CHAPTER 6

The Bar Is Open

With the successful completion of the 140 Foot Radio Telescope in 1965, and the increased use of the 300 Foot Telescope, NRAO finally began to serve its role as a national observatory. Any scientist with a good program had access to world class facilities without regard for institutional affiliation—a policy which later became known as “Open Skies.”

These were exciting years for radio astronomy. In addition to NRAO, new powerful radio telescopes at Caltech, MIT, and Cornell in the US, and in Australia, Canada, the UK, and later the Netherlands and Germany, were making exciting new observations. During a period of only a few decades in the middle of the twentieth century, radio astronomers made a series of discoveries which fundamentally changed our understanding of our Universe and its constituents. Radio astronomy was at last recognized as a legitimate part of astronomy. NRAO flourished in this exciting environment and became the poster child for the National Science Foundation’s (NSF) support for large expensive scientific facilities, an expansion of their traditional role of funding individual research grants.

6.1 NRAO Reaches Maturity

With the dedication of the 140 Foot Telescope in 1965, NRAO was finally a true national observatory with multiple state-of-the art facilities. The 300 Foot Telescope had been in operation for three years, the new 140 Foot Telescope offered unprecedented opportunities for centimeter wavelength research, and the Green Bank Interferometer was about to begin operation (Fig. 6.1).

Administration Partly as a result of the separation of activities between Green Bank and Charlottesville, but due also to the increasing size of the NRAO operation and the resignation of the NRAO Business Manager Frank Callender in 1965, NRAO Director Dave Heeschen reorganized the administrative struc-

K. I. Kellermann et al., *Open Skies*, Historical & Cultural Astronomy,
https://doi.org/10.1007/978-3-030-32345-5_6

Fig. 6.1 Aerial view of the NRAO Green Bank site showing the three element interferometer, the 300 Foot transit dish, and the 140 Foot Telescope in the background. Credit: NRAO/AUI/NSF

ture of the Observatory. Hein Hvatum and Ted Riffe (Fig. 6.2) were appointed as Assistant Directors of Technical Services and Administration, respectively, while Bill Howard became Assistant to the Director. Hvatum had responsibility for the electronics lab, the machine shops, and telescope operations. Riffe was in charge of business management and plant maintenance, and continued in his role as the NRAO Fiscal Officer. Hvatum moved to Charlottesville but the division heads who reported to him remained in Green Bank, creating an administrative challenge. Riffe remained in Green Bank, where he was responsible for the Green Bank site operations, but was replaced in 1968 by John Findlay as Assistant Director for Green Bank Operations. Fred Crews was formally in charge of only the Telescope Operations Division, but with time assumed more and more responsibilities for all operations in Green Bank. John Hungerbuhler, who had come to Green Bank to assist Max Small during the final years of the 140 Foot construction, was the Chief of the Engineering Division and Thomas Williams was in charge of Plant Maintenance. Heeschen ruled NRAO from Charlottesville with a firm (some would say iron) hand. Once, when describing the NRAO organizational structure, Heeschen drew two circles on a blackboard connected with a vertical line. In the upper circle he wrote "Me," and in the lower circle, "Everyone Else."

The commute between Green Bank and Charlottesville was not as easy one. In the first years after the move, before a series of road improvements, it would

Fig. 6.2 Ted Riffe served as the NRAO Assistant then Associate Director for Administration. Credit: NRAO/AUI/NSF

take a careful driver nearly three hours to make the trip between the two sites—more, if one were to get stuck behind a slow-moving logging truck. Several local speed traps along the way presented an additional challenge, but that did not inhibit the more ambitious drivers, including the NRAO Director, from an unofficial competition to see who could post the best time. Regular communication between Green Bank and Charlottesville was facilitated by a daily car shuttle and dedicated telephone lines. Each day cars departed from the two sites at precisely 9:00 a.m. carrying passengers, equipment, and data. The two cars met at a halfway point on a mountaintop which still shows the remains of a Confederate Civil War encampment (Fig. 6.3). The drivers exchanged cars so that each driver could return to his home, and the passengers and equipment continued to their destination, arriving at noon at the other site. Although visiting Green Bank observers could fly into more local airports in Elkins or Clarksburg, West Virginia, many chose to go through Charlottesville, where they could first meet with NRAO staff to discuss their observing programs. Green Bank staff returning from a trip would usually fly into one of the local airports where they would be met anytime of the day or night by an NRAO driver who would return them to Green Bank. The drivers were all long-time local residents who would help make the time pass by relating tales of local history, no doubt with some embellishment.

The split of operations between Green Bank and Charlottesville, and later Tucson and Socorro, was not without problems. Gone were the informal contacts between the scientists in Charlottesville and the engineers, who were mostly based at the observing sites, and the culture was akin to that of colonies

Fig. 6.3 Green Bank—Charlottesville daily shuttle cars meeting at the halfway point to exchange passengers, equipment, and data. Credit: NRAO/AUI/NSF

with all major decisions made at the Charlottesville Headquarters. Interestingly, after the Charlottesville office was opened in late 1965, it was mostly the US staff members who took advantage of the opportunity to move from Green Bank, leaving behind scientists who had come to NRAO from such varied places as England, Germany, Netherlands, Iraq, India, Poland, and Sweden. Often the only US member of the NRAO Scientific Staff found in Green Bank was one of the present authors, Kellermann. On one occasion, Sebastian von Hoerner's sons put up a sign on the road leading to the housing area reading, "You are now leaving the American Zone," a spoof on the then divided German city of Berlin.

In 1969, John Findlay was replaced by Mort Roberts as Assistant Director for Green Bank Operations, and in 1970, Dave Hogg returned to Green Bank as the Assistant Director. Hogg was succeeded by Bill Howard in 1974, when Hogg returned to Charlottesville to become Associate Director for NRAO Operations with broad responsibility for both the Tucson and Green Bank site operations. Reflecting the increased size and complexity of the Observatory, the Assistant Directors for Tucson and Green Bank Operations now reported to Hogg rather than Heeschen, who was increasingly turning his attention to the Very Large Array (VLA) (Chap. 7). Recognizing the increased responsibilities resulting from the growing administrative staff needed to deal with the VLA, as well as the increasingly complex NRAO operations, in 1976 Ted Riffe became the Associate Director for Administration and served in this capacity until he retired in 1987 and was succeeded by James (Jim) Desmond. Bill Howard left NRAO in late 1976 to become Assistant Director of the Astronomy Division at the NSF and was replaced by Ken Kellermann as Acting Assistant Director in Green Bank before Kellermann went to Germany to become director at the Max Planck Institut für Radio Astronomy in Bonn. Bob Brown became the Green Bank Assistant Director in June 1977, followed by Rick Fisher (1981), Martha Haynes (1982), and George Seielstad (1984). After Seielstad's departure to the more urban environment of Grand Forks, North Dakota, a number of technical and scientific staff cycled through as Green Bank Assistant Directors until 2008, when Karen O'Neill assumed that role.

Phyllis Jackson, who was born and educated in Marlinton, West Virginia, joined NRAO in April 1959 to provide secretarial support to the new Observatory in Green Bank. In 1965 Phyllis moved to Charlottesville with the Scientific Staff. For 38 years, until she retired in 1997, she ran the Director's office with great efficiency. Many believed that, in effect, Phyllis Jackson ran the organization. Among her numerous skills was her lightning fast typing speed, and she often typed scientific papers, correcting the spelling and English of young scientists lacking in those skills (Fig. 6.4).

The National Science Foundation Organizational changes also occurred at the NSF. Initially, NRAO reported to Randal (Randy) Robertson at the NSF, and was administered out of a separate division headed by Daniel Hunt, which

Fig. 6.4 Phyllis Jackson, longtime secretary to NRAO Directors, ca. 1983. Credit: NRAO/AUI/NSF

dealt with all of the National Facilities such as NRAO and the Kitt Peak National Observatory (KPNO). In this way, funding for grants to individual scientists, which was under the Division of Astronomy headed by Robert Fleisher, was kept separate from that of the National Centers. However, in 1976 the NSF placed the National Astronomy Centers under the Astronomy Division. This pitted NRAO funding against proposals for individual research grants, setting up a competition for funding that continues to this day.

Mark Price, who had previously been the first NSF Spectrum Manager, became the Acting Director of the new Astronomy Division until Bill Howard was appointed as the permanent Director in November 1976. Under Howard, Price remained in charge of the individual investigator grants program, and Ronald LaCount administered the facilities. Price left the NSF in 1979 to accept an appointment as Chair of the Physics Department at the University of New Mexico in Albuquerque, and was replaced by Morris Aizenman as head of the grants program. Throughout his tenure as AST Director, Howard strove to keep the centers and grants funding in the constant ratio of 2 to 1, but resigned in 1982 over the contentious issues surrounding the abandonment of the controversial NRAO 25 meter millimeter wave telescope (Sects. 8.7 and 10.3).

On 1 May 1986, the Astronomy Division was moved from the Directorate for Astronomy, Atmospheric, Earth, and Ocean Sciences (AAEO), sometimes referred to as the division for "Earth, Air, Fire, and Water," to the Directorate for Mathematical and Physical Sciences, and AAEO became simply the Directorate for Geosciences.

Scientific Staff The NRAO scientific staff was structured following the AUI policy originally put in place for Brookhaven. This typically consisted of a series of two- or three-year term appointments as Assistant, then Associate Scientist, followed by an "up-or-out" tenure decision and promotion to the rank of Scientist. Members of the NRAO Scientific Staff generally divided their time between independent research and the development of new facilities and instrumentation as well as providing support for visiting users. Although he delegated most operational responsibilities to others, throughout his tenure as the NRAO Director Dave Heeschen remained in direct charge of the scientific staff.

In addition to the regular scientific staff, there was a steady flow of Research Associate or postdoctoral appointments meant to give new PhDs full time opportunities for research. Research Associates generally had no observatory responsibilities and were expected to move on after a two- or three-year temporary appointment. To give the Research Associate appointments more prestige and to compete with the NASA Hubble Fellowship and various university prize fellowships, the NRAO Research Associates were later called Karl Jansky Fellows, and the doctoral students became Grote Reber Predoctoral Fellows.

Tenured appointments at NRAO were granted by AUI in recognition of outstanding research accomplishments or other intellectually creative activity appropriate to the mission of the Observatory, and could only be terminated by the AUI Board for financial exigency or what AUI called "moral turpitude," a concept which no one really understood, but which was apparently never tested. The meaning of tenure at an organization such as AUI is unclear, but was intended to offer some degree of security of continued employment. Tenured staff were expected to provide leadership in the planning, design, construction, and operation of the NRAO facilities as well as carry out a vigorous program of individual research. Tenured staff members had some freedom to direct their own efforts, but, starting in the 1970s, the design and operation of the VLA, and then the Very Long Baseline Array (VLBA), required more staff support than could be provided by the limited number of tenured staff, and NRAO adopted the practice of offering "continuing" or "indefinite" appointments that were neither tenured nor term appointments. Those scientists with continuing appointments reported directly to the relevant site director. However, with the increasing autonomy of the Green Bank, Tucson, and Socorro sites, the individual site directors complained that they had no management control over the tenured scientists at their site who reported only to the distant NRAO Director, and with time the tenured staff became more integrated into the site operational structure. This was especially true after 1999, when the new AUI President, Riccardo Giacconi, insisted that each staff member be assigned well-defined "functional responsibilities," a concept that he had introduced earlier as Director General of the European Southern Observatory (ESO).

During the 1960s and early 1970s many scientists rotated through NRAO, either after a Research Associate appointment, or following one or more term appointments on the scientific staff. They were generally able to find good academic positions in the post-Sputnik market, often with better professional opportunities than they might have had at NRAO. Many went on to distinguished careers as leaders in radio astronomy and started their own radio astronomy groups, and, in some cases, developed their own facilities or became Principal Investigators on NASA missions.

As discussed previously (Sect. 4.2), the early NRAO Scientific Staff was dominated by recent graduates from Harvard, but in 1959, Roger Lynds, who had received his PhD from the University of California, Berkeley, joined the NRAO staff after a one-year appointment in Canada. Following his Green Bank visit as a University Toronto graduate student, Dave Hogg joined the staff as an Assistant Scientist in 1961, followed by Frank Low from Texas Instruments in 1962 (Sect. 10.1), Peter Mezger from Germany in 1963, Mort Roberts in 1964, and by Barry Clark and Ken Kellermann from Caltech in 1964 and 1965 respectively. Unlike the other Harvard recruits, Roberts had received his PhD from the University of California, Berkeley, after which he became a Research Associate at Harvard before coming to NRAO.

In order to provide some theoretical support to the young scientific staff whose interests and expertise were mostly in technical and observational areas, in 1962 NRAO recruited the theoretical astrophysicist Sebastian von Hoerner from Germany. When the FBI called NRAO as a follow-up to von Hoerner's visa application, Ted Riffe received the call as the Head of Administration. Riffe responded to the routine questions confirming that von Hoerner would have a salary so would not become a welfare recipient and that he was not a known criminal. But when asked what he would be doing at NRAO, Riffe, not knowing anything about radio astronomy replied, "I can't tell you," to which the caller, assuming that NRAO was involved in some highly secret activity that was above his clearance level, responded, "Oh, I understand!"

At NRAO, von Hoerner initially did research on some cosmological problems, but infected by the Green Bank culture, he soon turned his attention to observing with the 140 Foot Telescope and to the design of large radio telescopes; he became a major player in the NRAO Largest Feasible Steerable Telescope program (Chap. 9). NRAO later recruited three young theoretical astrophysicists, Robert (Bob) Brown, Robert (Bob) Hjellming, and David DeYoung, but they too were seduced by the opportunities to make new discoveries by observing with the NRAO telescopes. Hjellming worked with Campbell Wade observing radio stars using the Green Bank Interferometer (Sect. 6.2) and later wrote the VLA Observing Guide (*The Green Book*) and was in charge of the VLA off-line software development (Sects. 7.6 and 7.7). Brown and DeYoung became dedicated observers, and both went on to assume responsible administrative positions. DeYoung left NRAO to join the Kitt Peak National Observatory, later the National Optical Astronomy Observatory (NOAO) where he rose to become the Associate Director. Bob Brown became a skilled observer, and after serving as Assistant Director for both Green Bank and Tucson Operations, became the Associate Director for Charlottesville Operations in 1985 and assumed responsibility for the Scientific Staff and NRAO Scientific Services. Starting in 1991, Brown oversaw the development of the NRAO Millimeter Array (MMA) and later ALMA, and became the NRAO Deputy Director in 2000. In 2003 Brown left NRAO to become Director of the Cornell National Astronomy and Ionospheric Center (NAIC) which oversaw operation of the Arecibo Observatory.

In order to get advice on Observatory priorities and policies, Heeschen instituted an Observatory Council, which met monthly and included all tenured members of the Scientific Staff as well as the key Division Heads and other administrative staff. In the first years following the completion of the 140 Foot Telescope, NRAO had a generous budget for new equipment. At least once a year the Council would hear from the Electronics Division about proposed new receivers or other instrumentation. Heated discussions followed. Each scientist vigorously defended personal priorities, but Weinreb generally decided what to do based more on technical considerations rather than astronomical whims. In those years only capital costs were considered, as it was assumed that the engineers and technicians were getting paid anyway. Invariably the

Electronics Division would take longer to deliver the promised instrumentation, as each engineer would be in charge of multiple projects. However, the engineering talent and motivation were exceptional, and soon the world looked to NRAO for expertise in radio astronomy instrumentation.

Publications In the early years of the Observatory, NRAO debated where to publish scientific and technical papers on radio astronomy. The *IRE Transactions of the Professional Group on Antennas and Propagation* was considered, but radio astronomy was more than just antennas. At the suggestion of AUI's Richard Emberson, there was broad agreement to use the *Astronomical Journal*, but that never materialized. Apparently the NRAO radio astronomers still did not consider their work to be appropriate for the *Astrophysical Journal*, and in 1961 NRAO started its own publication series as had been common at many optical observatories. By the mid-1960s, however, the NRAO staff was finally publishing largely in the peer-reviewed journals, and the *Publications of the National Radio Astronomy Observatory* was terminated after two years and 17 papers. In principle the Director was responsible for all Scientific Staff publications, but in order not to delay timely publications, Heeschen only asked that he be shown all papers; if he did not respond within 24 hours, that was to be considered approval to submit the paper. In order to allow publication of NRAO data by visiting scientists with no grant support, NRAO paid for publication costs, most of the cost of travel to Green Bank, and later to the other sites, as well as making the NRAO computing facilities available at no cost. MIT Professor Bernard Burke once explained that it was cheaper to pay his students to travel and to pay for Green Bank lodging than to pay the high costs of using the MIT computing facilities.

