CHAPTER 4

Growing Pains

The search for the director of NRAO turned out to be unexpectedly difficult, as various astronomers turned down offers, citing the remoteness of the Green Bank site and the need to give up their own research programs. Finally, in 1959, Otto Struve, a distinguished optical astronomer and member of AUI's Search Committee, agreed to take on the job. But in 1961 both he and AUI President Lloyd Berkner resigned. I.I. Rabi, the new AUI President, appointed Australian Joe Pawsey as NRAO director, but due to a fatal illness he never served, and in 1962, Dave Heeschen became the new NRAO Director.

The initial intent of the founders was that NRAO would build a very large antenna of the order of 600 feet in diameter. But in order to gain operating experience while the large antenna was being designed and constructed, AUI decided to first build an intermediate size dish, about 150 feet in diameter, which they thought could be easily and quickly constructed. Contentious arguments about the mounting and operating wavelength finally led to a contract to build a 140 foot equatorially mounted telescope with what turned out to be unrealistically optimistic cost estimates and time schedules. An uncertain funding schedule, poor design, use of faulty materials, contractor strikes, and management by committee, led to numerous delays and cost overruns which threatened the continued existence of the new radio observatory. To maintain its viability, NRAO first purchased a commercial 85 foot radio telescope, then built a 300 foot transit antenna which was limited to observations at relatively long wavelengths. Under Heeschen's leadership, problems were painstakingly solved and the 140 Foot Telescope was finally completed in 1965 at a cost of \$14 million, three times the initially budgeted cost. With both the 300 and 140 Foot Telescopes operational, NRAO was finally able to fulfill its role as a national radio astronomy center for visiting scientists.

However, living and working in rural Green Bank proved a challenge for the NRAO staff and their families. In 1965, much of the scientific and engineering

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staff moved to the new NRAO headquarters in Charlottesville, Virginia, which greatly changed the sociology of the Observatory.

4.1 Finding a Director

As early as 1955, Merle Tuve urged Lloyd Berkner to appoint a director for the new radio astronomy facility, but Berkner correctly pointed out that it would be difficult to recruit someone until AUI and NSF agreed on a contract and operating procedures. In early 1956, the AUI Steering Committee informally discussed the choice of director. Bart Bok was the overwhelming favorite, with John Hagen second. Berkner wanted someone with more radio astronomy experience, and approached Hagen to be Director of the radio astronomy facility and Bart Bok to be the Principal Scientist.[1] Hagen, however, had just accepted the Vanguard job (Sect. 3.3). Bok was considering an opportunity to go to Australia to head the Mt. Stromlo Observatory and did not consider Berkner's inquiry as a formal offer. In July 1956, hoping to defuse the issue of choosing a director for the radio astronomy facility, Waterman again approached Bok, asking if he might not change his mind about going to Australia and instead become the director. According to Bok, his reply was, "NUTS," and that he was very happy with his decision to go to Australia.[2]

After he learned that the National Science Board would select AUI as the manager of the new Radio Astronomy Observatory, Berkner realized the need to name a director who would "partake in the formation of policies and plans for the Observatory and play a major role in the technical decisions," and he wrote to Donald Menzel for his assistance. Berkner asked Menzel to form "an ad hoc nominating committee" to "nominate a panel of not less than three and preferably five individuals," and "take into account the ages and known commitments of possible Directors."[3] Berkner did not hesitate to express his own views on the qualities of the NRAO Director, stating that "in my personal opinion, the Director should be a US citizen." Somewhat optimistically, Berkner speculated that by the start of 1957, AUI "will already have bids for the construction of the 140-foot telescope and it is probable that a compromise between costs, altazimuth /equatorial mounts, surface and control tolerances, and similar factors may be necessary," so he saw the need to act quickly. He asked Menzel to provide nominations in time for the AUI Trustees Executive Committee meeting scheduled for 15 November 1956. Berkner appreciated that "in the temporary absence of a public announcement of AUI's future involvement, it is not proper that AUI openly take steps toward the selection of the Director" and cautioned Menzel that "it seems necessary that the matter be held closely."

Menzel wrote to Ira Bowen, C.D. Shane, W.W. Morgan, Otto Struve, and Jerry Wiesner to solicit their participation in a search committee to choose a director.[4] In his initial letter, Menzel stated, "It is for us to determine … whether this director should be primarily an astronomer or primarily a radio engineer." He then went on to express his view that, "Certainly, direction of the scientific program, in the long run, is more important than the ability to design electronics." The Committee debated the relative merits of previous research accomplishments, understanding of electronics, experience in radio astronomy, executive experience, good judgement, personality, and age. They noted that the most qualified individuals, such as Taffy Bowen, Joe Pawsey, and R. Hanbury Brown were not American citizens, but Menzel cautioned that, "the justification for support by the National Science Foundation was the need of American astronomers for the radio facility. It would look mighty queer, if among American astronomers, we could not find someone with proper qualifications."[5]

Bart Bok again clearly emerged as the top candidate and was formally approached by Menzel, who reported "His answer was definite and direct" that his commitment to Australia was firm.[6] Having a traditional background in astronomy, while initiating and leading what was then the pre-eminent US university radio astronomy program and training a new generation of radio astronomers, Bok was clearly uniquely qualified for the job. Had a formal offer from AUI been made earlier, most likely Bok would have accepted. As evidenced by his July 1956 letter to Tuve,[7] he was clearly interested, but again, Bok reiterated that he had made a commitment to go to Australia which he intended to honor.[8]

Just a week before the signing of the AUI-NSF contract, after several mail ballots and exchanges of letters commenting on the various candidates, the Search Committee met at AUI's New York offices on 12 November 1956 to consider 26 names. The Committee recognized that the top leadership should include both an astronomer and someone skilled in radio astronomy instrumentation. Their report stated that if the choice of director was an astronomer, then the second position should go to "someone in the electronics field" and "if the top post went to a physicist … or engineer … the appointment of an astronomer to the second position was imperative."[9] Leo Goldberg, director of the University of Michigan Observatory, emerged as the unanimous choice for NRAO Director.

