the SKA. The Committee did recognize that further development work was needed, and suggested that the SKA be revisited at a mid-term review.

Jacqueline Hewitt from MIT chaired a mid-term review in 2015, but the Committee only discussed the status of approved projects, and did not consider the SKA or any other new project.[32]

Earlier, the SKA had been better received by the European funding agencies, which placed the SKA and the planned Extremely Large ESO telescope on an equal basis, and, of course, both Australia and South Africa were committed to hosting their share of the SKA. While concerned about the absence of US expertise and funding, the international partners also recognized an opportunity to seize leadership in radio astronomy away from the US. In 2011, the funding agency representatives from Australia, Canada, Italy, New Zealand, the Netherlands, South Africa, and the UK[33] formed a new not-for-profit legal entity in the UK to be known as the "SKA Organization" with responsibility to oversee the "Pre-Construction" era SKA activities. The SSEC and the SPDO were dissolved effective 31 December 2011. The new SKAO Board that replaced the ASG agreed that SKA-1 should have a cost cap of 650 million Euros, a value not that different from what had been presented a few years earlier to the Blandford Committee for the full SKA project.

Each SKA Organization member country was expected to contribute 50,000 Euros to the activities of the SKAO, as well as to pledge in-kind technical development within their country using their own national resources. Although the USSKAC had no prospect of contributing money or significant in-kind resources, AUI President Ethan Schreier sent out some feelers to allow AUI to contribute to the SKAO and, on behalf of the USSKAC, to propose to the NSF for funding for the required technical development contribution. However, the AUI initiative was coolly received by both the SSEC and by the USSKAC. Reflecting the earlier agencies group concerns about Open Skies, the Founding Board adopted a no-pay no-play policy. Only scientists living and working in one of the SKA member countries would have access to the future SKA or to data from the SKA. US scientists were excluded from using the SKA, although it was noted that scientists from the SKAO Member countries traditionally had, and continued to have, free access to the NRAO VLA, VLBA, and the GBT.

John Womersley from the UK became the Chair of the new SKA Organization Founding Board, and in 2013, Phil Diamond became the new Director-General of the SKA Organization. In 2015, faced with continued project escalation and increasing cost, the SKAO was forced to a major re-baselining in order to keep to the original 650 million Euros (later inflated to 690 million) cost limit. Both SKA-1 Mid in South Africa and SKA-1 Low in Australia were descoped. Instead of starting fresh in South Africa, the SKAO decided instead to add 133 new SKA 15 m dishes to the 64 MeerKat 13.5 m dishes to form a 197 element array of dishes of mixed design. The planned survey telescope in Australia using phased array feeds based on the ASKAP Pathfinder was deferred, leaving Australia with only a descoped low frequency aperture array.

In March 2019, Ministers from Australia, China, Italy, the Netherlands, Portugal, South Africa, and the UK met in Rome to sign a treaty which established the Square Kilometre Array Observatory as an intergovernmental organization to build and operate the SKA. Guests from seven other countries, including NRAO Director Tony Beasley, were also present at the signing, but there was no official representation from the US. The agreement will enter into force after the governments of five signatories, including the hosts, Australia, South Africa, and the UK, have ratified the treaty.[34]

11.8 The Next Generation VLA (ngVLA)

Following the disappointing rejection of Phase II of the EVLA proposal (Sect. 7.8) and the lack of endorsement of either the NAA or SKA by the Blandford Committee, the future of US centimeter radio astronomy appeared uncertain. The JVLA was, by any measure, the most powerful radio telescope in the world, but faced with the unclear future of the GBT and VLBA, as well as the growing prominence of the SKA, Tony Beasley, the new NRAO Director, was concerned about where US radio astronomy would be in 20 or 30 years. In order to delineate the science goals and help define US radio astronomy for the 2030s and beyond, Beasley organized a series of three national meetings between 2016 and 2018 on *U.S. Radio/Millimeter/Submillimeter Science Futures in the 2020s*, which was supported in part by the Kavli Foundation. The first Kavli meeting concentrated on defining the key science questions. Kavli II reviewed the various large and intermediate scale projects proposed to address the science questions posed in the first meeting, and Kavli III concentrated on defining the next generation VLA (ngVLA) which had emerged from the two earlier meetings.[35]