The Green Bank US-USSR Radio Astronomy Conference Radio astronomers, as a species, are prolific travelers. As we have noted (Sect. 2.4), both Frank Kerr from Australia and Henk van de Hulst from the Netherlands happened to be at Harvard when Ewen detected the 21 cm hydrogen line. Earlier van de Hulst had visited Grote Reber in Wheaton, Illinois. Due to their relative isolation, Australian radio astronomers, including Taffy Bowen,[1] Joe Pawsey, and John Bolton, made frequent round-the-world trips to learn about radio astronomy progress in Europe and the US. Cambridge was more secretive about their work, but Peter Scheuer did spend two years in Australia working with Bernie Mills. It was not uncommon for this closely knit international community to stay in the homes of colleagues when visiting other observatories, and many lifelong international friendships were established among the radio astronomers as well as among their spouses.

An exception during the Cold War period was the USSR. Travel to the USSR was difficult due to both visa restrictions and the language differences. It was even more difficult for Soviet scientists to travel to the West. Most Soviet papers were published in Russian, while the availability of Western journals was very limited within the USSR. To foster better contact between Soviet and American radio astronomers, in 1961 Otto Struve organized a joint US-USSR Symposium on radio astronomy[2] that was held under the exchange agreement between the US and Soviet Academies of Science (Fig. 6.5). After the opening session held in Washington on the afternoon of 15 May 1961, all the delegates proceeded by overnight train to White Sulphur Springs, West Virginia, and then by bus to Green Bank to continue the following afternoon. Six Soviet and 28 American scientists participated in what was the first of many international scientific meetings held in Green Bank. Viktor Vitkevich led the Soviet delegation, while Otto Struve was the host in Green Bank. Frank Drake reviewed the history and status of US radio astronomy and Vitkevitch did the same for the Soviet Union. Most of the talks dealt with reports of recent observations or theoretical considerations, but on the last day, both sides presented their ideas on the design and construction of new radio telescopes.

In addition to the official presentations, informal groups discussed source polarization, 21 cm line studies, discrete sources, and radio telescope design. NRAO staff hosted members of the Soviet delegation at dinner parties in their Green Bank homes. Following the conference, the Soviet delegation travelled to Washington to visit the White House and the Carnegie Institution Department of Terrestrial Magnetism, but their request to visit the Sugar Grove station was not approved.

Fig. 6.5 Attendees at the USA-USSR Radio Astronomy Symposium, Green Bank, May 1961, left to right: Row 1 (seated)—G. Getmantsev, F. Haddock, M. Wade, S. Edmundsen (interpreter), R. Minkowski, V. Vitkevitch, O. Struve, R. Sorochenko, J. Firor, G. Keller, A. Kuzmin, R. Bracewell, F. Drake. Row 2—C. Wade, E. McClain, V. Sanamyan, P. Kalachev, G. Stanley, A. Barrett, H. Weaver, G. Swenson, C. Mayer, D. Heeschen, J. Kraus. Row 3—G. Field, T. Menon, C. Seeger, L. Woltjer, A. Sandage, A. Lilley, A. Blaauw, F. Kahn, B. Burke. Absent—G. Burbidge, J. Findlay, C. Lynds. Credit: NRAO/AUI/NSF

6.2 First Scientific Studies

While Berkner, Greenstein, Menzel, and the others involved in setting up NRAO certainly were looking forward to the expected contributions of radio astronomy, probably no one really appreciated the full potential of this new window on the Universe. As early as 1954, John Hagen had already reflected that "while we have perhaps 'skimmed the cream' of the top of radio astronomy, I feel it has a great future."[3]

Indeed, following the earlier discoveries of the non-thermal galactic radio emission, the hot solar corona, solar radio bursts, radio storms on Jupiter, radio galaxies, and the radio supernovae remnants that we discussed in previous chapters, in less than a few decades, radio astronomers went on to make another series of remarkable discoveries. They reported the first evidence for cosmic evolution, discovered quasars, pulsars, the microwave background, interstellar molecules, radio recombination lines, cosmic masers, the greenhouse effect on Venus, Jupiter's radiation belts, the first extra-solar planets, made the most precise tests of general relativity, and detected the first observational evidence for gravity waves (see e.g. Kellermann and Sheets 1984; Wilkinson et al. 2004). During the same period, active radar experiments disclosed the unexpected rotation of Mercury, were able to measure the rotation of cloud-covered Venus, determined the Astronomical Unit with new precision, and conceived of and confirmed a new fourth test of general relativity. Finally, starting with a simple experiment in Green Bank, the human race began the first credible research for intelligent counterparts elsewhere in the Universe. Subsequently, observations in other regions of the spectrum, obscured by the Earth's atmosphere, were opened by space-based observatories. But the radio spectrum was the first to be explored outside the narrow optical window, and the discoveries rolled in. These were truly the golden years of radio astronomy, and astronomy, limited for millennia to optical observations, would never be the same (Fig. 6.6).

A discussion of all these discoveries is beyond the scope of this book, and so we confine our discussion below to the early research with the Green Bank facilities.[4]

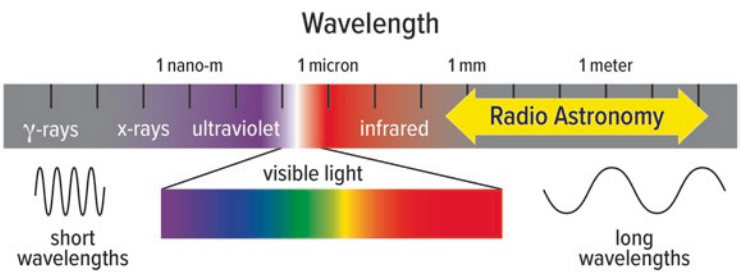

Fig. 6.6 Electromagnetic spectrum showing the range covered by radio astronomy. Credit: J. Hellerman/NRAO/AUI/NSF

The Tatel Telescope Observations with the new 85 foot Tatel Telescope were largely devoted to continuum studies of radio galaxies, supernovae remnants, and galactic ionized hydrogen (H II) regions and Solar System planets. Dave Heeschen (1961a) inaugurated a program of studying radio source spectra, with observations at four frequencies spanning the range from 440 MHz (68 cm) to 8 GHz (3.75 cm), and was able to confirm the reported decrease in the flux density of the Cas A supernova remnant of 1 to 2% per year at 1.4 GHz (Heeschen 1961b). Campbell Wade, Roger Lynds, and Hugh Johnson used the Tatel Telescope to study individual radio galaxies and the weak radio emission from the nearby normal galaxy M31. Dave Hogg, then a visiting graduate student from Canada and the first international observer at NRAO, used the Tatel Telescope to observe supernovae remnants and H II regions, while University of Indiana student Yervant Terzian studied planetary nebula, and Kochu Menon and Roger Lynds observed the thermal emission from the Orion Nebula and other H II regions. Frank Drake used observations at 3.75 cm to show the complex structure of the Galactic Center region.

Perhaps the most important observations made with the Tatel Telescope were Frank Drake's studies of radio emission from the planets that established the high temperature and greenhouse effect on Venus, the internal heating of Jupiter and Saturn, and the non-thermal radiation from Jupiter's Van Allen belt, all of which preceded confirmation by widely heralded NASA space-based observations.

The first spectroscopic observations at NRAO were by MIT student Sander (Sandy) Weinreb who brought his 21 channel digital autocorrelation receiver to the Tatel Telescope to search for the 327 MHz deuterium line and to try to detect the effect of Zeeman splitting of the 21 cm hydrogen line from interstellar magnetic fields. Although Weinreb did not detect either deuterium or the Zeeman effect after hundreds of hours of integration, his digital spectrometer (Weinreb 1961, 1963) was the forerunner of the very successful series of future NRAO autocorrelation spectrometers, as well as the implementation of similar devices at essentially every radio observatory in the world.

The 300 Foot Transit Telescope One of the first projects on the 300 Foot Telescope was a survey by Dave Heeschen (1964) of normal galaxies, while Ivan Pauliny-Toth et al. (1966) studied all sources in the 3C catalogue at 750 (40 cm) and 1400 MHz (21 cm) with the aim of determining accurate flux densities and positions free of interferometer lobe ambiguities. This work was later extended by Bridle et al. (1972), who used the 300 Foot Telescope to compile a complete sample of 234 sources above 2 Jy at 1.4 GHz. Dave Hogg (1966) observed a number of supernovae remnants, and Gart Westerhout showed up each summer with his family and his group of University of Maryland students to map the distribution of H I in the Galaxy (Fig. 6.7). At the same time, Mort Roberts used the 300 Foot Telescope to study H I in nearby galaxies. A particularly notable study was the investigation of the Andromeda galaxy (M31) by Roberts and Whitehurst (1975) which was able

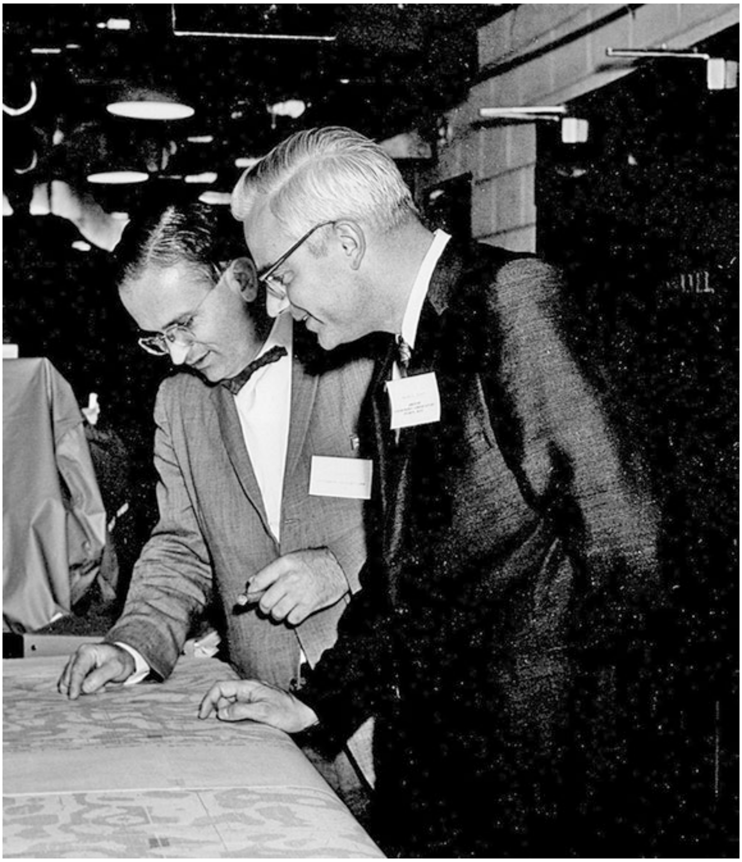

Fig. 6.7 Gart Westerhout (left) and Frank Drake examining 300 Foot telescope output. Credit: NRAO/AUI/NSF

to probe the kinematics of the Galaxy way beyond its optical boundary, convincingly demonstrating the existence of dark matter, suggested decades earlier by Fritz Zwicky (1933).

The 140 Foot Telescope The first astronomical observations with the 140 Foot Telescope were made in March 1965, even before the formal acceptance and dedication of the telescope in October. Earlier, Sebastian von Hoerner (1964) developed a widely used technique for restoring radio source brightness distributions from observations of lunar occultations, and, as soon as he could, von Hoerner began using the 140 Foot to observe lunar occultations of radio sources to determine the positions and angular structure. He was assisted by Joe Taylor, then a graduate student at Harvard who was working with von Hoerner on his PhD thesis.

When the 140 Foot Telescope was completed in 1965, there was only one known radio spectral line, the 1420 MHz (21 cm) line of neutral hydrogen. Van de Hulst's classic 1945 paper only devoted a few paragraphs to the 21 cm hydrogen line (van de Hulst 1945). The rest of the paper was devoted to free-free emission from ionized hydrogen and the possibility of detecting high order radio recombination lines (RRL) at radio wavelengths corresponding to changes in an electron energy level. However, van de Hulst erroneously concluded that due to Stark broadening, RRLs would not be observable, and until Nikolai Kardashev (1959) showed that the effects of Stark broadening were previously overestimated, there were no serious attempts to observe RRLs. At the 1962 IAU General Assembly in Hamburg, two Soviet groups from Moscow and Leningrad reported the detection of RRLs at 8872.5 MHz (H90α)[5] and 5763 MHz (H104α) respectively. However, due in part to the limited information about the instrumentation permitted by Soviet authorities and the poor quality of the visual presentation, compounded with language difficulties, their results were not generally accepted by radio astronomers in Europe or the US.

Peter Mezger had joined the NRAO scientific staff from Germany and first tried to detect RRLs using the Tatel Telescope in late 1964, but the results were inconclusive, and Mezger eagerly awaited completion of the 140 Foot to search for RRLs. Even before the formal acceptance of the telescope by NRAO, Mezger and Bertil Höglund, a visiting scientist from Sweden, shared time with the painters working during the day, and on 9 July 1965, they were able to detect the 5009 MHz (6 cm) H109α RRL in the galactic H II regions M17 and Orion. Recognizing the importance of demonstrating that the 140 Foot was really working and had made a major discovery, Höglund and Mezger quickly sent off a letter to *Nature*. When they didn't hear from *Nature* after a few weeks, Mezger sent a telegram to the editor, demanding prompt action, but was told in response that "*Nature* will not be dictated to with respect to publication. Your paper is rejected." Dave Heeschen then pulled some strings and their paper was published in *Science* (Höglund and Mezger 1965) (Fig. 6.8).

Mezger, T. K. Menon, and others at NRAO, as well Ed Lilley at Harvard and Bernie Burke at MIT, were excited by the new research opportunities made possible by studying RLLs. Lilley sent two of his graduate students, Pat Palmer and Ben Zuckerman, to Green Bank to use the 140 Foot to study recombination lines from helium as well as hydrogen transitions with $\Delta n = 2$. Burke sent two of his students, Ted Rifenstein and Thomas Wilson, who worked with Mezger and Wilhelm Altenhoff on a variety of galactic continuum as well as recombination line studies.

Concurrently with the RRL studies, Kellermann and Pauliny-Toth (1968, 1969) initiated a long running program to study extragalactic radio source spectra and variability. Their 140 Foot data were supplemented by 750 and 1400 MHz data from the 300 Foot along with low frequency data from Cambridge (Kellermann et al. 1969) and demonstrated the nature of very compact radio sources. Exploiting the high frequency capability of the newly

Fig. 6.8 Peter Mezger, Troy Henderson, Bertil Hoglund, and Neil Albaugh in the 140 Foot control room, 27 July 1965, a few weeks after their discovery of radio recombination lines. Credit: NRAO/AUI/NSF

completed 140 Foot Telescope, Pauliny-Toth and Kellermann (1966) followed the dramatic changes in the centimeter wavelength emission of radio galaxies and quasars which challenged existing radio source theories. During this same period, Heeschen (1968) used first the 140 Foot and then the 300 Foot and the Green Bank Interferometer (GBI) to detect the first active galactic nucleus in an Elliptical galaxy.

The biggest scientific impact of the 140 Foot Telescope was no doubt in the discovery and investigation of interstellar molecules. At the 1955 Jodrell Bank Symposium on Radio Astronomy, Charles (Charlie) Townes presented a classic paper speculating on the potential to detect lines at radio frequencies due to various atomic and molecular rotation transitions. Townes was an accomplished physicist who would share the 1964 Nobel Prize for Physics for the invention of the maser. In the published version of his Jodrell Bank paper, Townes (1957) derived microwave transition frequencies for a number of molecules including carbon monoxide (CO), ammonia (NH_3), water (H_2O), hydroxyl (OH), and hydrogen cyanide (HCN).

The calculation of the transition frequencies of ammonia and water go back even earlier than Townes' presentation at the Jodrell Bank Symposium. While working at Bell Labs following WWII, Townes (1946) and Townes and Merritt

(1946) published two seminal papers on the 22 GHz (1.3 cm) spectra of ammonia and water respectively that would later lead to the important discovery of these molecules at Hat Creek by Cheung et al. (1968, 1969) at 1.3 cm. The water lines turned out to be surprisingly strong due to maser action. But to the embarrassment of NRAO, an earlier proposal to detect the 1.3 cm water line by NRAO postdocs David Buhl and Lewis Snyder was turned down on the advice of a referee with distinguished theoretical credentials, but who had not considered the possibility of water masers.

Starting in 1967, the 140 Foot Telescope was used regularly for very long baseline interferometer high resolution studies of the continuum radiation from quasars and for OH, and H_2O interstellar maser emission (Sects. 8.1–8.5). The need to simultaneously schedule the 140 Foot together with an increasing number of other radio telescopes, each with their own scheduled maintenance, became a challenge to NRAO management.