In order to induce Goldberg to accept the appointment, AUI offered him a generous salary, a liberal allowance to spend at least one month every year at some other institution, and a semester leave every fourth year. But Goldberg declined, citing the loss of research opportunities and the freedom which he enjoyed in a university position.[10] Ironically, 15 years later, Goldberg would become Director of the National Optical Astronomy Observatory, which had its own broad range of administrative and operational problems. Albert Whitford from the University of Wisconsin was the Committee's second choice, but he delayed responding to Berkner's offer. Finally, after several months, following pressure to reply from Leeland Haworth, Brookhaven Director and an AUI Trustee, Whitford also declined. Jesse Greenstein and Fred Whipple were close alternates, and were followed by Charles Townes, Horace Babcock, and John Hagen in another close group. Greenstein declined the offer citing the remoteness of Green Bank and the loss of opportunities for personal research.[11] Charlie Townes received strong support from Greenstein himself as well as the East Coast scientists on the committee, but he was not well known by the West Coast astronomers, Bowen, Struve, and Shane. Berkner apparently gave serious consideration to offering Townes the directorship but there is no record that he ever actually discussed the possibility with Townes.

At the time the AUI contract was signed with the NSF in November 1956, AUI had not yet identified a director. Under pressure from the NSF, Berkner declared himself "Acting Director," although he probably assumed that this would be for only a short term. The AUI Advisory Committee and the Trustees repeatedly declared that "the appointment of a Director is the most important problem to be solved by the corporation."[12] By early 1959, with no solution in sight, the several Trustees conferred among themselves and suggested to Berkner that Otto Struve might consider an appointment as NRAO Director. Struve had been brought in as an at-large Trustee in response to the agreement to broaden the AUI Board to include expertise in astronomy and astrophysics. Following consultation with the NSF and NRAO senior staff, at their 17 April 1959 meeting, the AUI Board appointed Otto Struve (Fig. 4.1) as NRAO Director and Vice President of AUI, effective 1 July 1959.

Otto Struve came from a long line of famous astronomers and observatory directors, and was then a Professor of Astronomy and Director of the Leuschner Observatory at the University of California. Before that he had been the long-time Director of the Yerkes Observatory and editor of *The Astrophysical Journal*. He had an outstanding reputation as a scientist for his contributions to

Fig. 4.1 Otto Struve, NRAO Director from 1 July 1959 to 1 December 1961. Credit: NRAO/AUI/NSF

astrophysics, particularly in stellar spectroscopy and stellar variability. He served as President of the American Astronomical Society from 1947 to 1950 and as President of the International Astronomical Union from 1952 to 1955. He was a strong supporter of the effort to establish a national optical astronomy observatory, and in 1954, he became a member of the NSF Advisory Panel for Astronomy.

Struve was also an experienced and accomplished science administrator. As Director of the Yerkes Observatory, he recruited an outstanding staff including Subrahmanyan Chandrasekhar, Jesse Greenstein, Gerard Kuiper, and Bengt Stromgren, and also attracted such distinguished visitors as Jan Oort, Pol Swings, and Henk van de Hulst. While still Yerkes Director, Struve established the McDonald Observatory in Texas, and served simultaneously as the Director of both Observatories. As a member of the AUI Board of Trustees he had taken an active interest in the affairs of the Observatory. Struve was not a radio astronomer, but he had a history of association with radio astronomy and radio astronomers. He had tried to help Grote Reber transfer his Wheaton dish to a more suitable site in Texas in the 1940s, and sought an appointment for Reber at the University of Chicago. As early as 1953 he had written to Greenstein about the need for better instrumentation for radio astronomy (DeVorkin 2000, p. 82). While at Berkeley, he helped Harold Weaver initiate a radio astronomy program and hired Ron Bracewell to teach a course in radio astronomy in the 1954–1955 academic year.

Even earlier, Struve (1940) wrote, "that the small astronomical observatory is compelled to search for something that it is able to do, instead of doing what is scientifically important and interesting." And he went on to advocate a cooperative approach to observational astronomy to provide telescope access to astronomers, especially young astronomers and students, who were at institutions without good instruments and with poor skies. Struve was known as a strong supporter of what later became to be known as "big science," and had the right background and philosophy to lead NRAO. Most importantly, he brought a lot of prestige to NRAO at a time when it was badly needed.

As had happened earlier at Brookhaven (Sect. 3.1), AUI management was unwilling to delegate authority to their new NRAO Director. Responsibility for the 140 Foot construction remained with AUI, which expected Struve to concentrate on operation of the NRAO radio telescopes, overseeing the scientific program at Green Bank, and recruiting the scientific and engineering staff needed to carry out the NRAO mission as a radio observatory for visiting scientists. Struve agreed to this split of responsibility between AUI and NRAO, feeling it would give him more opportunity to concentrate on scientific matters, but according to Heeschen,[13] he later regretted this decision.