Starting in 2015, with funding from the NSF, NRAO, working with the US radio astronomy community, developed the science case (Murphy 2018), the performance specifications, and a reference design for the ngVLA, which will operate from 1.2 to 116 GHz (2.6 mm to 25 cm). With a total of 244 eighteen meter offset parabolic antenna elements spread throughout the US and 19 six meter dishes in a compact configuration, the ngVLA (Fig. 11.5) will have up to ten times better sensitivity than the JVLA and several times better sensitivity than SKA-1 Mid. In order to cover a wide range of surface brightness sensitivity and angular resolution, the antenna elements will be configured in four tiers and will have an angular resolution as good as 0.1 milliarcsec at the shortest wavelength.[36] When completed, the ngVLA will replace the current NRAO JVLA and VLBA.

Assuming both the ngVLA and SKA-1 are constructed, they will provide complementary science opportunities with locations in each hemisphere. SKA-1 Low in Australia will cover the frequency range from 50 to 350 MHz. SKA-1 Mid in South Africa will cover 0.35 to 15 GHz. The ngVLA will work from 1.2 GHz to 116 GHz with emphasis on the higher frequencies, and will fill in the gap between SKA-1 Mid and ALMA. In order to fully exploit these new opportunities, representatives of the SKA and ngVLA met in 2019 in Reykjavik, Iceland, to begin a discussion of a global alliance to allow the

Fig. 11.5 Artist's conception of the ngVLA. Credit: NRAO/AUI/NSF

exchange of observing time between the ngVLA and SKA-1, effectively continuing the Open Skies approach.

11.9 Divestment

As discussed in Sect. 8.10, following the NSF Senior and Portfolio Reviews, for two years the VLBA was operated separately from NRAO as the Long Baseline Observatory (LBO), but on 1 October 2018, the LBO was reintegrated into NRAO. As a result of the same NSF exercise, starting 1 October 2016, the Green Bank facilities became part of the new Green Bank Observatory (GBO), but was not later reintegrated into NRAO. Karen O'Neill, longtime NRAO Assistant Director for Green Bank Operations, became the Director of the GBO reporting to AUI Vice President Tony Beasley.

To help plan for any future GBO actions, the NSF initiated an Environmental Impact Study for five possible alternatives ranging from the preferred alternative of "Collaboration with Interested Parties for Continued Science and Education-focused Operations with Reduced NSF Funding" to the drastic "Demolition and Site Restoration."[37] Like the LBO, with the help of AUI the GBO was able to raise outside funds to help support its operations. GBO supporters included the *Breakthrough Listen* project (Sect. 5.7) and a contract with West Virginia University to support their GBT pulsar program, as well as various programs related to Space Situation Awareness. Although the non-NSF support for the GBO did not reach the NSF target goals, on 26 July 2019 the

NSF issued a Record of Decision that the GBO would continue science and education-focused operations but with reduced NSF funding.[38]

The NSF divestment of the GBO came at a price for radio astronomy. As a result of the decreased NSF funding, not only will astronomical observing with the GBT be reduced, but there will be less support for innovative new astronomical instrumentation such as PAFs and wideband spectrometers. Since the external funders are paying for GBT observing time, this means less time for Open Skies observing and, with time, it may get worse. The GBT is not only the largest fully steerable radio telescope in the world, it is the largest fully steerable microwave and millimeter wave antenna in the world, with a wide range of potential commercial, space, and defense related applications unrelated to radio astronomy. The pressure to use the GBT for other purposes, especially if defense related, combined with the NSF interest in constraining its related operating budget for astronomy, could lead to further loss of the GBT for astronomy.

NRAO started in Green Bank and for many years NRAO was synonymous with Green Bank. Hopefully, the visions of people like Lloyd Berkner, Richard Emberson, Dave Heeschen, and Alan Waterman will prevail, and Green Bank will to continue to provide world-leading radio astronomy facilities.