The Green Bank Interferometer (GBI) Although the Green Bank Interferometer was built primarily to give the young NRAO staff experience in interferometry, it was a powerful research instrument as well. The GBI complemented the Caltech interferometer that operated at longer wavelengths and over a shorter baseline and so had less angular resolution. Moreover, the GBI was probably unique in not being laid out in an east-west or north-south baseline. Even though the 243 degree azimuth of the GBI was determined by the Observatory site geometry, it turned out to have some unanticipated advantages in making absolute position measurements (Wade 1970). Dave Hogg et al. (1969) mapped the brightness distribution of several bright radio galaxies and the Cas A supernova remnant. Heeschen (1968) used the GBI to show that the radio sources in NGC 1052 and NGC 4278 were small and confined to the galactic nucleus, in contrast to radio galaxies whose radio dimensions typically exceeded the optical boundaries of the galaxy. Later, using the GBI, Hjellming and Wade (1971) discovered the first true radio stars.

The addition of the remote antenna at Spencer's Ridge and Huntersville (Sect. 7.3) improved the angular resolution of the GBI by more than a factor of ten, opening up new research opportunities. Probably the most exciting observation was the discovery by Bruce Balick and Bob Brown of the small radio source at the Galactic Center which they showed was less than 0.1 arcsec (1000 AU) (Balick and Brown 1974). Brown later named this compact source Sgr A*. This was the first evidence for a massive black hole at the center of a normal galaxy. Later VLBI observations using the 140 Foot together with other radio telescopes showed that Sgr A* was less than 10 AU in extent (Kellermann et al. 1977). Perhaps the most important GBI program, however, was the series of elegant measurements of the gravitational bending of radio waves by the Sun which confirmed the general relativity prediction to within 1 percent precision (e.g., Fomalont and Sramek 1975), far better than the then best contemporary optical observations made at the time of solar eclipses.

Little Big Horn One of the outstanding problems facing radio astronomers in the 1960s was the need to establish an absolute flux density scale. It was straightforward, using any of the NRAO telescopes, to measure the relative intensity of radio sources. But putting the measurements on an absolute scale required knowledge of the effective area of the telescope, including the illumination efficiency as well as losses due to diffraction and surface imperfections. It is difficult to calculate these quantities for parabolic antennas, but relatively straightforward for a simple horn. Conventional horn antennas, however, were historically too small to give sufficient sensitivity for meaningful measurements.

In 1958, John Findlay decided to address this problem by building a very large calibration horn in Green Bank, which became known as "Little Big Horn." Little Big Horn was constructed on the side of a hill pointing toward a position where the strong radio source Cassiopeia A would pass once a day through the antenna beam. It was 120 feet (36.7 m) long and had an aperture 17.6 by 13.1 feet (5.4 by 4 m), and was probably the largest horn antenna ever built anywhere (Fig. 6.9). Construction was completed in September 1959, and the first observations began the following month and lasted for several decades. After careful calibration and correction for the contribution from the galactic background, Findlay (1972) was able to measure an absolute flux density of Cas A with a precision of 1.8 percent, and he also determined the rate of

Fig. 6.9 Little Big Horn calibration antenna designed and used by John Findlay to establish an absolute 1.4 GHz flux density scale. Credit: NRAO/AUI/NSF

decrease of flux density as (1.38 ± 0.15) percent per year in good agreement with other measurements and the earlier prediction by Shklovsky (1960).

6.3 The Central Development Laboratory

The 140 Foot Telescope was smaller than the Jodrell Bank, Australian, Canadian (Sect. 6.6), and the later German (Sect. 9.2) dishes, and did not have the pointing accuracy or surface precision of the Haystack, Canadian or Australian antennas. Nevertheless, the 140 Foot was arguably more productive than any of the competing facilities due to the excellent instrumentation made available by the NRAO Central Development Laboratory (CDL) located in Charlottesville. This was particularly true for spectroscopic observations, due to the series of low noise receivers and multi-channel spectrometers built for Green Bank that were unequaled anywhere in the world. The CDL pioneered the development of actively cooled Field Effect Transistor (FET) and High Electron Mobility Transistor (HEMT) amplifiers for centimeter wavelengths, as well as cooled Schottky diode mixers and Superconductor-Insulator-Superconductor (SIS) devices for millimeter wavelengths.

The first receivers at NRAO were mostly based on commercial products from Ewen-Knight, Microwave Associates, or Long Island-based Airborne Instruments Laboratory (AIL). They used simple mixer receivers or, in some cases, parametric amplifiers, but their performance was not as good as at some other observatories, such as Caltech. In 1962 Hein Hvatum led an effort to purchase a 6 cm maser amplifier from AIL. It cost $135,000, a lot of money at the time, but not too much for the then generously funded young observatory. Stability issues limited the sensitivity, and the maser was never used for any astronomical programs. NRAO clearly needed to improve its instrumental support to complement the growing collection of antennas, the Tatel Telescope, the 300 Foot Telescope, and the finally completed 140 Foot Telescope.

When Joe Pawsey visited Green Bank in 1961 (Sect. 4.6), he noted the weakness of the technical staff, but took note of the young MIT graduate student, Sandy Weinreb (Fig. 6.10), who was using the 85 foot Tatel Telescope in an attempt to detect deuterium and the Zeeman effect with his novel digital spectrometer. After arriving in England, Pawsey wrote to AUI President I. I. Rabi suggesting that AUI might try to hire Weinreb.[6] Four years later, Weinreb joined NRAO at the age of 28 to become head of the NRAO Electronics Division reporting to Hein Hvatum. Initially Weinreb lived in Green Bank, where he led the development of receivers for the 140 and 300 Foot Telescopes and the Green Bank three element interferometer, and was also responsible for the growing electronics research and development group in Charlottesville.

In 1968 Weinreb and his young family moved to Charlottesville, where he set up the NRAO Central Development Lab (CDL). Mike Balister, who had come to Green Bank in 1966 from Canadian Westinghouse where he worked on several classified military programs, became Associate Head of the NRAO

Fig. 6.10 Sandy Weinreb led the NRAO Electronics Division, built the first radio astronomy digital spectrometer, and provided much of the architectural design of the VLA. Credit: NRAO/AUI/NSF

Electronics Division under Weinreb, as well as Head of the Green Bank Electronics Division, creating an awkward dual reporting line. Balister left Green Bank for Charlottesville to lead the low noise development group in 1972, and was replaced by Craig Moore as Head of the Green Bank Electronics group. In 1986 this group was placed under George Seielstad, then the Assistant Director for Green Bank Operations, and Weinreb became the NRAO Assistant Director for Technical Development. After a leave of absence from NRAO when he taught at the University of Virginia, Weinreb left NRAO in 1987 to join Martin Marietta. He later joined the faculty of the University of Massachusetts, then moved to California where he continued to develop low noise centimeter and millimeter wave amplifiers at the Caltech Jet Propulsion Laboratory (JPL). During his 23 years at NRAO, Weinreb pioneered the use of low-noise, cryogenically-cooled solid state amplifiers which greatly enhanced the sensitivity of the NRAO radio telescopes. He was also the architect for the electronic systems design for the VLA, and led the group which developed the VLA instrumentation. Weinreb was honored in 2008 with the Grote Reber Medal for his lifetime innovative contributions to radio astronomy and in 2011 with NRAO's Jansky Lecturership.

Following Weinreb's departure, Ballister became Acting Assistant Director for Technical Development as well as Head of the CDL. NRAO was unable to recruit a replacement for Weinreb, and in 1989 Balister became the permanent Assistant Director for Technical Development. Due to the rapid growth of the

NRAO staff resulting in part from the VLA program (Chap. 7), NRAO soon outgrew its new headquarters at the University of Virginia, and after 1972, the CDL was housed in rented space elsewhere in Charlottesville. Unlike the close collaboration between the scientists and engineers previously found in Green Bank, at CSIRO, and at many other radio observatories, the NRAO CDL and Basic Research staffs grew apart, primarily as a result of their physical separation, and there were few collaborative programs between NRAO scientists and engineers. Further, with the increasing independence of Green Bank, Tucson (Sect. 10.2), and Socorro (Sect. 7.7), new instrument construction and maintenance electronics work increasingly became the responsibility of the local electronics groups, which were more integrated into the local management structure, and there was less communication among the technical staffs at the different sites. The CDL increasingly concentrated on fundamental research and the production of low noise amplifiers for other observatories and for use in non-astronomical environments rather than in direct support of the instrumentation at NRAO facilities.

Low Noise Amplifiers and Mixers Probably the biggest success of the CDL was in the development of cryogenically-cooled centimeter wavelength low-noise HEMT and FET amplifiers under the leadership of Weinreb and Marian Pospieszalski (e.g., Pospieszalski et al. 1988). In addition to providing state of the art sensitivity for the NRAO telescopes, nearly every major radio observatory in the world used amplifiers designed and built at the NRAO CDL either as low noise front ends, or as IF amplifiers in millimeter wave receivers. The income from the sale of these amplifiers provided a valuable supplement to the eroding NSF funding, and supported the further research by the CDL staff.

NRAO cooled amplifiers were also used in support of several space missions, including the NASA Wilkinson Microwave Anisotropy Probe (WMAP) that measured the anisotropy of the cosmic microwave background with unprecedented precision and gave precise new constraints to the cosmological parameters (Bennett et al. 2003). The WMAP satellite contained 80 NRAO HEMT amplifiers in a dual-beam dual-polarization configuration (Jarosik et al. 2003) designed and built at the CDL by Pospieszalski. The NRAO amplifiers, which were passively cooled to about 90 K and covered the frequency range from 20 to 106 GHz in five bands, operated flawlessly for the nine year operational lifetime of the satellite. Later the CDL built 22 GHz (1.3 cm) amplifiers for use on the Russian RadioAstron space VLBI mission (Sect. 8.9). The RadioAstron amplifiers were similar in design to the lowest frequency WMAP amplifiers, and worked for the eight year duration of the mission, giving badly needed sensitivity at the shortest RadioAstron operating wavelength. The CDL also fabricated 8 GHz (3.75 cm) amplifiers for the VLA to support the 1989 NASA Voyager flybys to Uranus and Neptune (Sect. 7.7). The new 3.75 cm receivers also gave a badly needed boost to the VLA sensitivity and were used for a wide range of continuum observations.

Receivers for millimeter wavelengths were particularly challenging. When NRAO's Kitt Peak 36 Foot Millimeter-Wave Telescope first went on the air in early 1968, typical system temperatures were over 1000 K using simple mixer receivers. Weinreb and Kerr (1973) were able to achieve significant improvement by cooling Schottky diode mixers down to 15 K. By the 1980s, the introduction of SIS devices by Anthony (Tony) Kerr had replaced Schottky diodes as mixer elements for millimeter wave receivers. More recently, the frequency multipliers and wide bandwidth sideband-separating SIS mixers developed at the CDL along with Kerr's SIS mixers were critical to the technological success of ALMA (Sect. 10.7). Throughout this period, the millimeter-wave advancements made at the CDL were enhanced by a close collaboration with the University of Virginia Semiconductor Devices Laboratory led by Robert Mattauch.

All of the NRAO receivers used cooled radiometers. But commercial refrigerators were not fully reliable and were a constant source of downtime at the telescopes. To deal with the repeated breakdowns, and in anticipation of the coming needs of the 27 element VLA, Howard Brown and David Williams in Green Bank developed an innovative modification to the commercial refrigerators. Green Bank finally did obtain a successfully operating maser when Craig Moore spent time at JPL to fabricate a copy of the JPL 22 GHz (1.3 cm) traveling wave maser, and that operated on the 140 Foot Telescope for many years. The new maser gave unprecedented sensitivity for observing the water vapor (H_2O) and ammonia (NH_3) lines but was disappointing for continuum work due to gain fluctuations induced by the mechanical pump used to cool the liquid helium.

Spectrometers and Digital Back Ends Weinreb's MIT digital spectrometer was soon replaced by a series of more advanced systems designed and built at the CDL in Charlottesville. Even before Weinreb joined NRAO in 1965, NRAO had hired Art Shalloway from Cornell to develop digital spectrometers for Green Bank. Shalloway visited Weinreb, who was then working at MIT, to seek his guidance on building a digital spectrometer, and Weinreb continued to advise on the construction. The Model I autocorrelator, which had 100 spectral channels, was installed at the 300 Foot Telescope in 1964, and the Models II and III, with 384 spectral channels, on the 140 Foot and 300 Foot respectively in 1968 and 1972. The Model IV spectrometer, with 1024 channels, was based on the VLA custom chips (Sect. 7.7) and replaced the Model II spectrometer on the 140 Foot in 1980. In 1972, NRAO gave the original Model I correlator to Caltech to be used at Owens Valley Radio Observatory.

Digital spectrometers based on Weinreb's design were restricted by the limited sampling rate of existing digital hardware. To study the much broader spectral lines observed at millimeter wavelengths, Weinreb devised a hybrid system whereby an analogue filter bank system was used to divide the band into eight smaller bands, each of which could be analyzed by a digital spectrometer

(Gordon 2005, p. 104). Future digital systems at NRAO exploited the rapid developments in the speed of digital devices, enabling up to 262,536 spectral channels over a 1.6 GHz bandwidth on the GBT as well as capabilities for sophisticated analysis of pulsar data. Later digital correlator systems were built by Ray Escoffier for the VLA, and by Escoffier and Richard Lacasse for ALMA, all designed and built at the CDL. However, the JVLA WIDAR[7] correlator was designed and constructed by Brent Carlson and his group at the Dominion Astrophysical Observatory as part of the Canadian contribution to the JVLA.

Feed Systems Radio telescopes have historically used a single feed/receiver combination at the primary or secondary focus of the antenna, and so at any one time could observe only a single region in the sky. Soon after the 140 Foot antenna was completed, Jaap Baars (1966) introduced a dual beam system to reduce the effect of tropospheric emissions. Later multiple receiver/feed systems were built for use on the 300 Foot Telescope with up to seven dual polarization independent beams at 5 GHz.

Starting in the mid-1990s several radio observatories, including the NRAO CDL, began to develop multiple element phased array feeds (PAFs) (Fisher and Bradley 2000). Unlike the focal plane arrays, the signals from each interferometer pair of feed elements were correlated and used to form multiple beams in the sky in the same way that ground-based arrays are used. By proper adjustment of the weighting and phasing of the individual elements, PAFs can also correct for reflector surface errors. However, the construction and operation of PAFs is technically challenging since the elements need to be small and closely spaced, so mutual coupling among the elements makes it difficult to configure the system for optimum efficiency. In practice, the advantage of the multiple beams has been at least partially offset by the degradation in system temperature.

In order to address this shortfall, NRAO, in collaboration with Brigham Young University, the Green Bank Observatory, and West Virginia University, developed a 1.4 GHz cryogenically cooled PAF system. Using a 19-element array to form seven dual polarized beams, the system temperature is under 20 K, and the sensitivity of the seven synthesized beams is comparable to the best cooled single pixel systems, thus giving up to a factor of seven improvement in survey speed (Roshi et al. 2018). See Fig. 6.11.

6.4 Open Skies

Traditionally, astronomical observatories existed for their staff or for the faculty and students of a parent observatory or university. Observing time was allocated by the Director or by agreement among the staff members. Visitors were not uncommon, but generally they were either on long term sabbatical visits or were working with a host institution staff member. Often the larger and more

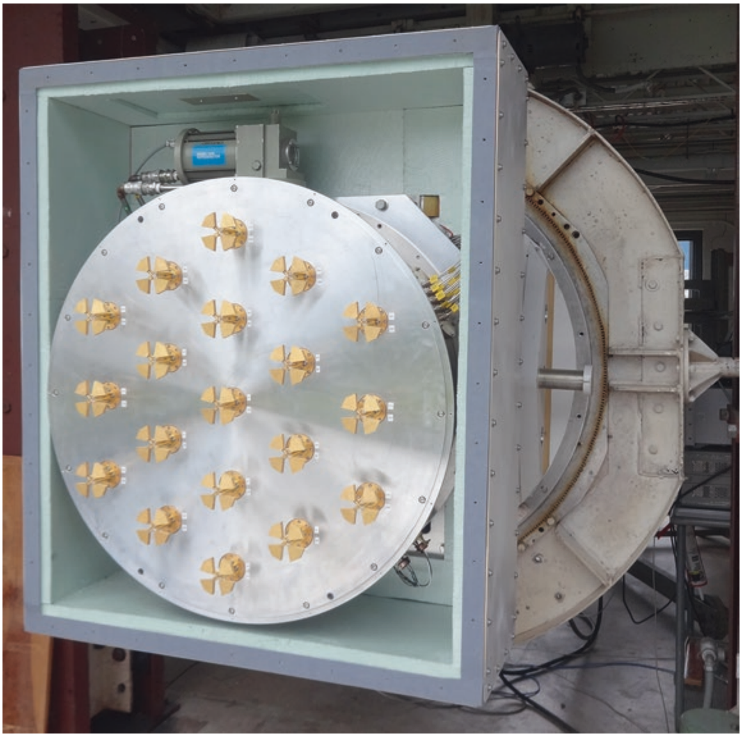

Fig. 6.11 NRAO 19 element dual polarized cryogenically cooled 1.4 GHz Phased Array Feed. Credit: J. Hellerman/NRAO/AUI/NSF

unique the telescope, the harder it was for outsiders to gain access.[8] NRAO was established to facilitate competition by American radio astronomers, especially those from the influential northeast universities, with their European and Australian counterparts. However, in October 1959, Heeschen wrote to the editors of *Astronomical Journal*, *Science*, and *Publications of the Astronomical Society of the Pacific* that "the facilities of the Observatory are open to any competent individual with a program in radio astronomy, regardless of institutional affiliation."[9] In practice, access to NRAO facilities was considered independent of not only institutional affiliation, but national affiliation as well. At the same time, NRAO declared that previous experience in the techniques of radio astronomy was not necessary to use the NRAO instruments.