Shortly after he became NRAO Director in the summer of 1959, Struve (1960) had already noted that NRAO was a national observatory in name only, and that there were more powerful facilities available elsewhere. Especially concerned about the isolation of Green Bank, he explained to the AUI Board that unless NRAO were to expand substantially, "Green Bank will become simply one of about a dozen observatories working in the field of radio astronomy," and added that both Caltech and Cornell looked more attractive to a scientist wishing to work in radio astronomy. He was supported by Board member Carl Seyfert who added that NRAO "should not be just one of a number of generally similar institutions."[14] Struve also cautioned Heeschen and other senior NRAO staff that, "NRAO is rapidly becoming one of many radio-observatories, some of which are better equipped than our own. I sense that even now the NRAO does not provide enough of an incentive for many visiting astronomers. If I were a young astronomer, I should be equally attracted by research opportunities at Stanford, Cal Tech [*sic*], Cornell, Illinois, and several others. Perhaps this is what the U.S.A. really needs; but if so, the original purpose of NRAO is not being met. My feeling is that an enormous amount of very clever thinking by many able physicists and astronomers has resulted in the invention and construction of a wide variety of excellent, but very expensive instruments."[15]

Unfortunately, Struve's short tenure as NRAO Director was marred by his conflict with AUI, and especially AUI President I.I. Rabi, over issues surrounding the 140 Foot Telescope construction, his continued attention to his research and publication on matters unrelated to NRAO, and by his declining health, due in part to wounds and multiple diseases acquired during WWI and then during the Russian Civil War when he served as an artillery and cavalry officer, first in the Russian then in the White Army.

4.2 Getting Started

Following the signing of the contract with the NSF in November 1956, the AUI Board established the new Advisory Committee for Radio Astronomy, which replaced the old Steering Committee.[16] To oversee the effort of building the Observatory in Green Bank, AUI established an office in Marlinton, a 45-minute drive and some 25 miles to the south of Green Bank. The Marlinton office was shared with the Army Corps of Engineers, who were charged with obtaining the land rights in Green Bank. The first office in Green Bank was opened on 14 May 1957. Initially, the NRAO staff included four people: Dick Emberson and his secretary Mary Beth Fennelly, John Carrol, an engineer working on the design of the 140 Foot Telescope, and Dave Heeschen (2008) (Fig. 4.2). Heeschen and Edward Lilley were the senior radio astronomy students in Bart Bok's radio astronomy group at Harvard, and the first to receive a PhD in radio astronomy at a US university. Following a year spent as an instructor at Wesleyan University in Middletown, Connecticut, Heeschen returned to Harvard as a Lecturer and Research Associate. While still at Harvard, encouraged by Bart Bok, he became a consultant to Dick Emberson at AUI, attended meetings of the AUI Steering Committee, and participated in the December 1955 NRAO site search. On 1 July 1956, four months before the NSF awarded the contract to AUI, Dave Heeschen accepted a full-time appointment with AUI in the office of the President, and then became the first member of the NRAO scientific staff.

Fig. 4.2 David S. Heeschen, NRAO Acting Director from 1 December 1961 to 19 October 1962; NRAO Director from 19 October 1962 to 1 October 1978. Credit: NRAO/AUI/NSF

John Findlay was the next person to join the NRAO staff. During WWII, Findlay had served in the Royal Air Force, where he supervised the installation of radar stations throughout North Africa, the Middle East, and South East Asia. Following his undergraduate education at Cambridge, Findlay started his academic career as a PhD student working for Lord Rutherford, who unfortunately died a few months after Findlay arrived in Cambridge in 1937, although according to Findlay there was no connection between these two events.[17] After two years of research in ionospheric physics under Jack Ratcliffe, Findlay became involved in the development of radar, during which time he met and got to know Martin Ryle. Following the War, Findlay led a radar development group in Britain and did research in ionospheric physics at Cambridge University. In 1952, he spent time at the Carnegie Institution Department of Terrestrial Magnetism, where he first met Merle Tuve and Lloyd Berkner, who were at the forefront of American ionosphere research. While working at the Ministry of Supply in Great Britain, under pressure from his American wife to return to the United States, Findlay wrote to Berkner and others asking about employment possibilities in the United States. Having just obtained the NSF contract to study the feasibility of establishing a new radio astronomy facility in the United States, Berkner offered Findlay a job to help establish the observatory, and at the end of 1956 he joined Berkner, Dick Emberson, and Dave Heeschen at the AUI offices on the 72nd floor of the Empire State Building in New York City.

Heeschen and Findlay were soon followed by other Harvard graduates, first by Frank Drake, later by Jack Campbell,[18] William E. Howard III, May Kaftan-Kassim from Iraq, T. K. Menon from India, and Campbell Wade, and they

Fig. 4.3 Early NRAO staff. Left to right from the top: John Findlay, Frank Drake, Cam Wade, Hein Hvatum, Sebastian von Hoerner, Frank Low, Dave Hogg, Sandy Weinreb, Ken Kellermann, Barry Clark, Mort Roberts, Bill Howard. Credit: NRAO/AUI/NSF

formed the core of the early NRAO scientific staff (Fig. 4.3). When asked why the early staff was all from Harvard, Heeschen explained that he was unable to recruit anyone else, but acknowledged that he had not tried to attract any of the then-recent Caltech graduates such as Alan Moffet or Robert Wilson.[19]

One of AUI's first tasks was to activate some sort of instrument, as the West Virginia Zoning Act grandfathered any source of interference existing before the Observatory went into operation. Working out of a small house in Green Bank that had been taken over by the US Army Corps of Engineers, and using equipment on loan from NRL, Heeschen, together with NRL's Ed McClain and Ben Yaplee, built a simple 30 MHz interferometer. It consisted of two half wave dipoles and a Hallicrafter's communications receiver, and they used it to observe the Sun on 25 and 26 October 1956. Although these observations occurred a few weeks before the signing of the actual contract between NRAO and the NSF and a year before the official 17 October 1957 NRAO dedication, this became the first radio astronomy observation made from the

Fig. 4.4 Dedication of NRAO in Green Bank, 17 October 1957. Left to right: Richard Emberson, Lloyd Berkner, G. Nay, John Findlay, Ned Ashton, Dave Heeschen, and H. Hockenberry, with a model of the planned 140 Foot Telescope. Credit: NRAO/AUI/NSF

Green Bank site.[20] A year later, John Findlay resurrected this simple interferometer to record the radio transmissions from the Russian Sputnik spacecraft.