11.10 Lessons Learned

The near fatal consequences of the 140 Foot experience (Sect. 4.4) served as a good lesson for future NRAO projects. The VLA and VLBA were built only after years of design, development, and prototyping combined with broad community involvement. They were finished on budget and on schedule, more than met their design specifications, and with later enhancements have continued to provide unique capabilities for research. The 36 Foot millimeter telescope was finished within the budget allocation, but the completion was significantly delayed due to manufacturing challenges. Like the 140 Foot, the 36 Foot did not perform to the design specifications, but due to its excellent instrumentation provided by the Charlottesville CDL, along with competitive scheduling, it opened up a whole new field of millimeter-wave radio astronomy. By the time the GBT was built, NRAO apparently had forgotten the lessons of the 140 Foot Telescope, and the GBT construction was fraught with many of the same problems reflecting the same ambitious goals, over optimism about the complexity, cost, schedules, and perceived urgency that resulted in prematurely starting construction before the design was complete.

The GBT and VLA experiences were different. NRAO management ran a tight ship with the declared determination to finish the VLA on time and on budget. That they not only succeeded, but ended up with an instrument better in almost every way than specified in the proposal, is largely credited to Dave Heeschen's determination, but the tight control by Hein Hvatum, and some innovative contracting by Jack Lancaster were also crucial to the success of the VLA. The VLA also differed from the 36 Foot, 140 Foot and GBT projects, in that, aside from the commercial procurement of the relatively straight forward antenna elements, the VLA project was largely run "in-house," with NRAO as the prime contractor. If a small sub-contractor did not perform, they could be replaced. The VLBA, except for the record-playback system and the correlator, was a straightforward extension of existing instrumentation and practices. Many of same people involved in the VLA construction played the same role with the VLBA, which also was completed essentially on budget.

ALMA was a much more complex project. Interestingly, there was never any proposal for ALMA, nor was it ever considered by a decade review committee. Starting out in the ashes of the proposed 25 meter millimeter-wave telescope, ALMA began as the NRAO Millimeter-Array (MMA). As described in Sect. 10.7, following a series of trilateral negotiations with Japan and Europe, the MMA morphed into the more ambitious Atacama Large Millimeter/Submillimeter Array (ALMA). While ALMA was clearly a remarkable scientific success, the complexities of an international project, possibly coupled with unrealistic cost estimates, resulted in the 2004 so-called "re-baselining," with a reduction in the number of antenna elements, decreased initial instrumentation, delayed completion, and a large increase in the construction costs. Although the nature of the international ALMA agreement provides some long-term funding security, it is unlikely that the NRAO would again enter into an international project as an equal partner, but would likely be more favorably inclined toward participation either as the leading partner or as a minor partner.

Notes

1. Martin Ryle and Antony Hewish in 1974, Arno Penzias and Robert Wilson in 1978, Russell Hulse and Joe Taylor in 1993, John Mather and George Smoot in 2006.
2. The Kitt Peak National Observatory (KPNO) was established in 1958, two years after NRAO. In 1982, KPNO was combined with the Cerro Tololo Inter-American Observatory and the National Solar Observatory to form the National Optical Astronomy Observatory (NOAO).
3. AUI-BOTXC, 16 November 1967.
4. Operation of the NRAO 12 Meter mm wavelength telescope on Kitt Peak by NRAO with NSF funding ceased in July 2000. However, with the support from the state of Arizona, the University of Arizona has continued to operate the telescope for astronomical observations.
5. J. Oort to GR, 30 August 1945, NAA-GR, Correspondence, General Correspondence I. https://science.nrao.edu/about/publications/open-skies#section-11
6. A detailed description of the events surrounding the 1959 Administrative Radio Conference is given by Findlay (1960). The NRQZ is described in https://science.nrao.edu/facilities/gbt/interference-protection/nrqz
7. Until 1993, it was called the World Administrative Radio Conference (WARC).
8. Military activities in all countries, including the US, are often the most egregious violators of ITU regulations.