This NRAO policy became known as "Open Skies" following the nomenclature adopted by the international airlines governing reciprocal landing rights. The NRAO Open Skies policy had a profound and long-lasting impact on how global astronomical research evolved. For the first time, any qualified scientist with a good idea could gain access to a world class facility, independent of his or her national or institutional affiliation. Starting with the 1969 Mansfield Amendment to the Military Authorization Act, which shifted the burden of federal support for the university radio observatories from the Defense Department to the NSF, the NSF required as a condition of receiving operating funds that a fraction, typically one-half, of the available observing time be made available to users from outside the university receiving the grant. With time, under pressure from the NSF and NASA, the Open Skies concept impacted all large American astronomy observatories, whether on the ground or in space. Ultimately, following the US model, other observatories, especially radio observatories worldwide, have adopted an Open Skies policy for at least a fraction of their observing time. Within the US, the Open Skies concept has become a matter of US policy applying to all federally operated research facilities.

Open Skies produces the best science because there is a broader pool of investigators, and the competition sharpens the US investigators. Interestingly, with the limited support available for individual investigator grants, Open Skies also means that other countries provide the labor to use and interpret the results from NRAO and other US facilities, but at no cost to the US taxpayer because salary and training are provided elsewhere. On the other hand, if the facility use becomes dominated by international users, it may be interpreted that US scientists are less capable and do not have the best ideas. Indeed, the NSF constantly draws attention to the high fraction of non-US scientists using NRAO facilities, and this may be reflected in the level of support received by NRAO from the NSF (Sect. 11.7).

By the mid-1970s, the NRAO instruments were becoming increasingly complex and a growing fraction of users did not have the experience needed to effectively use the NRAO radio telescopes. To provide added support for visiting scientists, a staff scientist was appointed as a "friend" of each telescope. The telescope friends were responsible for the calibration of each instrument, and for instructing visiting observers on how best to use the telescope, informing them of any new equipment or computer software, and alerting them to any known problems with the telescope or instrumentation. The concept of "telescope friend" has now spread to other radio observatories, both in the US and internationally.

Allocating Observing Time With the suite of world-class observing facilities provided by the 300 Foot and 140 Foot Telescopes, as well as the Green Bank Interferometer, and the corresponding increase in requests for observing time from visiting scientists, the informal allocation of observing time by consensus of the staff or by the Director was no longer tenable. Starting in the mid-1960s, each proposal, whether from staff or from visitors, was reviewed by outside referees. The allocation of observing time on all NRAO facilities has remained the responsibility of the NRAO Director, but has been generally delegated: initially to Bill Howard, Assistant to the Director; by the mid-1970s to the local site directors; then to an in-house committee; evolving to committees of mixed NRAO and outside members; and finally to a Time Allocation Committee (TAC) composed entirely of non-NRAO staff. The referee reports remain, in principle, only advisory, but with time have played a stronger and stronger role in the assignment of observing time. More recently, the TAC has been assisted by a series of discipline-related panels that provide priority ranking of proposals within the discipline, which are then assembled by the TAC into a master list of priorities for each NRAO telescope. NRAO staff receive no special treatment and there is no time reserved for scientific observing by NRAO staff, although time needed for commissioning of new equipment, calibration, or testing after a change of instrumentation between observers has been allocated as needed to NRAO support staff. See Hogg (2006) for more details on the NRAO telescope time allocation process.

Later, NRAO established new rules for so called "Large Proposals" in excess of 1000 hours that were subject to more extensive review, and required additional commitments from the observing team to make their results available in a timely manner. Also, in response to the increasing interest in multi-wavelength observations, NRAO implemented agreements with NASA-operated space-based facilities whereby small amounts of telescope time on these facilities or on NRAO facilities may be granted by the other TAC in response to a single joint proposals for the two facilities.

Data from all NRAO facilities are archived. Soon after the start of VLA operations, NRAO started to receive requests for data taken by other observers. Starting in August 1983, all observers were allowed an 18 month period where they had exclusive use of the data, after which time the data became available to the public. Approximately ten percent of the publications that use NRAO facilities are based on archival data rather than on new observations.

6.5 Community Interactions

The strength of NRAO is derived from its user community. In order to receive scientific, technical, and management advice from the national as well as international community, both NRAO and AUI receive input from a variety of committees.

Advisory Committees Top level advice and support to NRAO has been derived from the AUI Board, which appoints the Observatory Director, approves all senior level appointments, grants tenure to qualified staff members, and is the legal entity entering into contracts and agreements with the NSF and other organizations. In 1958 the previous AUI Advisory Committee on Radio Astronomy morphed into the AUI Advisory Committee for the National Radio Astronomy Observatory. AUI had a long tradition of Visiting Committees to advise on their operation of the Brookhaven National Laboratory, and starting in 1961, the AUI Advisory Committee became the AUI Visiting Committee, with a mandate to report to AUI on the management of NRAO and how the Observatory was responding to national needs.

To complement the Visiting Committee, in 1965 Dave Heeschen convened a Users Committee reporting to the NRAO Director to evaluate the performance of the telescopes and advise on priorities for new instrumentation. The

User Committee meetings were often heated, especially when something was not working or a promised new receiver was late. On one occasion, after a particularly critical comment, Heeschen told the committee that if they weren't happy they could find a new Director, and he walked out. From time to time, in response to special needs such as the design or early construction of a new telescope, the Director would convene a special advisory committee. There was also a Computer Advisory Committee to advise the Director on the long-standing hardware and software issues that seemed to continually plague NRAO and frustrate observers. NRAO hosted many other meetings and conferences, including scientific symposia and workshops that brought together visiting scientists and members of the Scientific Staff. All of these meetings, including the Visiting and User Committee meetings, were opportunities for staff and colleagues to meet informally, and were generally highlighted by a nice dinner at a nearby restaurant or country club. Heeschen detested after dinner talks. Invariably at the conclusion of the dinner, he, as the host, would stand up, ceremoniously bang an eating utensil on a glass to get attention, and announce, "The bar is open," then sit down so the participants could continue their informal discussion.

The Jansky Lectures Starting in 1966, AUI initiated the Karl G. Jansky Lectureship as an honor recognizing outstanding contributions to the advancement of radio astronomy. Each recipient has presented an annual public lecture in Charlottesville and usually at one or more of the other NRAO sites in Green Bank, Socorro, or Tucson. In addition, the recipient often presents a professional colloquium on his or her research to the local staff and spends a few days interacting with staff members. Since the mid-1980s the Jansky Lecture has been attended by Karl's son David Jansky and other members of the Jansky family. The recipient is chosen each year by the NRAO Scientific Staff based on nominations received from the broader community. The first Jansky Lecture was given by John Bolton from Australia in 1966, followed by Jan Oort in 1967, Iosef Shklovsky in 1968, Fred Hoyle in 1969, and Robert Dicke in 1970. More than 50 scientists have been recipients of the Jansky Lectureship, many of whom were not themselves radio astronomers, but who, through their theoretical contributions or observations in other wavelength bands, contributed to the enhancement of radio astronomy.

Student Programs As part of its mandate to educate the next generation of radio astronomers and to provide for a scientifically literate public, NRAO has since 1959 brought in undergraduate students during the summer to work with staff members. John Findlay was the first administrator of the program, which was later expanded to include graduate students. Many former NRAO summer students later joined the NRAO scientific or engineering staff or went on to distinguished careers in astronomy and astrophysics or other areas of science and engineering or government service. Stephen Chu, a 1970 student, went on to win a Nobel Prize in Physics and later became Secretary of Energy in Barack Obama's administration. Stephen Hawley, who spent the summers of 1973 and 1974 in Green Bank, became a NASA astronaut who deployed the Hubble Space Telescope and participated in several of the HST servicing missions. In addition to the summer student program, each year a few graduate students are typically in residence working on their dissertation research under the joint supervision of an NRAO scientist or engineer and a faculty member from their home institution.

The NRAO-KPNO Exchange Visits Perhaps in response to the concerns that had been raised earlier by Tuve and others about the segregation between radio and optical astronomers and the intellectual isolation of the Green Bank staff, NRAO and the Kitt Peak National Observatory Directors in 1959 initiated a series of alternating annual exchange visits which were used to exchange ideas about running a national astronomy observatory for visitors as well as for scientific presentations on current research by the two staffs. These visits were greatly appreciated and enjoyed by both staffs, but died out in the late 1960s, ostensibly due to their expense and the concern that these visits did not directly help the Observatory's user communities.

6.6 Growing Competition

NRAO was not alone in benefitting from the Sputnik-inspired wave of support for science, especially for astronomy and space science, which provided generous financial support to NRAO, but also led to other new American radio astronomy facilities and a certain amount of competition for recognition and continued funding. New university facilities were funded by the Office of Naval Research (ONR) and the Air Force, as well as by the NSF. Other US radio astronomy facilities were expanded and new facilities initiated, also mostly with Department of Defense (DoD) funding. Meanwhile Australia, Britain, Canada, Germany, and the Netherlands were building on their earlier successes and embarking on new radio astronomy initiatives characteristic of the transition of radio astronomy to big science.

Under Ed Lilley's leadership, the Harvard radio astronomy program gradually shifted emphasis from the 60 foot telescope to the more powerful new 120 foot Haystack antenna. Additional competition to NRAO would come from the Caltech two-element interferometer and the Cornell 1000 foot spherical dish at Arecibo. In Australia, Taffy Bowen was building a 210 foot (64 m) steerable dish at Parkes, and in Canada, the National Research Council was building a 150 foot (46 m) radio telescope at Algonquin Park. In Cambridge, Martin Ryle was developing a series of innovative synthesis radio telescopes that were setting the benchmark for high resolution sensitive imaging of radio galaxies (Sect. 7.1).

Ohio State and Big Ear John Kraus' helical element array at Ohio State University (Sect. 2.5) had limited bandwidth, and it was not realistic to consider a significant increase in collecting area using an array of helices. With support from the NSF, the Air Force, and the University, Kraus built a novel fixed paraboloid 360 feet long by 70 feet high (109 × 21 m) oriented in the east-west direction. Declination adjustment was made with a 260 foot long by 100 foot (79 × 30 m) flat tiltable reflector that was illuminated by feeds covering the frequency range 20 MHz (15 m) to 2 GHz (15 cm). Although basically a transit instrument, the feed system was mounted on a movable carriage that allowed motion in hour angle up to 30 min from the meridian. The angular resolution ranged from 12.5 degrees by 50 degrees at 20 MHz to 7 by 28 arcmin at 2 GHz.

Plans to increase the collecting area by a factor two never materialized, but the Ohio State Radio Telescope was used over a period of six years, primarily for a discrete source survey covering 8.66 steradians at 1.4 GHz (21 cm) down to a limiting flux density of 0.25 Jy. The Ohio State catalog of nearly 20,000 radio sources was published in a series of papers in the *Astronomical Journal* between 1967 and 1975 and summarized by Rinsland et al. (1975). The Ohio State surveys uncovered a number of flat and peaked spectrum radio sources, many of which were optically identified with quasars and BL Lac Objects. However, the Ohio State survey was limited by confusion resulting from the large north-south fan-beam and side-lobe responses and was overshadowed by the emergence of more reliable source catalogues from Parkes and NRAO. Starting in late 1973, "Big Ear," as Kraus (1995) called it, began a search for narrow band 21 cm radio signals from extra-terrestrial intelligent civilizations (SETI). In 1998, after years of opposition by Kraus and many Big Ear supporters, the Ohio State radio telescope was demolished and the land turned into an 18-hole golf course.

The University of Illinois Vermilion River Observatory (VRO) The University of Illinois Astronomy Department was headed by George McVittie, a well-known theoretical cosmologist. Like John Kraus, McVittie was fascinated by the prospects of addressing cosmological problems by using radio sources, and in 1956 he recruited George Swenson from Michigan State University to begin a radio astronomy program. Swenson had a strong background in electronics, radio propagation, and acoustics, but no experience in astronomy. Following a global familiarization tour of radio observatories, and with support from ONR, Swenson built a radio telescope with sufficient sensitivity and resolution to detect radio sources an order of magnitude weaker than those that had been cataloged at Cambridge or Sydney.

To satisfy the requirements of collecting area, resolution, and low sidelobes, as well as the constraints of cost, Swenson (1986) constructed a fixed parabolic cylinder 600 by 400 feet (183 × 122 m), oriented in the north-south direction. The parabolic surface was lined with a one-inch steel wire mesh reflecting surface. The antenna was steered in declination by appropriate phasing of the 276 receivers and feeds located 153 feet (47 m) above the parabolic surface oriented along the north-south axis. No hour angle motion was provided, so the telescope operated in a transit mode in the unused 608–614 MHz (49 cm) Channel 37 TV band, which was later allocated world-wide as a protected band for radio astronomy. The initial receivers included electron beam parametric amplifiers, replaced later by Field-Effect-Transistor amplifiers.

Although Swenson had to deal with weather-induced degradation of the parabolic surface and parametric amplifier reliability, over a period of nearly a decade the VRO detected and catalogued over a thousand discrete radio sources, mostly radio galaxies and quasars. Notable among these was the radio source known as VRO 42.22.01 which was identified with what was presumed to be a long recognized star, BL Lacerte, or BL Lac (Schmitt 1968). However, BL Lac turned out to be a quasar-like object of the class of radio sources since referred to as BL Lac objects, which typically have weak or no optical emission lines and are highly polarized.

By 1969, ground erosion had altered the parabolic surface beyond repair and the telescope was abandoned for use. Its work was completed, but the 49 cm protected radio astronomy band remains as a legacy of the Vermilion River Observatory.

The University of Michigan 85 Foot Telescope During WWII Fred Haddock worked at the Naval Research Laboratory (NRL), where he developed a submarine mounted radar that was used to locate Japanese ships. After the war he remained at NRL, working primarily at short centimeter and millimeter wavelengths to study the Sun and thermal radio sources, and he became a strong advocate for pushing the NRAO 140 Foot Telescope to the shortest possible wavelengths. In 1956, Haddock left NRL to begin a radio astronomy program at the University of Michigan that was funded by ONR. Under Haddock's leadership, Michigan acquired a Blaw-Knox 85 foot antenna similar to the NRAO 85 Foot Tatel Telescope, but inexplicitly the surface accuracy and pointing were about a factor of two better than the Green Bank antenna. Haddock, who was a gregarious, outspoken scientist, later took pride in pointing out that his Michigan antenna was better than the one delivered to Green Bank. As a result, Michigan radio astronomers and students were able to push their observations to 4 cm and later 2 cm to study flat spectrum radio sources (Dent and Haddock 1965) and radio variability (Dent 1965) while operation of the Green Bank antennas was essentially limited to 4 cm minimum wavelength. The University of Michigan 85 foot radio telescope remained in operation for more than half a century, during which Hugh and Margo Aller led a program to monitor the variability of extragalactic radio sources at 1.3, 2, and 6 cm wavelengths.

The Naval Research Laboratory Following the construction of their first 25 meter-class radio telescope at their Maryland Point Observatory, ten years later

NRL purchased a new high-precision 85 foot radio telescope from the Rohr Corporation (McClain 1966). The new dish was designed by Robert Hall and was based on his earlier design of the 85 foot antennas that were built by Blaw-Knox for NRAO (Sect. 4.3) and the University of Michigan, but the NRL antenna was modified to allow good operation at wavelengths as short as 1 cm. It was used in 1967, together with the Green Bank Tatel Telescope, as part of the first successful NRAO independent-oscillator-tape recording interferometer (Sect. 8.1).

The Haystack 120 Foot (37 m) Precision Antenna In parallel to NRAO's construction of the 140 Foot radio telescope, the US Air Force was building a radome-enclosed 120 foot antenna. Like the Jodrell Bank Mark I, or the Arecibo 1000 foot dish, the Haystack antenna was not originally conceived to do radio astronomy, but rather as multi-purpose facility to operate as a ground station for satellite communication, for radio propagation experiments, and as a satellite tracking radar facility.[10] In fact, much of the motivation for building the Haystack facility was the military interest in evaluating the use of metal-space frame supported radomes to protect large precision antennas against potential deleterious environmental effects of wind, snow, ice, and uneven solar heating. More conventional types of air-supported or self-supported plastic radomes were not considered practical for such large antennas due to the significant loss that would occur from any dielectric surface strong enough to support its own weight. A 120 foot antenna was the largest that could fit inside a 150 foot radome that the US Air Force was considering for an Arctic environment, although a radome specifically designed for the more benign New England weather could probably have been built with less transmission loss.