In July 1957, three months before the official dedication of NRAO, Findlay and Heeschen moved to West Virginia to begin the task of building the Observatory. Six months later they were joined by Frank Drake. By this time, the Observatory had moved its offices from Marlinton to Green Bank. The formal groundbreaking and dedication of the Observatory, which took place on 17 October 1957, appears to be the first use of the name "National Radio Astronomy Observatory"[21] (Fig. 4.4). Prior to that time, AUI and NSF referred to the "radio astronomy project," "radio astronomy facility," or "radio astronomy observatory." Indeed, the concept of a truly "national" observatory remained somewhat contentious, at least until the actual dedication, when it became known as the "National Radio Astronomy Observatory." Although 17 October was billed as the "groundbreaking," actual construction work on the site had begun earlier with the building of roads, sewers, wells, and the preparation of the sites for the 85 foot and 140 Foot Radio Telescopes.

The day before the dedication, the AUI Advisory Committee met with a number of the visiting radio astronomers to discuss their observing plans for the soon to be completed 85 foot and 140 Foot Radio Telescopes. Emphasis was on solar and 21 cm work, but several participants also mentioned studies of H II regions, planets, and accurate source positions. Two participants indicated they were setting up new radio astronomy groups at the University of Virginia and the University of Pennsylvania that would be based on use of the Green Bank instruments, and they expected to hire radio astronomers to exploit these opportunities. Anticipating the future use of maser amplifiers, Charles Townes pointed out the need for accommodating receivers cooled by liquid helium or nitrogen at the antenna focus.

In November 1957, Heeschen laid out a detailed plan for the Observatory. Based on planned starting dates for scientific observing of 1 September 1958 for the 85 foot telescope and 1 January 1960 for the 140 Foot, Heeschen outlined the expected growth of the scientific, technical, business, and supporting staffs, which he projected would reach 55 to 62 persons by mid-1960.[22] In a separate document, he described his views on how the NRAO should be organized, pointing out NRAO's multiple responsibilities: to provide equipment and aid for visiting scientists, to anticipate the need for future developments in radio astronomy, to play a leading role in developing new instrumentation, to provide absolute flux density measurements, and to be a source of national standards for radio astronomy. He outlined a comprehensive research philosophy that guided the growth of NRAO for the next half century. There would be no "Observatory Program," but each staff member should expect to carry out their own independent research in their particular field of interest, and the staff would share the obligations of the Observatory in equipment development, long range planning, calibration, and assisting visitors.[23] At the same time, NRAO laid out a site development program that would accommodate the 85 foot and 140 foot antennas as well as the "very large antenna" that was expected "in the next four or five years." Buildings were planned to accommodate "an outstanding scientific staff, both permanent and visiting, … an equally competent … engineering and technical staff," along with "the minimum auxiliary and supporting staff and equipment necessary to manage and maintain the site." With enviable optimism as to the staff requirements, as well as construction schedules, the site plan including the need for three radio astronomers to support the 85 foot telescope by 1 July 1958, three more by 1 July 1960 to support the 140 Foot, and a total of nine by the time "the very large antenna is constructed in late 1961."[24]

4.3 The 85 Foot Tatel Radio Telescope (aka 85-1)

Recognizing that the 140 Foot Telescope would take some time to construct, and needing to get established with an observational capability, the initial plan for NRAO called for the quick construction of a more modest sized instrument of 60 foot diameter, presumably to be modeled after the Harvard 60 foot radio telescope. However, Heeschen became aware of a commercially designed, equatorial mounted 85 foot diameter antenna that the Blaw-Knox Corporation was building for the University of Michigan. NRAO determined that a copy could be built in Green Bank for $255,730, or well within the budgeted $310,000. On 1 October 1957, two weeks before the Observatory groundbreaking, AUI signed a contract with Blaw-Knox to construct an 85 foot radio telescope.

The conceptual design of the Blaw-Knox 85 foot antennas was initially developed by DTM scientist Howard Tatel for the DTM 60 foot radio telescope. Unfortunately, Tatel died before the antenna could be constructed, and the detailed engineering design was completed by Blaw-Knox engineer Robert (Bob) Hall, who would later play major roles in the design and construction of future NRAO antennas, including the 300 Foot Green Bank transit telescope, the Tucson 36 foot mm telescope, and, finally, the 100 meter Green Bank Telescope. There was no specified delivery date in the AUI contract, although Blaw-Knox had initially claimed that 15 July 1958 "was easily in reach." As Bob Hall preferred to work by himself, the design took longer than planned, but he anticipated that the lost time could be made up during fabrication. However, in an effort to reduce their expenses, Blaw-Knox laid off half their factory workers and went from two daily shifts to one. Worried that they also might be laid off when the jobs were complete, the remaining crew slowed their work, while the unions forbad any overtime when the plant had just laid off a shift.[25] The delivery date slipped to 1 October 1958. Apparently confident of the October date, AUI scheduled a dedication timed to coincide with previously scheduled Green Bank meetings of the AUI Board and the NRAO Advisory Committee.