9. The Committee on Space Research was established by the International Council of Scientific Unions (ICSU) in 1958 to promote international scientific research is space. During the Cold War period, COSPAR served as an important non-government conduit between the US and USSR on all issues of scientific space research.
10. The need for the shared use of the radio spectrum is discussed in the NAS report, *Spectrum Management for Science in the 21st Century*, 2010 (Washington: Nat. Acad. Press) https://doi.org/10.17226/12800. More details about radio spectrum management and the allocation of frequencies for radio astronomy are given in *The Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses, 2015* (Washington: Nat. Acad. Press). https://doi.org/10.17226/21774
11. In 2019, a Virginia Tech professor was found guilty of spending NSF grant money "for research Zhang knew had already been done in China. Zhang intended to use the grant funds for other … projects rather than for the projects for which the funds were requested." https://www.justice.gov/usao-wdva/pr/former-virginia-tech-professor-found-guilty-grant-fraud-false-statements-obstruction
12. Described in the NSF Proposal & Award Policies and Procedures Guide https://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf18001 as "full participation of women, persons with disabilities, and underrepresented minorities in science, technology, engineering, and mathematics (STEM); improved STEM education and educator development at any level; increased public scientific literacy and public engagement with science and technology; improved well-being of individuals in society; development of a diverse, globally competitive STEM workforce; increased partnerships between academia, industry, and others; improved national security; increased economic competitiveness of the US; and enhanced infrastructure for research and education."
13. 28–29 October 1963 meeting notes, NAA-NRAO, Founding and Organization, Antenna Planning, Box 2.
14. Bolton to Bowen, 1 December 1964. NAA-KIK Open Skies.
15. PVB at Jansky Monument Dedication, NAA-KGJ Additional Materials Related to Jansky.
16. Reber's array operated at relatively long wavelengths where a large effective collecting area can be built out of wire dipoles and is relatively cheap. It is much more complex and much more expensive to achieve the same collecting area at decimeter and centimeter wavelengths.
17. A Luneburg lens is made from a spherical dielectric with an index of refraction that varies radially from the center. It has the property to focus incoming radio emission at point that can then be detected with a horn and conventional radiometer. The idea for the SKA was to have a large number of feed-receiver arrangements all looking in different directions. However, the cost of building sufficiently large Luneburg lenses and the losses in the dielectric were both too great to seriously consider this technology for the SKA.
18. NAA-KIK, Square Kilometre Array, USSKAC.
19. SKA Report 84, Report of the SKA Operations Working Group, https://www.skatelescope.org/uploaded/37483_memo_84.pdf
20. The construction of the Five-hundred-meter Aperture Spherical Telescope (FAST) in southern China was completed in 2016. Patterned after the Arecibo

radio telescope, FAST has about twice the effective collecting area as Arecibo. Its 4,400 triangular panels form an active surface that can be adjusted to form a 300 m diameter parabolic surface pointing as much as 40 degrees from the zenith. https://arxiv.org/ftp/arxiv/papers/1105/1105.3794.pdf