Construction of the Haystack facility by North American Aviation, Inc. began in 1960 and was completed in 1964 as part of the Lincoln Laboratory, which was operated by MIT for a variety of defense related activities. Haystack construction was under the direction of Lincoln Laboratory scientist Herbert Weiss who had previously been in charge of the Defense Department's Distant Early Warning (DEW) Line radar facility. At the time, Haystack was the largest radome ever built. As the Haystack facility was motivated primarily by defense needs, there was little or no input from the conservative astronomers who insisted on an equatorial mount for the NRAO 140 Foot. Rather, Haystack pioneered the use of digital computers to control the alt-az mounted antenna as well as to evaluate the data. The pointing accuracy of the radome enclosed Haystack 120 foot antenna was not affected by the wind and the effects of solar heating were minimized. The pointing accuracy was much better than that of the NRAO 140 Foot and the alt-az mounted dish did not suffer from the same astigmatic deformation when the telescope was tipped in elevation. Early use of the Haystack antenna was for a variety of experiments in space communication and space situation awareness, but gradually more time was devoted to astronomy, particularly for radar studies of the Moon and planets. A particularly important and innovative experiment was the verification by Irwin Shapiro and colleagues (Shapiro et al. 1971) of the so-called Fourth Test of General Relativity.[11] Starting in 1967, with support from NASA, the Haystack antenna was also used in a series of Very Long Baseline Interferometry (VLBI) experiments, particularly involving high resolution studies of interstellar hydroxyl (OH) and water (H_2O) vapor masers, as well as innovative applications of VLBI to precise measurements of the rotation of the Earth with applications to global timekeeping and for studies of tectonic plate motions (continental drift). Much of the instrumentation and techniques used for VLBI, including several generations of the VLBA recording system, have been developed at the Haystack Observatory (Sect. 8.4).

Subsequent upgrades to both the 120 foot dish as well as the radome and radar capability have enabled effective operation to short millimeter wavelengths for both radio astronomy and for a variety of passive and active communication and space surveillance activities. Although initially funded by the Air Force and later by the Defense Department Advanced Research Project Agency (ARPA),[12] as a result of the 1969 Mansfield amendment to the 1970 Military Authorization Act, the Haystack Observatory was turned over to MIT to operate primarily for radio astronomy programs sponsored by the North East Radio Observatory Corporation (NEROC) with financial support from the NSF.[13] But starting in the late 1980s, with decreasing support from the NSF, the amount of time available for radio astronomy has been reduced.

The Arecibo 1000 Foot Dish[14] Meanwhile, further competition to NRAO was appearing on the Caribbean island of Puerto Rico where Cornell University was constructing a 1000 foot (305 m) fixed spherical antenna 10 km south of the city of Arecibo. Like the Haystack and Jodrell Bank antennas, the Cornell antenna was not initially designed for radio astronomy, but for studies of the ionosphere. The Arecibo antenna was conceived in 1958 by Cornell Professor of Electrical Engineering William Gordon to study the density and temperature distribution in the ionosphere using incoherent radar backscatter (Gordon et al. 1961). Gordon calculated that even using the most powerful radar transmitters then available, a dish diameter of 1000 feet would be required in order to obtain a decent return signal from the upper F-layer of the ionosphere. Marshall Cohen noted that with such a huge antenna, it would also be possible to detect radar reflections from the Sun and the planets. Further discussion at Cornell led to increasing interest in using the proposed dish for general radio astronomy.

After rejecting potential sites in the Philippines and Cuba, a suitable site centered on a sinkhole was located in the Puerto Rico karst district south of Arecibo, and funding was obtained from the new ARPA. There was considerable interest within the military establishment in better understanding the ionosphere, since it might contain traces of disturbances by Soviet ICBMs or satellites as well as by high altitude nuclear explosions. Moreover, the ionosphere plays an important role in the world-wide propagation of high frequency radio communications, and the International Geophysical Year (1957–1958) and the 1957 launch of the Russian Sputnik were added incentives to study the ionosphere.

However, Gordon's calculation of the required sensitivity was faulty. Gordon assumed that the returned signal would be Doppler broadened by the random motions of ionospheric electrons. But the radar scattering is mostly from electrons moving with the singly ionized oxygen ions and so the width is given by the Doppler broadening of the ions, not the electrons, and is about a factor of a hundred more narrow than that calculated by Gordon. Gordon's goals could have been attained with a substantially smaller dish than 1000 feet, but by time this was recognized both Cornell and ARPA had become enamored with the concept of a 1000 foot dish with its potential non-ionospheric applications, and there was apparently no consideration of reducing the size of the dish (Cohen 2009).

When completed in 1963, the 20-acre collecting area of the Arecibo antenna was by far the largest of any radio telescope in the world, and would not be exceeded for another half a century when the Chinese 500 meter dish was completed in 2017. The Arecibo dish had a spherical instead of parabolic surface so that the beam could be steered up to 20 degrees from the zenith by moving the feed structure.[15] However, with a spherical surface there is no single focal point; rather the incoming radiation is focused along a line, so that simple horn or dipole feeds used on conventional parabolic antennas had to be replaced with elaborate line feeds. Unfortunately, due to a design error the original line feeds, including the high-powered 440 MHz radar feed, had poor sensitivity and unacceptably high sidelobes, and it would take years before they were replaced by properly designed line feeds.

For many applications, including 21 cm spectroscopy, SETI, and pulsar research, the Arecibo telescope was more sensitive than any radio telescope in the world. Active radar programs also allowed the exploration of solar system objects out to the orbits of Jupiter and Saturn. However, in common with other filled aperture radio telescopes, continuum observations were limited by confusion and gain stability. For the first few years, the Arecibo Ionospheric Observatory (AIO) was operated as part of the Cornell-Sydney University Astronomy Center with funding from ARPA. In 1971, the AIO became a national observatory and part of the Cornell National Astronomy and Ionospheric Center (NAIC) with primary funding from the NSF, while planetary and ionospheric radar programs were supported by NASA. In 1973 the antenna was upgraded by replacing the original wire mesh surface with 38,788 perforated aluminum panels which permitted operation up to 3 GHz (10 cm), and a new 420 kW 2.3 GHz radar was installed. A second upgrade was completed in 1997 when the line feeds were replaced by a Gregorian subreflector, the surface was reset to increase the maximum observing frequency, and a more powerful 1 MW transmitter installed for planetary radar.

Soon after completion of the antenna, radar observations of Mercury showed that, contrary to all text book descriptions, Mercury was not in synchronous rotation with its 88 day period of revolution, but instead rotated at

2/3 of the 88 day period or 59 days (Pettengill and Dyce 1965). Later observations included the discovery of the first millisecond pulsars (Backer et al. 1982), the first exoplanets (Wolszczan and Frail 1992), and the first detection of the effects of gravitational radiation (Taylor et al. 1979). In 1966 Frank Drake became Director of the Arecibo Observatory and initiated a vigorous program of pulsar research. As discussed in Sect. 5.5, with its extraordinary collecting area and sensitivity, the Arecibo telescope became a home for SETI observations by Frank Drake, Carl Sagan, and others.

Caltech and the Owens Valley Radio Observatory As was discussed in Sect. 3.2, following the lengthy discussions among Caltech's Jesse Greenstein, Robert Bacher, and Lee DuBridge, Taffy Bowen from Australia, Mt. Wilson and Palomar director Ira Bowen, and Carnegie's Vannever Bush and Merle Tuve, Greenstein and Tuve organized the January 1954 Washington conference on radio astronomy which led to an unintended shift in US radio astronomy planning toward the East Coast establishment and ultimately in the formation of the NRAO. However, Bacher, DuBridge, and Greenstein had not lost interest in creating a radio astronomy program at Caltech, one that would have a unique relation with the Mt. Wilson and Palomar Observatories (MWPO). Shortly after the conclusion of the Washington conference, ONR Science Director Randal Robertson visited Caltech and began a discussion with DuBridge and Bacher about possible funding from ONR for a Caltech/MWPO radio astronomy program. Although excited about the potential of radio astronomy, DuBridge hesitated, in part because of his uncertainty about how to proceed, his concern about whether the US should or could support two major facilities, and by the threat of competition from the planned Jodrell Bank 250 foot radio telescope or Taffy Bowen's planned large Australian radio telescope.

By July 1954, Greenstein had succeeded in convincing DuBridge of the need for Caltech to establish its own radio astronomy program, and DuBridge asked ONR Chief Scientist Emanuel (Manny) Piore "to keep a few dollars earmarked off in a corner for such a program."[16] DuBridge added that he had selected Caltech Professor Bill Pickering, then temporarily at JPL, to lead the new Caltech radio astronomy program. Robertson quickly responded that since his visit to Caltech in February, "I have had some funds mentally set aside for your project."[17] Within a few days, Elliot Montroll, the ONR Director of Physical Sciences, followed up, saying he wanted to meet with DuBridge in early August to "discuss the projected ONR program on radio astronomy."[18] Things were moving fast. Pickering accepted DuBridge's offer to take charge of the radio astronomy program starting 1 January 1955 and had already "begun to develop ideas in this direction."[19] Then JPL Director Luis Dunn suddenly and unexpectedly resigned to accept an industrial position at Ramo Woolridge, leaving DuBridge with the problem of finding a new JPL Director. JPL was a $13 million a year program, providing needed overhead funds to Caltech, and was a key component of the then burgeoning US space program.

DuBridge needed to appoint the best man as JPL director and that was Bill Pickering, leaving his radio astronomy program without a leader.[20]

A few months earlier, Grote Reber, who apparently had gotten wind of the developing Caltech interest in radio astronomy, had written DuBridge to inquire if there might be place for him in the Caltech program.[21] DuBridge wisely consulted Greenstein, who reported that while Reber was "extremely original and has done remarkable good work, … I'm not sure he would be a suitable person to build an organization around."[22] DuBridge responded to Reber that "our plans for radio astronomy at Caltech are at a very elementary and formative stage and we do not know if it will be possible to get any work underway in the near future or not," and went on to say in the traditional way, "if we do find it possible to undertake a project in which you might be interested, I will get in touch with you."[23] There is no evidence, however, that Reber was ever considered for a position in the Caltech radio astronomy group, even when DuBridge was desperately in need of finding someone to replace Pickering.

The "Old Boy Network" then went into quick operation. While DuBridge was pondering how to find a new leader for his radio astronomy project, Taffy Bowen, who was in the US to raise money for his planned radio telescope, stopped at Caltech and met with DuBridge, Bacher, Greenstein, and Walter Baade from the Mt. Wilson and Palomar staff. Recognizing the lack of experienced American radio astronomers, DuBridge suggested to Bowen that one of his men be invited to Caltech to help start a radio astronomy program. Several possibilities were discussed, but they agreed that John Bolton would be the best person. Following his remarkable discoveries described in Sect. 2.1, Bolton had run into conflict with his Radiophysics boss, Joe Pawsey. To ease tensions, Bowen had transferred Bolton from radio astronomy to his own rain-making program, but recognized the opportunity afforded by Caltech to get Bolton back into radio astronomy and perhaps to get him out the difficult situation at the Radiophysics Lab.[24] Although Bowen claimed that he did not want to lose Bolton, he agreed to talk to Bolton and explore his interest in going to Caltech. Encouraged by his discussions with Bowen, DuBridge rather casually suggested to Piore that "possibly you could add say $50,000 to the contract at ONR for radio astronomy purposes."[25]

Only after Bowen had talked with Bolton and obtained in principle Bolton's interest in going "to Cal. Tech. to help you start a Radio Astronomy programme,"[26] did DuBridge finally contact Bolton with an offer of an appointment "as a Senior Research Fellow in Physics and Astronomy…. The initial appointment would be for a two-year period, beginning whenever you would find it possible to arrive. At the end of the two years, we would like to explore the question of your future with a definitive possibility in mind that it may be mutually agreeable for you to remain with us."[27] DuBridge, who was sensitive to the growing interest from AUI and other east coast scientists, was anxious to get started and expressed the hope that Bolton would start at the beginning of 1955.

John Bolton arrived at Caltech with his family in February 1955, initially on a two year leave of absence from CSIRO. At Bolton's urging, Caltech also hired his long-time friend and colleague Gordon Stanley, who arrived a few months later to provide expert technical support. To the surprise of DuBridge, Bolton announced that he did not intend to build another Mills Cross as DuBridge had discussed with Bowen, but rather had his own ideas about a variable spacing interferometer to measure accurate radio positions and morphology of discrete radio sources.

To carry out their planned radio astronomy program Bolton and Stanley needed to find a large, flat radio-quiet site. Stanley located an appropriate site in the Owens Valley nestled between the Sierra Nevada on the west and the Inyo Mountains to the east. Starting early in the twentieth century, the city of Los Angeles diverted water from the Owens Valley to the rapidly growing and water-starved city of Los Angeles, destroying farms and leaving the Owens Valley as a dry wasteland. With a diminishing source of livelihood, the population of the Owens Valley stagnated or even declined.[28] In order to minimize population growth in the area, in 1920, the Los Angeles Department of Water and Power (LADWP) purchased a large tract of land located near the small town of Big Pine about 250 miles north of Pasadena. Caltech seized the opportunity to rent for $1 per year several hundred acres of land from the LADWP about five miles from Big Pine where they could be assured of minimal population growth in the area and relative freedom from RFI.[29]

DuBridge had already laid the foundation with ONR for support of Bolton's proposal, and for the first few years the construction and operation of the OVRO was supported primarily by generous funding from ONR, with some private funding raised by Caltech for the buildings needed to house the control room, workshops, and living quarters for visiting staff. Arnold Shostak, the ONR program officer, did not bother with formal proposals or project reviews, but had an informal unmilitary-like seat-of-the pants approach to deciding who and what to fund and what not to fund. Aside from Caltech, Shostak provided ONR funds for George Swenson at the University of Illinois and Fred Haddock at the University of Michigan.[30] However, starting with the construction of the OVRO 130 foot (40 meter) antenna in 1964, OVRO, as well as the other ONR funded American radio observatories, depended more and more on NSF funding, fomenting an increasing level of competition between NRAO and the university-operated radio observatories.

Although much of the heavy construction of the OVRO interferometer was initially carried out by commercial contractors, as Bolton began to run out of ONR funds, the construction and operation at OVRO was increasingly done largely by his graduate students, who were mostly recruited from the Caltech physics rather than the astronomy departments. Under Bolton and Stanley's supervision, and especially Bolton's iron handed management, the students designed much of the instrumentation as well as ran bulldozers and tractors, dug trenches, laid cables, painted antennas, designed and built electronic systems, etc. The students were paid only a small fraction of what the commercial contractors were paid, which did not escape the attention of the local contractors. On one hot summer day, a local union organizer showed up while Bolton, along with a group of students, were laboring out in the desert sun and demanded to know if this was a union job. Bolton assured him that he was a member of the International Astronomical Union and that was the last time any labor union was involved at OVRO. For the students, who provided skilled, but cheap, labor, the experience was invaluable in their later careers, and many of Bolton's students and junior staff themselves went on to distinguished careers in radio astronomy. Robert Wilson received the 1978 Nobel Prize for Physics, along with Arno Penzias, for their discovery of the cosmic microwave background, which created a new field of precision observational cosmology from what previously had been a mathematical exercise. Six other former students later served as directors of radio observatories in the US, Europe, India, and Australia.

When the OVRO East-West interferometer went into operation at the end of 1959, NRAO had only a single 85 foot antenna and was struggling with what turned out to be only the beginning of extensive problems with the 140 Foot antenna. By the end of 1960, OVRO had a fully functional two-dimensional interferometer using two 90 foot (27.4 meter) antennas that could be moved on railroad track to various stations separated by up to 1600 feet in both the east-west and north-south directions. Young radio astronomers were recruited from around the world to join the OVRO staff. Jim Roberts and Kevin Westfold arrived from Australia and were soon followed by Venkataraman Radhakrishnan (known as "Rad") from India by way of Sweden, Per Maltby from Norway, and Dave Morris from Jodrell Bank. Tom Matthews, who had been Bolton's host while at a visit to Harvard, was the sole US-trained staff member.

At the end of his initial two-year appointment, Bolton resigned from CSIRO and accepted an indefinite appointment at Caltech, and on 1 January 1958 he became Director of the Owens Valley Radio Observatory (OVRO) and Professor of Radio Astronomy. To the surprise of many, citing Caltech bureaucracy, what he perceived as excessive overhead charges, pressures to teach, and family reasons, Bolton left Caltech and returned to Australia at the end of 1960 to take charge of the Parkes 210 foot radio telescope and to oversee the final stages of its construction.