The dedication of the 85-1 antenna, as it later became known at NRAO, took place as planned on 16 October 1958, just a year after the dedication and groundbreaking of the Observatory, and it was formally named "The Howard E. Tatel Radio Telescope" (Fig. 4.5). Although Michigan had ordered their 85 foot antenna before NRAO, for reasons the authors have been unable to determine, Blaw-Knox delivered the first dish to Green Bank. Since the wiring and instrument installation by Blaw-Knox contractors and NRAO staff was not yet complete, the Green Bank antenna was not available for use until four months later, seven months behind the original schedule. This was "a source of considerable embarrassment" to NRAO and AUI, which had planned observing programs by visitors and staff to begin in the summer, with the intention of announcing results at the forthcoming Paris Symposium on Radio Astronomy (30 July–6 August 1958) and at the triennial International Astronomical Union meeting in Moscow (12–20 August 1958).[26]

The initial observations with the Tatel Telescope, which marked the beginning of the first real research capability at NRAO, took place on 13 February 1959. Even then, the antenna failed to meet many of the performance specifications, and there were still serious deficiencies in the structure which needed fixing, including loose bolts, leaking lubricant, gear misalignment, excessive backlash, and the need to replace the feed support structure. Nevertheless, in view of the already scheduled observing programs, it was agreed that the

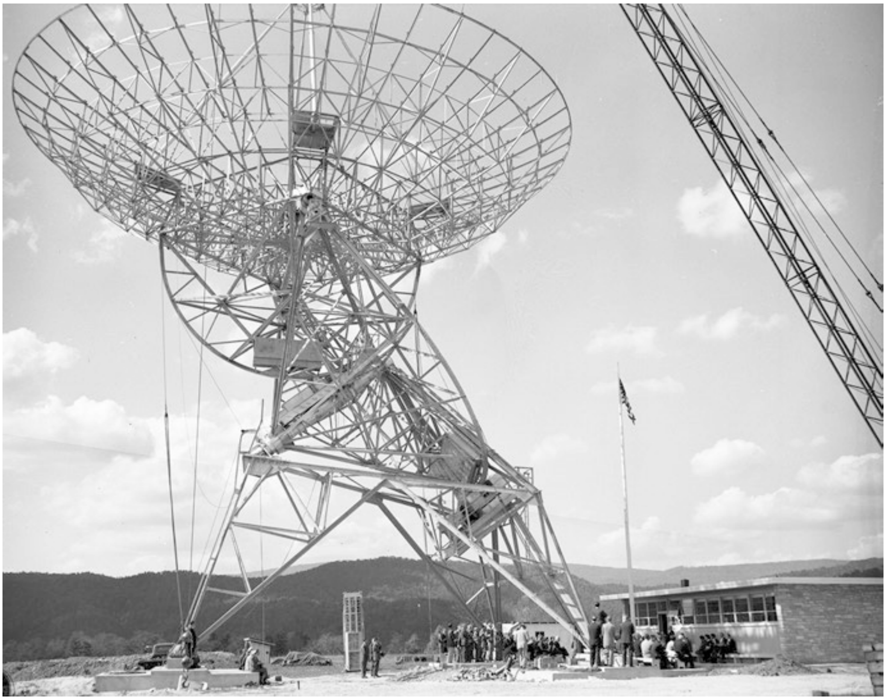

Fig. 4.5 Dedication of the 85 Foot Howard E. Tatel Telescope, 16 October 1958. The telescope, still lacking surface panels at dedication, was completed in February 1959, with first observations on 13 February 1959. Credit: NRAO/AUI/NSF

scheduled observations could take place before AUI accepted the antenna. It was not until the end of 1959 that NRAO would agree to accept the antenna, although even by then, Blaw-Knox had not met all of the contract performance specifications. In hindsight, the schedule delay in the construction of the Tatel Telescope was a forerunner of the much longer and more serious delays later encountered by the 140 Foot, 36 Foot, and 100 meter GBT projects.

Since NRAO did not yet have an engineering staff, the 85 foot antenna was initially equipped with commercial receivers and a feed system consisting of a 1.4 GHz (21 cm) receiver built by Airborne Instruments Laboratory, an 8 GHz (3.75 cm) receiver built by Ewen-Knight, and a dual band 3/21 cm feed developed by Jasik Laboratories. According to Heeschen[27] this was the only time in its history that NRAO used completely commercially built receivers, although for many years following, NRAO would purchase low noise maser and parametric amplifiers.

Blaw-Knox had earned their reputation by building road-paving equipment and had no previous experience in radio astronomy. Indeed, the design was well underway when they realized that, due to the latitude difference, the Green Bank and Michigan equatorial mounted antennas could not be identical.

However, they did go on to produce a number of 85 foot antennas of the same design as the NRAO and Michigan antennas. The next one was for the Jet Propulsion Laboratory (JPL) Goldstone tracking station. One was for the Harvard College Observatory near Fort Davis, Texas, to support a program in solar radio astronomy by Alan Maxwell, a New Zealander, who had arrived at Harvard from Jodrell Bank. More than 10 other nearly identical antennas were located at the NASA Deep Space Network (DSN) tracking stations around the world. Comparably-sized radio telescopes were constructed by other manufacturers for the University of California at Hat Creek, California, and the Naval Research Laboratory at Maryland Point, Maryland. Some of these antennas remain in operation after more than 50 years. Years later the DSN antennas in South Africa and in Australia were decommissioned from their role in spacecraft tracking, and ownership was transferred to the host countries, where some were used for radio astronomy.