21. The LOw Frequency ARray (LOFAR) began as a joint project of the US, the Netherlands, and Australia to construct a large aperture array to operate at meter wavelength below 250 MHz. An evaluation of potential sites and consideration of potential RFI suggested a preference for Australia, the US Southwest, or Europe in that order. However, Dutch radio astronomers were able to secure funding from the Dutch government to build LOFAR in the northeastern Netherlands as a multi-disciplinary sensor array to facilitate research in geophysics, computer sciences, and agriculture, as well as astronomy. International stations located throughout Europe have since been added.
22. The MWA is an international project including MIT/Haystack with partial funding from the NSF, and includes 256 tiles each containing 16 antenna elements. The MWA simultaneously images an area about 30 degrees in diameter at multiple frequencies in the range 70–230 MHz (1.3–4.3 m). http://www.mwatelescope.org/
23. The Precision Array to Probe the Epoch of Reionization (PAPER) was an aperture array SKA precursor first tested in Green Bank, further developed in Western Australian, and later built at the South African SKA site. PAPER was succeeded by the Hydrogen Epoch of Reionization Array (HERA). HERA, which abandoned the aperture array concept, consists of a large grid of 14 meter (46 foot) non-tracking dishes.
24. The University of New Mexico had been heavily involved in promoting the location of LOFAR in the US southwest. When the decision was made to build LOFAR in the Netherlands, the University of New Mexico proceeded to build the Long Wavelength Array (LWA) on the VLA site. http://www.phys.unm.edu/~lwa/index.html
25. Each 12 m diameter ASKAP antenna contains a 94-element dual polarization focal plane array that forms 36 independent beams on the sky. ASKAP operates in the frequency range 700 MHz to 1.8 GHz (16.7–43 cm) and is co-located with the MWA on the Australian SKA site in Western Australia. https://www.atnf.csiro.au/projects/askap/index.html
26. The plan to site the SKA in the US was considered inadequate by many due to the expected higher levels of RFI, but there was also concern among some US ISSC members that a US site would likely mean undesired control by NRAO. Because of changing staff, the University of New Mexico was not able to proceed with the planned study of site availability and the existing fiber network. At the time, NRAO was preoccupied with building both the EVLA and ALMA and could not spare the resources needed to develop a credible site proposal.
27. The headquarters selection panel included representatives from Australia, South Africa, the Netherlands, and ESO.
28. http://hosting.astro.cornell.edu/~haynes/rmspg/docs/rmspgreport.pdf
29. NAA-AUI.
30. https://www.nrao.edu/nio/naa/
31. Having seen huge cost escalation in projects recommended by previous decade surveys, especially for NASA space missions, the Blandford Committee was

more sensitive to cost estimates than was the case for previous Decade Reviews, and commissioned the Aerospace Corporation to provide independent cost estimates for projects being considered by the Committee. The Aerospace Corporation reported that the true cost of constructing the SKA was at least five times greater than what was presented to the Committee.

32. New Worlds, New Horizons: A Midterm Assessment. https://www.nap.edu/catalog/23560/new-worlds-new-horizons-a-midterm-assessment
33. Later, China and Sweden also joined the SKA Organization (SKAO), and India joined as only an Associate Member. Germany has not formally joined the SKAO but through the German Max Planck Society plans to contribute resources to MeerKat and SKA-1 Mid. The 2011 site proposal from Australia included long baseline sites in New Zealand, which were later dropped when the decision was made to locate SKA-1 Mid in South Africa. Faced with no clear role in the SKA and competing programs for limited resources, New Zealand decided in 2019 to withdraw from the SKAO.
34. The Anticipated SKA1 Science performance is given by Braun at https://astronomers.skatelescope.org/wp-content/uploads/2017/10/SKA-TEL-SKO-0000818-01_SKA1_Science_Perform.pdf
35. Kavli I was held in Chicago on 15–17 December 2016. https://science.nrao.edu/science/meetings/2015/2020futures/program, Kavli II was held in Baltimore, Maryland from 3–5 August 2017, http://www.cvent.com/events/u-s-radio-millimeter-submillimeter-science-futures-ii/custom-18-b7c37ec376c44055b80cfb2f5ef030b5.aspx, and Kavli III held in Berkley, California from 2–4 August 2017, http://www.cvent.com/events/u-s-radio-millimeter-submillimeter-science-futures-iii/custom-22-a7c6d735d0b141eca298518ce31cbaae.aspx
36. McKinnon, M. et al. ngVLA: The Next Generation Very Large Array, White Paper submitted to the Astro2020 Decade Review Committee. http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/5043187/137-fe4771da409a7413465c9bb1cb579ae7_McKinnonMarkM.pdf
37. NSF Environmental Impact Statement for the Green Bank Observatory, 22 February 2019. https://www.nsf.gov/mps/ast/env_impact_reviews/greenbank/eis/FEIS.pdf
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