Following Bolton's departure, Caltech tried to recruit Robert Hanbury Brown as OVRO director, but he had already committed to go to the University of Sydney to build a large optical intensity interferometer. It is not clear to what extent Caltech low-keyed the radio astronomy program for fear it would compete with either the ONR funded program at the Caltech synchrotron or Caltech/MWPO ambitions to build a southern hemisphere 200 inch telescope. Finally, in 1965 Caltech appointed Gordon Stanley as OVRO director. Stanley had even fewer academic qualifications than Bolton, and unlike Bolton was never given a professorial appointment. When Stanley retired in 1975, Professor of Radio Astronomy Alan Moffet, who had been one of the earliest radio astronomy students at Caltech, became the OVRO director.

The early OVRO research program fully met Greenstein and DuBridge's ambitions to bring together radio and optical astronomy at Caltech. During his six years at Caltech, Bolton led the development of the OVRO which became in those years the most productive radio observatory in the world. The OVRO interferometer measured radio source positions with an accuracy of a few arc seconds (e.g., Read 1963; Fomalont et al. 1964) leading to secure identifications with radio galaxies at ever increasing distances (Minkowski 1960; Maltby et al. 1963). Caltech students and staff demonstrated the pervasive double nature of radio galaxies (Maltby and Moffet 1962), discovered the first quasars, made a number of important solar system discoveries (e.g., Clark and Kuzmin 1965), and pioneered interferometric radio spectroscopy (Clark et al. 1962; Clark 1965) and interferometric polarization studies (Morris et al. 1964). By the mid-1960s, the Owens Valley Radio Observatory with its modest funding from ONR was a clear success, in contrast to the much better NSF-funded NRAO, which was struggling with the 140 Foot antenna, and until the 1962 completion of the 300 Foot transit antenna, NRAO did not have a competitive radio telescope.

Tensions between NRAO and Caltech had existed since DuBridge had announced at Berkner's July 1953 meeting that he was going to begin a radio astronomy program at Caltech (Sect. 3.2). Bolton, and later Gordon Stanley, served on various NRAO advisory committees, and never missed an opportunity to criticize the NRAO operation. Stanley's mixer receivers were more sensitive than NRAO's expensive receivers using commercial parametric and maser amplifiers, and he was not hesitant to remind NRAO of their problems. One Caltech student, unenthusiastic about doing manual labor in the Owens Valley, asked Bolton if he could instead spend the summer at the NRAO summer student program, which offered an apparently better opportunity to be involved in research as well as a series of interesting lectures. Bolton flatly told him, "Sure, but, if you go to NRAO, you don't need to come back." That student never got his PhD.

The rivalry between NRAO and OVRO reached its peak in late 1960s and 1970s when both organizations proposed to build the array of dishes that had been recommended by the first decade review of astronomy (Whitford 1964) (Sect. 7.2) and later, to a lesser, extent the competing proposals for a dedicated Very Long Baseline Array (VLBA) (Sects. 8.6 and 8.7). Ironically, however, nearly 40 former Caltech students, staff, and faculty later worked at NRAO, including two NRAO directors as well as a number of NRAO assistant directors. After the early influx of Harvard graduates, it was the Caltech graduates and postdocs who played major roles in planning and designing the new instrumentation and software that kept NRAO at the forefront of radio astronomy over the next half century. In particular, Barry Clark, Ed Fomalont, Eric Greisen, and Richard Sramek were key players in the design, construction. and operation of the NRAO VLA, and Ron Ekers, who had been a Caltech postdoc, became the first director of the VLA (Sect. 7.7). Clark, Jon Romney, and Craig Walker, along with one of the present authors (KIK) were heavily involved in planning for the VLBA (Sects. 8.6 and 8.7) while Alwyn (Al) Wootten became the ALMA Project Scientist for North America (Sect. 10.7).

The Caltech plan to build an eight-element array led to the construction of the first 130 foot (40 m) prototype dish which was used in conjunction with the two 90 foot (27 m) antennas as a three element interferometer (Sect. 7.2). But following the failure of the Caltech Owens Valley Array proposal in favor of the NRAO VLA, Caltech turned its attention first to Very Long Baseline Interferometry (Sect. 8.1) using the 130 foot telescope and then to millimeter astronomy based on a novel 10 meter dish designed by Caltech physics professor Robert Leighton (Sect. 10.4).

Jodrell Bank American ambitions were dwarfed by Bernard Lovell's 250 foot (76 m) fully steerable radio telescope at Jodrell Bank, near Manchester in the UK. Lovell was familiar with Grote Reber's work and, indeed, during WWII Lovell had implemented some of Reber's receiver designs in developing British radar systems. As early as 1950, Lovell (1987) began talking about building a very large fully steerable dish at the University of Manchester. Interestingly, Lovell's plans were not motivated by radio astronomy, but by his interest in detecting radar echoes from ionized trails left by cosmic rays as they passed through the Earth's atmosphere. Lovell's 250 foot Jodrell Bank radio telescope was finally finished in 1957, and would remain an icon of radio astronomy for many years. However, the years of delay and cost escalation during the 250 foot construction were sadly prophetic of many of the other large steerable radio telescope projects which were to follow throughout the twentieth century.

After nearly a decade of continual operation, the Mark I telescope was beginning to show signs of wear resulting from stresses induced by the repeated elevation motion. The antenna needed a major overhaul, more than could be accomplished from the regular maintenance program. Lovell managed to raise £350,000 to not only overhaul the Mark I, but to upgrade it to what he called the Mark IA, which would work at frequencies up to several GHz. This was to be accomplished by overhauling the azimuth track, reducing the load on the elevation bearing, strengthening the backup structure, increasing the dish diameter by 15 feet (4.5 m), putting a new surface on the dish, strengthening the single feed support, and revamping the control system. But the cost estimate turned out to be over £500,000, and it was admitted by the designer, Charles Husband, that this was only an estimate, and that the price could not be determined without actual contractor bids. Once again, repeated delays and design changes ran the final cost of the overhaul and upgrade to £650,000, even including some descoping of the upgrade, including the decision to strengthen the single feed support structure rather than replace it with a tetrapod and abandoning any plan to increase the dish diameter. In 1987, the Jodrell Bank 250 foot Mark IA radio telescope was renamed the "Lovell

Telescope" and remains in operation more than 60 years after its completion in 1957.

In addition to extensive stand-alone radio astronomy research programs, the Jodrell Bank telescope was a key component of the very successful Manchester long baseline interferometer program, and later MERLIN, the Multi-Element Radio Linked Interferometer Network (Sect. 8.1).

The 250 foot's delays and cost increases were in part the result of upgraded performance specifications following the Harvard discovery in the US of the 21 cm hydrogen line. Lovell naturally wanted to exploit this exciting discovery, and introduced costly design changes which the University was unable or unwilling to meet. Following the accelerated space program resulting from the Sputnik launch by the USSR, the US found itself with inadequate facilities to track either Russian or American spacecraft, especially those in so-called "deep space," beyond Earth orbiting satellites. Rather embarrassingly to the US, NASA had to contract with the University of Manchester to use their still unfinished 250 foot antenna at Jodrell Bank to track the rocket that launched the Sputnik spacecraft and for subsequent tracking of the first US satellites. Probably only the fortuitous launch of Sputnik and the income from the NASA contract saved Lovell from going to prison for his alleged misuse of University funds. Lovell himself became perhaps the best-known figure in radio astronomy, and was rewarded by knighthood a year earlier than Martin Ryle, who headed the very innovative and successful, but contentious, radio astronomy program at Cambridge (Sect. 7.1).

The Australian 210 Foot Parkes Radio Telescope The events leading to the construction and early operation of the Parkes 210 foot radio telescope have been described by Robertson (1992). After first flirting with Caltech, Taffy Bowen succeeded in raising $500,000 from the US-based Carnegie and Rockefeller Foundations for his Giant Radio Telescope (GRT) in Australia. Although he was able to obtain matching funds from the Australian government, they were not sufficient to meet Bowen's ambitions for an antenna that would compete with Lovell's 250-footer. Moreover, the Australian government money came with strings attached. The other, still very productive, Radiophysics radio astronomy programs would need to be cut, so there was little support for Bowen's GRT among the Radiophysics staff, who saw it as competition to their own ambitious plans. Bernie Mills wanted to build an expanded version of his successful Mills Cross, the so-called "Super Cross." Chris Christiansen and Paul Wild each had plans for solar radio telescopes. Ultimately Mills and Christiansen would leave Radiophysics for the University of Sydney where they could pursue their goals. Wild almost accepted an attractive offer to go to Cornell University in New York, but with the help of Joe Pawsey, he was able to obtain additional funds to build his solar radioheliograph near Culgoora in northern New South Wales. Later, as discussed in Sect. 4.6, Joe Pawsey planned to leave to become Director of NRAO, but became ill and died before he could take up the NRAO position. John Bolton supported

Bowen's plans for building a GRT, but Bolton had gone off to Caltech with Gordon Stanley to start the Owens Valley Radio Observatory.

Bowen first recruited Barnes Wallis to help design his radio telescope[31] and then engaged Freeman Fox, who had designed the Sydney Harbor Bridge, for the detailed engineering design. Freeman Fox produced several designs for various sized telescopes. The available funds suggested a diameter of 210 foot (64 meter) if the elevation was limited to 30 degrees above the horizon and if the operating wind speed was limited to only 30 miles per hour. The shortest operating wavelength was specified as 10 cm (3 GHz). A site near the farming town of Parkes in the rural New South Wales Goobang Valley was chosen due to its isolation from local sources of radio interference, expected low winds, mild snow-free climate, geological stability, and relative proximity to Sydney. With a 210 foot diameter, the Parkes radio telescope was clearly too large to use a conventional equatorial (polar) mount. Instead Wallis developed a novel "Master Equatorial" consisting of a small equatorially mounted unit located at the intersection of the antenna's azimuth and elevation axis (Robertson 1992, p. 147). Using a light beam reflected off a mirror on the back of the dish, the pointing of the radio antenna was servo-controlled to the position of the Master Equatorial and provided remarkable stable and precise pointing. Although the Master Equatorial design was known to the AUI Planning Committee, it was never seriously considered for the Green Bank 140 Foot Telescope.

After he returned to Australia from Caltech at the end of 1960, John Bolton oversaw the completion of the Parkes radio telescope, which was opened on 31 October 1961, a full four years before the completion of the NRAO 140 Foot Telescope (Sect. 4.4). As with the Jodrell Bank 250 foot antenna and many subsequent large radio telescope systems built in the US and in other countries, there were many construction delays and cost increases. The final cost of the Parkes radio telescope was about US$2 million, considerably more than the initial budget estimates, but only about one-seventh the cost of the 140 Foot. Although smaller than the Jodrell Bank radio telescope, the Parkes dish had far better surface and pointing accuracy than Lovell's telescope, and twice the collecting area of the NRAO 140 Foot Telescope. At least initially it did not operate at the same short wavelengths as the 140 Foot antenna, but subsequent upgrades, resurfacing, and strengthening resulted in it being used up to 22 GHz (1.3 cm) with a sensitivity comparable to that of the 140 Foot Telescope.

During the first few years of operation, Bolton began a variety of research programs, including a systematic survey of the sky south of +20 degrees Declination. Following his close involvement with optical astronomers at Caltech and at the Mt. Wilson and Palomar observatories, Bolton initiated a very productive collaboration with astronomers and students from the Mt. Stromlo Observatory near Canberra, leading to the discovery of many new quasars and the determination of their redshifts. Later, Richard (Dick) Manchester led a vigorous Parkes pulsar program and the first Fast Radio Burst was discovered at Parkes in 2007 by Duncan Lorimer et al. (2007). Along with the Sydney Opera House and the Sydney Harbour Bridge, the Parkes radio telescope has become an Australian icon, and the role of the Parkes telescope in support of the Apollo 11 Moon landing was the subject of the well-known movie, *The Dish*.

The Canadian Algonquin Park 150 Foot Dish Canadian scientists had developed a modest program in radio astronomy, mostly centered at an attractive and relatively radio quiet site near Penticton, British Columbia. Research at Penticton was based on several simple and inexpensive arrays operating at relatively long wavelengths of 15 to 30 meters, as well as a small instrument to monitor solar radio noise at 10 cm. The daily solar monitoring program, which began in 1947 near Ottawa, continues to this day, providing important data on solar activity and its impact on short wave radio proportion. It is certainly the longest running uninterrupted program in radio astronomy, and arguably the longest running scientific study of any kind. However, with the growing interest in the exciting developments leading to the discoveries being made in in Europe and Australia, Canadian radio astronomers needed a competitive radio telescope that would operate at centimeter wavelengths.

In 1966 the Canadian National Research Council completed a 150 foot antenna at Algonquin Park in Ontario. The Algonquin Radio Observatory (ARO) antenna was designed by Freeman Fox, who built the Parkes radio telescope, and followed many of the same design concepts, including a Master Equatorial to control the antenna pointing. The ARO radio telescope had a more precise surface and better pointing than the NRAO 140 Foot, and, owing to the alt-az design, gravitational deflections were better understood than they were for the polar-mounted 140 Foot. However, there was limited funding in Canada for instrumentation or operation. Except for the early success of the Canadian VLBI program, the scientific impact of the Algonquin Park 150 foot radio telescope was limited. After an ambitious plan to upgrade the telescope for operation at short millimeter wavelengths was cancelled following an NRC review, further radio astronomy observations with the Algonquin Park radio telescope ceased.

The Giant Metrewave Radio Telescope (GMRT) in India Radio astronomy in India began later than in many other countries. Govind Swarup started his radio astronomy career at the CSIRO Radiophysics Laboratory under the tutelage of Joe Pawsey. After spending a year at Harvard's Fort Davis radio telescope, Swarup earned his PhD at Stanford working under Ron Bracewell. In 1961, T. Krishnan, M. R. Kundu, T. K. Menon, and Swarup proposed starting a radio astronomy program in India. But only Swarup actually returned to India, where he led the design and construction of a novel new radio telescope located near the small town of Ooty and intended to observe lunar occultations. During the 1970s, Swarup and his growing cadre of young scientists used the Ooty radio telescope to determine the positions and morphology of more than a thousand extragalactic radio sources. With the construction of the more powerful VLA and the WSRT (Chap. 7), however, the time for lunar occultations had passed.

Swarup then led his young group to design and build the GMRT, comprised of thirty parabolic dishes each 45 meters (148 feet) in diameter. The GMRT, which went into full operation in the year 2000, is 25 km in extent, is located about 100 km from the city of Mumbai (Bombay), and covers the frequency range from 40 to 1700 MHz. Each dish is based on Swarup's novel SMART (Stretched Mesh Attached to Rope Trusses) design intended to exploit the low labor costs in India. Following a series of upgrades, the GMRT remains one of the world's most powerful radio telescopes, especially in the frequency range below 1 GHz.

6.7 Grote Reber Challenges NRAO[32]

Since Karl Jansky's early work, and starting with Reber's activities at Wheaton, radio astronomers have steadily moved to ever-shorter wavelengths in the quest for better angular resolution and to study the multitude of molecular transitions that exist in the millimeter and submillimeter bands. In 1953 Reber was approached by Merle Tuve of the Carnegie Institution to return to Washington to help develop plans for building a large parabolic dish. Characteristically departing from conventional wisdom, Reber decided to concentrate instead on the extremely long hectometer wavelengths where he felt he could make a bigger impact. While he was working in Hawaii, he had access to ionospheric records which showed regions of minimum ionospheric attenuation between latitudes of 40 and 50 degrees in both hemispheres. Reber chose Tasmania, with its access to the rich southern sky and more favorable climate compared with Canada. In November 1954 he moved to Bothwell, Tasmania, where, except for visits to the United States and Canada, he lived and worked for almost the next 50 years.

In Tasmania, Reber designed and built a series of arrays to study galactic radio emission at wavelengths as long as 2.1 km. Reber hoped to exploit the fluctuations in the ionosphere which he claimed led to the creation of narrow holes which would form a high resolution window to the Universe. Observing at hectometer wavelengths, he noted that the sky is very bright everywhere, especially at the poles, and that the Milky Way appears as a dark absorption band which he correctly understood was due to free-free absorption by interstellar electrons (Reber and Ellis 1956). Unfortunately, increasing levels of ionospheric absorption and the increased density of the interplanetary plasma following the unusually low sunspot minimum of 1955, combined with increasing levels of broadcast interference, limited the results of Reber's hectometer observations. But Reber's 144 meter (2045 kHz) array, which he built in a local farmer's pasture, consisted of 192 dipoles covering a full square km and remains the largest "filled-aperture" radio telescope ever built (Reber and Ellis 1968).