Initially, scientists wanting to use the 85 foot Tatel Telescope were unencumbered by the need for detailed scientific proposals, referees, time assignment committees, etc., so planning the Observatory's first scientific programs was a simple affair. Over a meal at the local diner, the NRAO scientific staff discussed the initial observing program that included the planets, the Galactic Center, H II regions, planetary nebulae, and the spectra of extragalactic sources. The observations were scheduled by Heeschen, based on handwritten requests from NRAO and visiting staff members for specific days and times, but unaccompanied by any scientific justification. The first controversial proposal came from Doc Ewen, who requested a large block of observing time for a Venus radar experiment. As Chair of the NRAO Astronomy Department, Heeschen had been assigning telescope time, but was reluctant to assign such a large block of time to one observer, and sought Berkner's advice. Due to the time-dependent nature of his planned radar experiments, Ewen ultimately withdrew his proposal, but, by the middle of 1960, the anticipated demands for nighttime observing on the Tatel Telescope caused Heeschen to inform the staff, "I think it would be well if each person with an observing program (or contemplated program) would write a short description of it—including present status, why it's being done, and with what receiver, and an estimate of the telescope time required to complete it."[28]

The spring of 1959 saw NRAO's first visiting observers, including George Field from Princeton, Hein Hvatum from Chalmers Technical Institute in Sweden, T. K. Menon from the University of Pennsylvania, Morton Roberts from the University of California, and Gart Westerhout from Leiden University. Although the Tatel telescope had only modest capabilities compared with NRAO/AUI's ambitions, as Heeschen (1996) pointed out, it served a variety of purposes. NRAO learned how to develop and manage a visiting observer program, and instrumentation being developed for the 300 Foot and 140 Foot Telescopes was tested on the 85 foot antenna. In particular, in fall 1961 Sandy Weinreb, then an MIT graduate student, brought his original 21 channel digital autocorrelation spectrometer to use on the 85 foot Tatel antenna in an attempt to detect the Zeeman splitting of the 21 cm hydrogen line[29] (Weinreb 1962a) and interstellar deuterium (Weinreb 1962b). Frank Drake's 1960 Project Ozma on the Tatel Telescope brought national recognition to NRAO and Green Bank, although it was not all favorable (Chap. 5). Later the Tatel Telescope became the first antenna of the three element Green Bank Interferometer (Chap. 8).

Characteristic of common practice at the time, NRAO started its own Observatory publication series, called "Publications of the National Radio Astronomy Observatory," which was privately distributed. Volume 1, covering the period from April 1961 to August 1963, included 17 publications. Reflecting what was then a general isolation of radio astronomy from mainstream astronomy, the absence of external peer review, and their limited distribution, the NRAO Publications were not widely recognized or cited, and from 1963 onwards NRAO staff and visitor publications appeared only in recognized peer-reviewed astronomy and technical journals.

4.4 The 140 Foot Saga[30]

Planning for the New Radio Telescope During the years leading up to the formation of NRAO, a range of antenna sizes up to the ambitious dimension of 600 feet were discussed. Both the NSF and AUI committees provided advice on the flagship telescope for the new national observatory, but they were not always in agreement. Although the value and feasibility of the 600 foot telescope were hotly contested, there was a consensus to start with a so-called "intermediate" size reflector in the 150 foot range. However, the tradeoffs between size and precision and between an equatorial and alt-az mounting were debated for years. For smaller antennas, it was agreed that a traditional equatorial mount was optimum, while for larger antennas, it was clear that only an alt-az mount could work. The planned antenna was in the awkward class that Grote Reber said was neither big enough to be interesting nor small enough to easily build. With some foresight, he commented that being of intermediate size, much time and effort would be wasted fighting over whether it should be on an equatorial or alt-az mount.[31] The initial specification for a 150 foot diameter dish was redefined to be 40 meters, then rounded up to 140 feet (42.7 m) because, according to Struve et al. (1960), someone felt that the size of the national instrument should be expressed in feet, not in meters.

At this point, essentially everyone concerned was convinced, unrealistically as it turned out, that the construction of an intermediate-size dish would be a straightforward extrapolation of existing 60 to 82 foot designs. Initially, the main scientific driver for building the 140 Foot antenna was to do both galactic and extragalactic 21 cm research. As project planning developed, there was increasing interest in going to shorter wavelengths to investigate radio galaxy spectra, to study the thermal emission from the planets and H II regions, and to study polarization. Interestingly, in a 1957 letter to the NSF, with foresight Heeschen noted that the 140 Foot would be uniquely capable of detecting spectral lines at centimeter wavelengths.[32] At the same time, the exciting work being done on radio galaxies in the UK and Australia (Sect. 2.1) led to increased interest in the identification of discrete radio sources and greater emphasis on precise pointing of the antenna to measure accurate source positions. This gradual specification creep led to a telescope that would not be available off-the-shelf, but would be at the cutting edge of technology and both more difficult and more expensive to build than anyone at AUI anticipated.

At their 28 May 1955 meeting, the AUI Steering Committee prepared a Request for Proposals for a 140 foot diameter radio telescope which specified that the pointing should be better than 30 arcsec and the surface accuracy 1/4 inch over the inner half and 3/8 inch over the remaining part.[33] After considerable debate, the decision between an equatorial and altazimuth mount was left open, but full sky coverage remained a stated requirement. In June, Emberson reported that he had requested proposals from 21 commercial companies for the design and construction of an intermediate-sized dish.[34] However, the resultant cost estimates for the intermediate-sized dish varied widely, and none of the companies seemed prepared to produce an antenna meeting all of the challenging AUI specifications. Most of the manufacturers contacted indicated they would work on only a specific portion of the project, and could not deliver the full antenna. Significantly, several companies stated that AUI would need to supply a complete design before they could make a firm bid.[35] At this point, the Steering Committee agreed to defer the issue of construction and to concentrate just on the design. AUI anticipated that a 140 Foot Telescope would cost $2.2 million to design and construct, although the bids ranged from $1.3 million (D.S. Kennedy & Company) to $3.3 million (American Machine and Foundry). The full costs of developing the observatory, including other research equipment, roads, power, water, and buildings, was estimated to be about $4.6 million. Annual operating costs, which included salaries for the Director, two radio astronomers, one electrical engineer, and two technicians, as well as one mechanical engineer, were projected to reach $259,000 by 1959.[36]