To overcome ionospheric absorption, Reber conceived the idea of releasing liquid hydrogen into the ionosphere so it could recombine with free electrons and thus make the ionosphere temporarily transparent to wavelengths as long as 300 meters. For the last twenty years of his life, he relentlessly tried to obtain demobilized American ICBMs to carry a canister of hydrogen into space, but he was frustrated by the seemingly endless bureaucracy and the large cost associated with any rocket activity. Letters to colleagues (including one of us, KIK), friends, observatory directors, NASA laboratory heads, and Congressmen gave no encouragement, but he stubbornly refused to take "no" for an answer and continued to seek surplus rockets until shortly before his death. However, Reber, Ellis, and others did convince NASA to fire the engines for 16 seconds on the ill-fated Challenger space shuttle during a pass over Bothwell on the night of 15 August 1985. A quarter ton of fuel was released in an attempt to create a temporary hole in the ionosphere. But the results of these hectometer observations were inconclusive (Ellis et al. 1987).

In 1967, Reber applied for an NSF grant of $1.25 million to construct a large array in the northern hemisphere to operate at a wavelength of 144 meters, but was turned down. Reber did not easily accept the rejection of his proposal or the growing emphasis on short wavelengths. His suggestion that his array could be funded by "slight curtailment of routine operations at Green Bank," and that "N.R.A.O. should be gradually contracted in favor of scientifically more auspicious long wave programs at other places throughout the country"[33] was not well received in Washington or by NRAO. He researched previous NSF astronomy grants and challenged the legality of the national astronomy centers, which he argued were prestige institutions designed to impress the ignorant, which constituted "a mortgage on astronomy money," and said that the members of the National Science Board were stuffy old men.

Reber wrote letters to the NSF Director Leeland Haworth; the President of the National Academy of Sciences Frederick Seitz; various Congressmen, including Senator William Proxmire, as well as Ralph Nader and his Center for the Study of Responsive Law. He testified before Congress that too much NSF funding for radio astronomy was going to NRAO instead of individual investigators[34] and claimed that the "staff at the NSF are mostly clerks quite uninterested and incapable of imaginative scientific leadership."[35] From the National Academy of Sciences he asked for "positive leadership instead of basking in renown."[36] To establish his credentials so that that the recipients of his letters did not think they were coming from a crank, he would often start his letters referring the reader to the *Encyclopedia Britannica* article describing his accomplishments.

Reber also expressed great concern at the National Academy of Sciences report (Whitford 1964) on the future of ground-based astronomy in the US, in particular what he considered an overemphasis on "huge instruments." In a letter to *Science*, Reber (1966) argued against the construction of a large radio array [the VLA, Chap. 7] and commented that the plans for a 400–600 foot radome enclosed dish "displays an acute lack of imagination." He was especially critical about NRAO and about the present and future NRAO scientists, writing,

> Green Bank might as well be closed down. The best work likely to ever be done there has already been completed and published: namely my beans.[37] Some of the things that go on there in the name of administration shouldn't happen to a dog. The net effect is that of a mortgage on astronomy. Only the duller members of the new generation will try to find a place at these institutions.[38]

His prescient remarks about the need for a tracking multi-beam array made of simple wire elements preceded by more than a quarter of a century the international discussions about building a Square Kilometre Array (e.g., Ekers 2013), but his uninhibited comments about mainstream radio astronomy, especially concerning NRAO, left Reber as a bit of a pariah.

6.8 Changing Leadership

NRAO By 1977, Dave Heeschen was getting tired of dealing with the increasing NSF bureaucracy and announced his desire to step down as Director of NRAO and spend more time with his family, sailing on Chesapeake Bay, and in reactivating his research career. During his 17 years, first as NRAO Acting Director and then as Director, Heeschen had transformed NRAO from an organization on the brink of failure into a highly respected facility that was universally acknowledged as the leading radio observatory in the world. During his tenure as NRAO Director, Heeschen established NRAO as the national observatory that had been envisioned by Menzel, Bok, Stratton, Berkner, and others. He saw the completion, finally, of the 140 Foot Telescope, led the drive to build the VLA, established millimeter radio astronomy at NRAO, and enthusiastically supported the early VLBI program and later the initiative to build the VLBA. He recruited an outstanding scientific and engineering staff and oversaw NRAO's transition into a true visitor institution. He took particular interest in the professional growth of the scientific staff, and throughout his tenure as Director, he remained the head of the "Basic Research Division." Accustomed to the informal discussions with Randy Robertson in the early years, he was annoyed when the NSF started to record their discussions and rebelled against the NSF request to review and edit the lengthy transcript of one of their meetings. Instead, he sent it back with the terse note, "If that's what we said, then that's what we said."[39] Nevertheless, he was greatly respected at the NSF which considered NRAO to be the best run of the national centers.[40]

After his retirement, Heeschen broke his personal tradition and gave an after dinner talk at an NRAO internal scientific symposium where he outlined his "advice to directors and managers and to would-be-directors and managers:"[41] (1) Hire good people, then leave them alone; (2) Do as little managing as possible; (3) Use common sense; (4) Don't take yourself too seriously; and finally, (5) Have fun.

Throughout his tenure as Director, Heeschen expressed concern that NRAO was getting too large and that university operated facilities were not receiving adequate support. In a letter to then AUI President, Keith Glennan, Heeschen wrote,[42]

> For all its logical, quantitative aspects, I think the best science is a highly personal, individualistic activity—as much so as art or music or writing—and it needs the right kind of atmosphere. If NRAO, in one context, or AUI in another, gets so large that the atmosphere can't be maintained then we become just high-level technicians or facility operators, and while it may be necessary that someone do this, I don't think it is for us.

When Heeschen announced his retirement, AUI, under the direct leadership of President Gerry Tape, initiated a search for a new Director. But running a "user" oriented observatory does not necessarily appeal to the typical research scientist. After a national search, the top three candidates all turned down the NRAO Directorship, and AUI asked Mort Roberts to become the NRAO Director. Roberts was a long time member of the NRAO Scientific Staff and had previously served for a year as the Green Bank site director from 1969 to 1970. He had a distinguished research career primarily using 21 cm spectroscopy to study the kinematics of nearby galaxies which led to best evidence for the existence of dark matter.

Roberts became the Director of NRAO just as the construction of the VLA was being completed and NRAO was gearing up for the 25 meter millimeter radio telescope and the VLBA. He oversaw the completion of the VLA construction (Sect. 7.6) and the complex transition from VLA construction to VLA operations (Sect. 7.7), hired Ron Ekers, then working in the Netherlands, to become director of VLA operations, and helped procure the funding for the VLBA (Sect. 8.7). However, he was blamed, probably inappropriately, for the failure of the popular 25 meter millimeter-wave telescope proposal (Sects. 8.7 and 10.3).

Roberts strongly believed that NRAO should have a world class scientific staff, and tried to protect the research time of the staff. Young staff members, especially those on term appointments, were encouraged to concentrate on their research. As he put it, their job was "to get tenure." This led to some resentment from those staff members on continuing or indefinite appointments, as they had to absorb the full load of supporting Observatory operations, but, in return, they weren't subject to the threat of termination at the end of a few-year term appointment.

After the completion of his five year term as NRAO Director in 1984, Roberts returned to full time research. Hein Hvatum became the Interim Director for three months until Paul Vanden Bout arrived as NRAO Director from the University of Texas on 1 January 1985. Vanden Bout had built a solid reputation for making the University of Texas Millimeter Wave Observatory a major player in millimeter spectroscopy, and he had trained a new generation of millimeter wave astronomers. Before coming to NRAO, Vanden Bout had served on both the NRAO Visiting and Users Committees, and chaired the Advisory Committee charged with selecting the site for the VLBA Operations Center, so he was well known to the AUI Board. During his 17 years at the helm of NRAO, Vanden Bout oversaw the construction of the VLBA (Sects. 8.7 and 8.8); dealt with the unprecedented circumstances surrounding the collapse of the 300 Foot Telescope leading to funding and construction of the Green Bank Telescope (Sects. 9.6 and 9.7); began the Expanded Very Large Array project (Sect. 7.8); together with Bob Brown, initiated the design of the Millimeter Array (MMA); and was an important part of the complex negotiations that lead to the international partnership and the funding and construction of ALMA (Atacama Large Millimeter/submillimeter Array) (Sects. 10.6 and 10.7). Vanden Bout resigned as NRAO Director in June 2002 to become Interim Director of ALMA, and W. Miller Goss became the Interim NRAO Director.

AUI reached out to Kwok-Yung (Fred) Lo, then director of the Taiwan Institute of Astronomy and Astrophysics to fill the Director position. Earlier, Lo had been the Chair of the University of Illinois Department of Astronomy and had served on the faculty at Caltech. He received his PhD in physics from MIT in 1974 and had a wide range of research interests including star formation and VLBI. Lo's management style contrasted with that of Vanden Bout, who tried to rule by consensus, whereas Lo ruled more by edict. During his ten year, sometimes contentious, tenure as NRAO Director, Lo oversaw the complex transformation of the VLA to the JVLA (Sect. 7.8); made the tough decision to curtail the long running AIPS++ project; and played a crucial role in the establishment of ALMA and the North American ALMA Science Center at NRAO in Charlottesville. Lo stepped down as NRAO Director in May 2012 and died in 2016 after a 25-year-long struggle with cancer (Fig. 6.12).

The next Director of NRAO was Anthony (Tony) Beasley who arrived at NRAO with impressive credentials obtained as a result of his forceful management of some of the NSF's largest projects. Beasley first came to NRAO in 1991 on a postdoctoral appointment after receiving his PhD in Astrophysics from the University of Sydney. He rapidly rose through the ranks, becoming Deputy Assistant Director for VLA/VLBA Operations and for Computing in 1997, and Assistant Director in 1998. In 2000 Beasley left NRAO to become Project Manager for the Combined Array for Research in Millimeter-Wave Astronomy (CARMA) which combined the Caltech and BIMA millimeter arrays (Sect. 10.4) at a relatively dry site in the Inyo Mountains east of OVRO. In 2004 he returned to NRAO as an Assistant Director and International Project Manager for ALMA, under construction in Chile by NRAO and ESO (Sect. 10.7). His next challenge was as Chief Operating Officer and Project Manager for the NSF-funded National Ecological Observatory Network (NEON), a continental-scale ecological observatory designed to detect ecological change and enable forecasting of its impacts. In 2012 Beasley returned as Director of NRAO and in 2016 he also became AUI Vice President for Radio Astronomy Operations. He brought a new style of aggressive no-nonsense management to an Observatory faced with NSF-mandated changes and was committed to bringing under-represented groups to NRAO.

While open to input and criticism, Beasley responded decisively to each crisis situation facing NRAO. Hitting the ground running, he initiated the new VLA Sky Survey, began the effort to provide Science Ready Data Products to enhance the productivity of the increasingly complex NRAO telescopes, and initiated the early development of the next generation VLA (ngVLA) project[43] (Sect. 11.2) to provide the US response to the international SKA project (Ekers 2013).

AUI Following the rapid turnover in the AUI Presidency discussed in Sect. 4.6, Gerry Tape returned from his appointment as Ambassador to the International Atomic Energy Commission to become President of AUI from 1969 to 1980. Tape was succeeded by Cornell chemist Robert E. Hughes, who had previously served as the NSF Assistant Director for Math and Physical Sciences. Hughes retired in 1997 and was replaced by Lyle Schwartz from the

Fig. 6.12 Four NRAO Directors at the NRAO 50th anniversary symposium, June 2007. Left to right: Fred K. Y. Lo (5th Director), Paul A. Vanden Bout (4th Director), Morton S. Roberts (3rd Director), David S. Heeschen (2nd Director). Credit: NRAO/AUI/NSF

National Institute of Standards and Technology (formerly the National Bureau of Standards). Schwartz was immediately confronted with the Brookhaven controversy over the alleged leakage of radioactive tritium into the local drinking water (Sect. 9.7), resulting in the loss of the contract with the Department of Energy to operate Brookhaven.

AUI was in serious trouble. Faced with the loss of the lucrative Brookhaven contract which was an order of magnitude larger than the NRAO contract, Schwartz resigned just over a year after he arrived. Some of the AUI Trustees also resigned, and AUI was restructured to become a self-perpetuating not-for-profit manager of scientific facilities. No longer were the nine original universities represented on the Board by a university scientist and administrator, and AUI was governed by a new, more diverse Board of Trustees.

The new AUI Board asked long-time Trustee and Cornell Professor of Astronomy Martha Haynes to act as Interim AUI President until they could find a permanent replacement for Schwartz. Around this time Riccardo Giacconi was about to complete his term as Director of the European Southern Observatory (ESO) where he oversaw the construction of a suite of four 8 meter telescopes in Chile known as the Very Large Telescope. Giacconi had previously served as the first Director of the Space Telescope Institute in Baltimore, Maryland, where he defined how the Hubble Telescope would serve the astronomical community. Earlier, at the Harvard-Smithsonian Center for Astrophysics, he directed the effort leading to the Einstein Observatory and initiated what later became the Chandra X-ray Observatory. In 2002 Giacconi received the Nobel Prize for Physics for his "pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources."

Giacconi had a reputation both in the US and Europe as a strong, some felt too strong, leader who could return AUI to its former prominence, and on 1 July 1999, he became the first president of AUI with a background in astrophysics. Coupled with the fact that, for the first time, AUI had no responsibilities other than NRAO, it meant Giacconi brought a strong hand to his close management of NRAO and its Director Paul Vanden Bout.

At ESO, there were no permanent members of the Scientific Staff, and Giacconi questioned the appropriateness of tenure at NRAO. He expected that all of the scientists should have well-defined "functional" responsibilities, instituted strong project management, and full cost accounting for all NRAO projects. Until his retirement in 2004, Giaconni also played a strong role in the management of ALMA (Sect. 10.7), a project which he helped to initiate while still at ESO.

Giacconi was succeeded as AUI President by his long-time friend and colleague Ethan Schreier, who not only had a background in astronomy, but who had even been a user of the VLA. Schreier took an active role in the US participation in the planning for the international Square Kilometre Array (SKA) (Sect. 11.6), until it became apparent in 2011 that the US would not play a role in the project. In 2017 Adam Cohen, who had been the Deputy Under Secretary for Science and Energy at the US Department of Energy, became the new AUI President. Cohen greatly expanded the AUI corporate office and initiated a number of new scientific, technical, and business initiatives to broaden AUI's purview.

Notes

1. Strictly speaking, Taffy Bowen was not a radio astronomer, but was effectively a member of the international radio astronomy community.
2. NAA-NRAO, DO, Conferences, Symposia, Colloquia.
3. Hagen to Greenstein, 16 August 1954, CITA-LAD, Box 35, Folder 2.
4. See Kellermann and Sheets (1984) and Wilkinson et al. (2004) for reviews of these discoveries.
5. Nomenclature to describe atomic RRLs is given by the name of the element followed by the lower electron energy, followed by Greek letter denoting the number of energy levels involved in the transition.
6. Pawsey to Rabi, 5 October 1961, LOC-IIR, Box 36.
7. Wideband Interferometric Digital Architecture.
8. Carl Borgman, Director of Science and Engineering at the Ford Foundation, reported that 97 to 98 percent of the time on the Palomar 200 inch was used by the Observatory staff, but only 25 percent of the 100 inch time (Edmondson 1997, p. 179).
9. NAA-NRAO, Founding and Organization, Correspondence. Heeschen's notice was published in *Science* (**130**, 1179) and the *AJ* (**64**, 1273), but we have found no record of any publication appearing in *PASP*.
10. The design and construction of the Haystack 120 foot antenna has been described by Weiss (1965). Much of the description given here is taken from this paper.
11. Albert Einstein proposed three tests of his General Theory of Relativity: the precession of Mercury's orbit; the bending of light by the Sun; and the shifting of spectral lines in a gravitational field. In 1965 MIT professor Irwin Shapiro proposed a fourth test resulting from the excess delay of the reflected radar signal from a planet as the signal passes close to the Sun (Shapiro 1964). Using Mercury and Venus as targets when they were near superior conjunction, Shapiro and his colleagues confirmed the delay calculated due to General Relativity (Shapiro et al. 1971).
12. The agency has been variously known as ARPA or DARPA.
13. Further background on the history of the Haystack facility can be found at http://www.haystack.mit.edu/hay/history.html
14. This section is adopted from Altschuler (2002) and Cohen (2009).
15. When using a parabolic reflector, the feed system must remain close to the focal point in order to minimize losses due to aberration.
16. DuBridge to Piore, 9 July 1954, CITA-LAD.
17. Robertson to DuBridge, 19 July 1954, CITA-LAD, Box 35, Folder 2.
18. Montroll to DuBridge, 23 July 1954, CITA-LAD, Box 35, Folder 2.
19. Bacher to Piore, 12 August 1954, CITA-LAD, Box 35, Folder 2.
20. DuBridge to Priori, 21 September 1954, CITA-LAD, Box 35, Folder 2. After the launch of Explorer I, just a few months after the launch of Sputnik, Pickering

led the JPL development of US missions to the Moon and planets for the next two decades.

21. GR to DuBridge, 8 April 1954, CITA-LAD, Box 35, Folder 2.
22. Greenstein to DuBridge, 8 April 1954, CITA-LAD, Box 35, Folder 2.
23. Dubridge to GR, 13 April 1954, CITA-LAD, Box 35, Folder 2.
24. John Bolton's early career at the CSIRO Radiophysics Laboratory, his exile to cloud physics research, his time at the Caltech Owens Valley Observatory, and his return to direct research with Bowen's 210 foot radio telescope are discussed in the book by Peter Robertson (2017).
25. DuBridge to Piore, 21 September1954, CITA-LAD, Box 35, Folder 2.
26. Bowen to DuBridge, 28 September, 1954, CITA-LAD, Box 35, Folder 2.
27. DuBridge to Bolton, 8 October 1954, CITA-LAD, Box 35, Folder 2.
28. See *The Story of Inyo* by W. A. Chalfant (1933) for a descriptive account of the impact to the Owens Valley by the city of Los Angeles.
29. Oral History, Robert Bacher, CITA.
30. Arnold Shostak's son, Seth, studied radio astronomy at Caltech and became one of the first people to recognize that 21 cm observations of the rotation of galaxies suggested presence of more matter than was visible to optical telescopes, which later became known as dark matter. Seth later went on to a prominent career in SETI research and as a well-known spokesman for understanding life in the Universe.
31. During WWII, Wallis had designed bombers and had developed innovative techniques for destroying German dams critical to the war effort. Wallis conceived the concept of an independently mounted small "master equatorial" unit located at the interion of the antenna axes and optically coupled to the telescope.
32. This section on Grote Reber is adapted from Kellermann (2004), with permission from the Astronomical Society of the Pacific.
33. GR to E. H. Hurlburt, 20 February 1967, NAA-GR, Correspondence, General Correspondence.
34. GR Testimony before US Senate Committee on Independent Offices and Department of Housing and Urban Development Appropriations for Fiscal Year 1970, 11 July 1969, NAA-GR, Correspondence, General Correspondence.
35. GR to Connecticut Representative E. Q. D'Addario, 14 July 1966, NAA-GR, Correspondence, General Correspondence.
36. Ibid.
37. In 1959 and 1960 Reber spent time in Green Bank during which he tried to increase the harvest of beans by forcing them to wind in the reverse direction (Reber 1964).
38. One of the current authors (KIK) joined the NRAO scientific staff in 1965 where he remained for 52 years.
39. WEH III to KIK, 2 April 2012, NAA-KIK, Open Skies, Chapter 6.
40. Ibid.
41. DSH, 12 June 1992, NRAO Internal Symposium, Green Bank, WV, NAA-DSH, Radio Astronomy History, US Radio Astronomy, Undated talks.
42. DSH to Keith Glennan, 22 November 1967, NRAO-DO, Organizational Charts and Memos, 1958–2012.
43. https://ngvla.nrao.edu/

Bibliography

References

Altschuler, D.R. 2002, The National Astronomy and Ionospheric Center's (NAIC) Arecibo Observatory in Puerto Rico. In ASPC **278**, *Single–Dish Radio Astronomy: Techniques and Applications*, ed. S. Stanimirovic et al. (San Francisco: ASP), 1

Baars, J.W.M. 1966, Reduction of Tropospheric Noise Fluctuations at Centimetre Wavelengths, *Nature*, **212**, 494

Backer, D.C. et al. 1982, A Millisecond Pulsar, *Nature*, **300**, 615

Balick, B. and Brown, R.L. 1974, Intense Sub-Arcsecond Structure in the Galactic Center, *ApJ*, **194**, 265

Bennett, C.L. et al. 2003, Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations, *ApJS*, **208**, 20

Bridle, A.H. et al. 1972, Flux Densities, Positions, and Structures for a Complete Sample of Intense Radio Sources at 1400 MHz, *AJ*, **77**, 405

Chalfant, W.A. 1933, *The Story of Inyo* (Chicago: The Author)

Cheung, A.C. et al. 1968, Detection of NH^3 Molecules in the Interstellar Medium by Their Microwave Emission, *Phys. Rev. Lett.*, **21**, 1701

Cheung, A.C. et al. 1969, Detection of Water in Interstellar Regions by its Microwave Radiation, *Nature*, **221**, 626

Clark, B.G. 1965, An Interferometric Investigation of the 21-centimeter Hydrogen-Line Absorption, *ApJ*, **142**, 1398

Clark, B.G. et al. 1962, The Hydrogen Line in Absorption, *ApJ*, **135**, 151

Clark, B.G. and Kuzmin, A. 1965, The Measurement of the Polarization and Brightness Distribution of Venus at 10.6-CM Wavelength, *ApJ*, **142**, 23

Cohen, M.H. 2009, Genesis of the 1000-Foot Arecibo Dish, *JAHH*, **12**, 141

Dent, W.A. 1965, Variation in the Radio Emission of 3C273, *Science*, **148**, 1458

Dent, W.A. and Haddock, F.T. 1965, A New Class of Radio Source Spectra, *Nature*, **205**, 487

Ekers, R.D. 2013, The History of the Square Kilometre Array (SKA) Born Global, In *Resolving the Sky – Radio Interferometry: Past, Present, and Future*, ed. M.A. Garrett and J.C. Greenwood (Manchester: SKA Organization), 68

Edmondson, F. 1997, *AURA and Its US National Observatories* (Cambridge: CUP)

Ellis, G. et al. 1987, Low-Frequency Radioastronomical Observations During the Spacelab 2 Plasma Depletion Experiment, *Austr. J. Phys.*, **24**, 56

Findlay, J.W. 1972, The Flux Density of Cassiopeia A at 1440 MHz and its Rate of Decrease, *ApJ*, **174**, 527

Fisher, J.R. and Bradley, R.F. 2000, Full-Sampling Array Feeds for Radio Telescopes, *Proc. SPIE*, **4015**, 308

Fomalont, E.B. et al. 1964, Accurate Right Ascensions for 226 Radio Sources, *ApJ*, **69**, 772

Fomalont, E.B. and Sramek, R.A. 1975, A Confirmation of Einstein's General Theory of Relativity by Measuring the Bending of Microwave Radiation in the Gravitational Field of the Sun, *ApJ*, **199**, 749

Gordon, M.A. 2005, *Recollections of Tucson Operations* (Dordrecht: Springer)

Gordon, W.E. et al. 1961, The Design and Capabilities of an Ionospheric Radar Probe, *Trans. IRE*, **AP-9**, 17

Heeschen, D.S. 1961a, Observations of Radio Sources at Four Frequencies, *ApJ*, **133**, 322
Heeschen, D.S. 1961b, Secular Variation of the Flux Density of the Radio Source Cassiopeia A, *Nature*, **190**, 705
Heeschen, D.S. 1964, A Radio Survey of Galaxies, *AJ*, **69**, 277
Heeschen, D.S. 1968, Radio Properties of Elliptical Galaxies NGC 1052 and NGC 4278, *ApJ*, **151**, L35
Hjellming, R. and Wade, C.M. 1971, Radio Stars, *Science*, **197**, 173
Hogg, D.E. 1966, Radio Emission from a Number of Possible Supernovae Remnants, *ApJ*, **144**, 819
Hogg, D.E. et al. 1969, Syntheses of Brightness Distribution in Radio Sources, *AJ*, **74**, 1206
Hogg, D.E. 2006, Selecting and Scheduling Observing Proposals at NRAO Telescopes. In *Organizations and Strategies in Astronomy Vol. 7*, ed. A. Heck (Dordrecht: Springer), 181
Höglund, B. and Mezger, P.G. 1965, Hydrogen Emission Line n_{110} to n_{109}: Detection at 5009 MHz in Galactic H II Regions, *Science*, **150**, 339
Jarosik, N. et al. 2003, Design, Implementation, and Testing of the MAP Radiometers, *ApJS*, **145**, 413
Kardashev, N.S. 1959, On the Possibility of Detection of Allowed Lines of Atomic Hydrogen in the Radio-Frequency Spectrum, *Astron. Zh.*, **36**, 838. English translation in *SvA*, **3**, 813
Kellermann, K.I. 2004, Grote Reber (1911–2002), *PASP*, **116**, 703 https://doi.org/10.1086/423436
Kellermann, K.I. and Pauliny-Toth, I.I.K. 1968, Variable Radio Sources, *ARAA*, **6**, 417
Kellermann, K.I. and Pauliny-Toth, I.I.K. 1969, The Spectra of Opaque Radio Sources, *ApJ*, **155**, L71
Kellermann, K.I. et al. 1969, The Spectra of Radio Sources in the Revised 3C Catalogue, *ApJ*, **157**, 1
Kellermann, K.I. et al. 1977, The Small Radio Source at the Galactic Center, *ApJL*, **214**, 61
Kellermann, K.I. and Sheets, B. eds. 1984, *Serendipitous Discoveries in Radio Astronomy:* (Green Bank: NRAO/AUI)
Kraus, J.D. 1995, *Big Ear Two* (Powell: Cygnus-Quasar Books)
Lorimer, D. et al. 2007, A Bright Millisecond Radio Burst of Extragalactic Origin, *Science*, **318**, 777
Lovell, A.C.B. 1987, *Voice of the Universe: Building the Jodrell Bank Telescope* (New York: Praeger)
Maltby, P. and Moffet, A.T. 1962, Brightness Distribution in Discrete Radio Sources. III. The Structure of the Sources, *ApJS*, **7**, 141
Maltby, P., Matthews, T.A., and Moffet, A.T. 1963, Brightness Distribution in Discrete Radio Sources IV. A Discussion of 24 Identified Sources, *ApJ*, **137**, 153
McClain, E.F. 1966, A High-Precision 85-foot Radio Telescope, *S&T*, **32** (7), 4
Minkowski, R. 1960, A New Distant Cluster of Galaxies, *ApJ*, **132**, 908
Morris, D. et al. 1964, On the Measurement of Polarization Distribution over Radio Sources, *ApJ*, **139**, 55
Pauliny-Toth, I.I.K. et al. 1966, Positions and Flux Densities of Radio Sources, *ApJS*, **13**, 65

Pauliny-Toth I.I.K. and Kellermann, K.I. 1966, Variations in the Flux Densities of Radio Sources *AJ*, **71**, 1
Pettengill, G.H. and Dyce, R.B. 1965, A Radar Determination of the Rotation of the Planet Mercury, *Nature*, **206**, 1240
Pospieszalski, M.W. et al. 1988, FETs and HEMTs at Cryogenic Temperatures – Their Properties and Use in Low-Noise Amplifiers, *IEEE Tr. Microwave Theory and Tech*, **MTT-36**, 552
Read, R.B. 1963, Accurate Measurement of the Declinations of Radio Sources, *ApJ*, **138**, 1
Reber, G. 1964, Reversed Bean Vines, *Journal of Genetics*, **59**, 37
Reber, G. 1966, Ground Based Astronomy: The NAS 10-Year Program, *Science*, **152**, 150
Reber, G. and Ellis, G.R. 1956, Cosmic Radio-Frequency Radiation near One Megacycle, *J. Geophys. Res.*, **61**, 1
Reber, G. and Ellis, G.R. 1968, Cosmic Static at 144 Meters Wavelength, *J. Franklin Inst.*, **285**, 1
Rinsland, C.P., Dixon, R.S., and Kraus, J.D. 1975, Ohio Survey Supplement 2, *AJ*, **80**, 759
Roberts, M.S. and Whitehurst, R. 1975, The Rotation Curve and Geometry of M31 at Large Galactocentric Distances, *ApJ*, **201**, 327
Robertson, P. 1992, *Beyond Southern Skies – Radio Astronomy and the Parkes Telescope* (Cambridge: CUP)
Robertson, P. 2017, *Radio Astronomer – John Bolton and a New Window on the Universe* (Sydney: NewSouth Publishing)
Roshi, A. et al. 2018, Performance of a Highly Sensitive, 19-element, Dual-polarization, Cryogenic L-band phased-array Feed on the Green Bank Telescope, *AJ*, **155**, 202
Schmitt, J.L. 1968, BL Lac Identified as a Radio Source, *Nature*, **218**, 663
Shapiro, I.I. 1964, Fourth Test of General Relativity, *Phys. Rev. Lett.*, **13**, 789
Shapiro, I.I. et al. 1971, Fourth Test of General Relativity: New Radar Result, *Phys. Rev. Lett.*, **26**, 1132
Shklovsky, I.S. 1960, Secular Variation in the Flux and Intensity of Radio Emission from Discrete Sources, *AZh*, **37**, 256
Swenson, G.W. 1986, The Illinois 400-ft Radio Telescope, *IEEE Ant. Prop. Newsletter*, **28** (6), 13
Taylor, J.H. et al. 1979, Measurements of General Relativistic Effects in the Binary Pulsar PSR1913+16, *Nature*, **277**, 437
Townes, C.H. 1946, The Ammonia Spectrum and Line Shapes Near 1.25 cm Wave-Length, *Phys. Rev.*, 7**0**, 665
Townes, C.H. 1957, Microwave and Radio-Frequency Lines of Interest to Radio Astronomy. In *IAU Symposium No. 4, Radio Astronomy*, ed. H.C. van de Hulst (Cambridge: CUP), 92
Townes, C.H. and Merritt, F.R. 1946, Water Spectrum Near One-Centimeter Wave-Length, *Phys. Rev.*, **70**, 558
van de Hulst, H.C. 1945, Origin of Radio Waves from Space, *Nederlandsch Tijdschrift voor Natuurkunde*, **11**, 210. English translation in Sullivan, W.T. III 1982, *Classics in Radio Astronomy* (Cambridge: CUP), 302
von Hoerner, S. 1964, Lunar Occultations of Radio Sources, *ApJ*, **140**, 6
Wade, C.M. 1970, Precise Positions of Radio Sources. I. Radio Measurements, *ApJ*, **162**, 381
Weinreb, S. 1961, Digital Radiometer, *Proc. IRE*, **49**, 1099

Weinreb, S. 1963, *A Digital Spectral Analysis Technique and its Application to Radio Astronomy*, PhD Dissertation, Massachusetts Institute of Technology
Weinreb, S. and Kerr, A.R. 1973, Cryogenic Cooling of Mixers for Millimeter and Centimeter Wavelengths, *IEEE J. Solid-State Circuits*, **8**, 58
Weiss, H.G. 1965, The Haystack Microwave Research Facility, IEEE Spectrum, February, 50
Whitford, A. 1964, *Ground-based Astronomy: A Ten Year Program* (Washington: National Academy of Sciences)
Wilkinson, P.N. et al. 2004, The Exploration of the Unknown. In *Science with the Square Kilometre Array*, ed. C. Carilli and S. Rawlings (Amsterdam: Elsevier), 1551
Wolszczan, A. and Frail, D. 1992, A Planetary System Around the Millisecond Pulsar, *Nature*, **355**, 145
Zwicky, F. 1933, Die Rotverschiebung von Extragalaktischen Nebeln, *Acta Helvetica Physica*, **6**, 1102

Further Reading

Berge, G.L. and Seielstad, G.A. 1967, New Determinations of the Faraday Rotation for Extragalactic Radio Sources, *ApJ*, **148**, 367
Berge, G.L. and Seielstad, G.A. 1969, Polarisation Measurements of Extragalactic Radio Sources at 3.12 cm Wave-Length, *ApJ*, **157**, 35
Burke, B.F. 2003, Early Years of Radio Astronomy in the U.S. In *Radio Astronomy from Karl Jansky to MicroJansky*, ed. L.I. Gurvits et al. (France: EDP Sciences), 27
Cohen, M.H. 1994, The Owens Valley Radio Observatory: The Early Years, *Engineering and Science*, **57** (3), 8
Cohen, M.H. 2007, A History of OVRO: Part II, *Engineering and Science*, **70** (3), 33
Giacconi, R. 2008, *Secrets of the Hoary Deep: A Personal History of Modern Astronomy* (Baltimore: Johns Hopkins University Press)
Goddard, D.E. and Milne, D.K. eds. 1994, *Parkes: Thirty Years of Radio Astronomy* (Melbourne: CSIRO)
Graham-Smith, F. 2003, The Early History of Radio Astronomy in Europe. In *Radio Astronomy from Karl Jansky to MicroJansky*, ed. L.I. Gurvits et al. (France: EDP Sciences), 1
Kellermann, K.I. 1996, John Gatenby Bolton (1922-1993), *PASP*, **108**, 729
Kraus, J. 1963, The Large Radio Telescope at Ohio State University, *S&T*, **26** (1) 12
Leverington, D. 2017, *Observatories and Telescopes of Modern Times* (Cambridge: CUP)
Lockman, F.J., Ghigo, F.D., and Balser, D.S. eds. 2007, *But It Was Fun* (Green Bank: NRAO/AUI)
Lovell, A.C.B. 1985, *The Jodrell Bank Telescopes* (Oxford: Oxford University Press)
Lovell, A.C.B. 1990, *Astronomer by Chance* (New York: Basic Books)
Munns, D.P.D. 2013, *A Single Sky* (Cambridge: MIT Press)