Designing the Telescope After receiving the second NSF grant of $140,000 in July 1955, AUI decided to proceed in two phases: first, develop the design for a 140 Foot Radio Telescope, and second, contract to build the antenna. AUI issued three contracts for the design. At this time, everyone agreed that an equatorial mount would be too complex for a telescope as large as 140 feet, so the requested designs were all for an altazimuth mount using an appropriate coordinate converter. Jacob Feld from New York agreed to scale his 600 foot design to 140 feet. Charles Husband was asked to develop a design for a 140 foot telescope based on his experience with the Jodrell Bank telescope, which was soon to become the largest, fully steerable radio telescope in the world. D.S. Kennedy & Co. of Cohasset, Massachusetts, had already built several modest sized antennas for radio astronomy, including the Harvard 60 foot telescope, as well as other antennas for commercial and military applications, and agreed to develop a third design for a 140 foot radio telescope. In the Feld design, the dish was supported by two towers that rotate on a track, while the

Husband design followed the concept outlined nearly a decade earlier by Grote Reber (Chap. 9) for his proposed 220 foot antenna, in which the dish is supported at the two ends of a single supporting ring. In the Kennedy design, the dish was supported by two rings on a rotating structure mounted on a concrete pedestal (Fig. 4.6).

In order to operate at wavelengths shorter than 10 cm, even as short as 3 cm, the surface accuracy was now specified as ±1/4 inch, without defining whether that referred to peak-to-peak or rms deviations. The pointing accuracy was initially specified to be 10 arcsec, corresponding to 5% of the HPBW at 3 cm. The designers indicated that they could easily meet a 30 arcsec specification, could probably obtain 20 arcsec pointing accuracy, but that 10 arcsec pointing "may have to wait on the development of improved technology and components."[37]

By this time the NRL 50 foot alt-az dish had been in operation for four years, and it was known that the Dwingeloo, Jodrell Bank, and Parkes dishes were to be alt-az mounted. Moreover, as was certainly known by at least some members of the AUI Steering Committee, digital computer-controlled alt-az mounted antennas were already in common use in military radar systems.[38] Nevertheless, the AUI Committee, led by John Hagan and Dick Emberson, expressed concern that the required pointing precision of the Green Bank telescope could not be met with an alt-az design and mechanical coordinate converter.[39] Hagan's concern was no doubt based on the recognized pointing issues with the NRL 50 foot dish, so he argued, probably correctly, that an analogue computer of the type used at NRL and Dwingeloo could not meet the desired 140 foot pointing specifications. Although digital computers were already available, there was a widely held view that the operation of a precision scientific instrument should not be trusted to a computer.

The concerns about an alt-az design were shared by Merle Tuve and his NSF Panel, who questioned the potential precision of any servo system that would be needed in the alt-az design. According to Heeschen (1996), Tuve's lack of faith in servo drives was at least in part the result of his wartime experiences

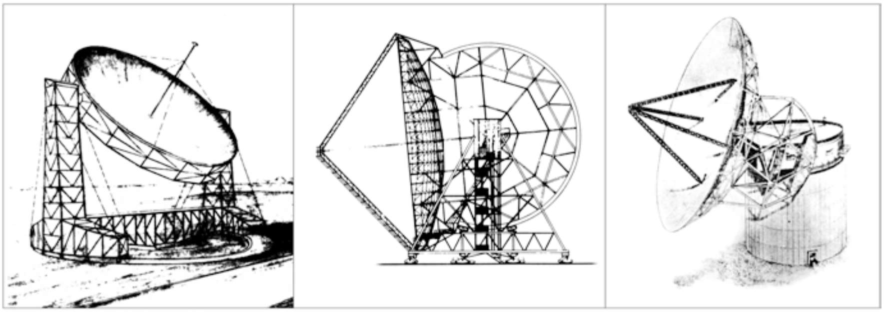

Fig. 4.6 Left to right: Feld, Husband, and Kennedy telescope designs for the Green Bank antenna. Credit: NRAO/AUI/NSF

with servo-driven gun mounts. Further, the optical astronomers on both the AUI and NSF committees, and the Harvard astronomers in particular, who had experience with their 24 and 60 foot equatorial dishes, viewed the equatorial mount more favorably. So Tuve and his NSF Advisory Panel told the NSF to specify that at least one design should be for an equatorial mount, although they acknowledged that the cost would be greater than for an alt-az mount. Moreover, Tuve claimed that the specified pointing precision was unrealistic and that AUI was "accepting from all advisers their desired performance characteristics and then asking the designers to meet these high specifications." He also made the valid point that the same specifications must be used in evaluating the two designs.[40] In view of the engineering challenges for both designs, Tuve proposed to relax the 140 foot pointing specifications and to eliminate the requirement that the dish be able to track the Sun, Moon, and planets. But Berkner was firmly opposed to relaxing the tolerances laid down in the design specifications, since he argued "this would diminish the range of experiments for which the instrument could be used."[41] Tuve was supported by Greenstein, who claimed that the "equatorial design might not be feasible," but that "the problems on the altazimuth mount are far from solved," and he informed Tuve that the Caltech 90 foot dishes would be on equatorial mounts.[42] Following pressure from Tuve's Panel, the NSF instructed Berkner to divert $10,000 originally planned for studies of the large reflector to "an immediate study of a polar type mount for the 140 foot reflector."[43]

At their March 1956 meeting,[44] the AUI Advisory Committee reviewed the Feld, Husband, and Kennedy designs. The Husband design adopted the same welded steel surface that later turned out to be so unsuccessful on his Jodrell Bank 250 foot antenna.[45] Tuve, claiming to speak for the NSF Advisory Panel, noting the difficulty in achieving the design specifications, urged that the design be relaxed to allow the telescope to work at 7 or 8 cm rather than 3 cm and stated that he saw "no particular value in having a telescope capable of operating at less than 10 cm wavelength." Haddock, who was using the NRL dish for 3 cm wavelength observations of planetary nebulae and H II regions,[46] was "greatly disturbed at the suggestion of relaxing the tolerances," and wanted to go to even shorter wavelengths where the thermal radiation would be stronger. Bok argued that "as accurate a reflector as possible is what is wanted." Tuve retaliated, advocating the need to determine what observations were desired, and then build with that objective in mind. Similar arguments and counterarguments relating to the relative importance of solving old problems and discovering new questions would be expressed about almost every proposed new radio telescope over the next half century.

All three designers agreed that the additional cost of an equatorial mount would outweigh the cost savings from the simpler drive and control mechanism on an alt-az antenna, and that further funds would be needed to explore the equatorial designs in more detail. Aside from the cost differences, Berkner reminded everyone that an alt-az design for the planned 140 Foot Telescope would give valuable experience in the design of bigger antennas. Pointing out that AUI had one or more workable alt-az designs, Berkner asked for authorization to proceed on the basis of one of those designs rather than delay further the establishment of the National Radio Astronomy Facility which was still in the proposal stage. Although it was agreed that if AUI followed the urging of the NSF Advisory Committee to obtain an equatorial design, it would take another four to six months. Bok pointed out that since construction funds were not available anyway, it would be "desirable to undertake a study of an equatorial mount." Berkner relented, and as instructed by the NSF, he agreed to "use funds in the amount of $10,000, previously allocated for studies of large dishes, to obtain a preliminary design of an equatorial mount." However, already at this time it was clear that at best, the FY57 NSF budget request of $3.5 million for the radio facility was more than a million dollars below the amount Emberson felt was needed for land acquisition, site development, equipment, and antenna construction.[47]

Berkner, Emberson, and much of the AUI Steering Committee favored the structurally simpler alt-az mounting, in part because it would also serve to evaluate the design of the planned and much larger 600 foot telescope. Tuve, on the other hand was concerned about the more complex variable speed drive and computer systems needed for the alt-az mount, and argued that "no comparison between equatorial and altazimuth suitability can be made unless at least one of them is a complete design." He was particularly concerned about the cost of a computer to do the coordinate conversion and the requirements for the servo system, which he claimed was "outside the contract," for the three designs provided by Feld, Kennedy, and Husband. "Unless a second independent computer is added," he argued, "there is no way of knowing at all times where the dish is actually pointing."[48] As Frank Drake[49] later pointed out, Tuve apparently did not appreciate that the direction of the forces on the declination bearings, and on the fork supporting the dish of a polar mounted telescope, changes as the telescope moves in hour angle, so that an equatorial mount is much more difficult to design than an alt-azimuth mount. The problem is compounded because adding more weight to give stiffness increases issues of the load on the bearing.

The AUI and NSF committees debated the minimum operating wavelength and the tradeoff with antenna diameter and cost. Fred Haddock argued that 1 cm would be ideal to study the thermal emission from planetary nebulae and H II regions, but 2 or 3 cm would be a reasonable compromise with cost. John Bolton claimed that even a factor of two improvement in surface accuracy would double the cost of the reflector, but Dave Heeschen and Bart Bok countered that in practice, previously built radio telescopes, such as the one at Harvard, had exceeded their design specifications, so that it should be possible to reach wavelengths as short as a few centimeters at no increase in cost.

As early as July 1956, Merle Tuve discussed the 140 Foot challenges with Blaw-Knox. Using the "Tatel-Carnegie design" for the DTM 60 foot antenna, he asked if Blaw-Knox would be able to give a "quotation or estimate" on the cost of a 140 foot equatorially mounted parabolic dish. Tuve reiterated his often stated view that the AUI specifications were too tight, and asked how the cost might be reduced by relaxing the specifications, or if a larger dish could be built with reduced specifications "without extreme increase in costs." Tuve also asked that the telescope be able to point down to the horizon over a range of 210 to 240 degrees of azimuth, a specification which would later turn out to be very expensive.[50] Around this time, Emberson was becoming concerned about the apparent difficulties inherent in the equatorial design, and predicted that "the alt-azimuth design will be the one chosen in the end."[51] But only a month later, based on optimistic input from Feld, Emberson expressed more confidence in an equatorial approach and proposed setting up a small group to further investigate an equatorial design for the 140 Foot Telescope.[52] As later described by Emberson and Ashton (1958), the choice between an alt-az and equatorial mount depended on whether one had more confidence in a complex mechanical structure or a complex drive and control system, and since the telescope would be used by astronomers who may have had "unhappy experiences with electronic and electrical equipment," AUI decided in favor of an equatorial mount.

Initially, some of the Advisory Committee members wanted to retain true full sky coverage, even for an equatorially mounted dish, in order that observations of transient celestial phenomena or geophysical activity could be studied at lower culmination. This would have meant tipping the dish structure over the zenith, but fortunately, at the October 1956 AUI Advisory Committee,[53] it was agreed to restrict the sky coverage appropriate to the equatorial mount. Measuring the surface accuracy was recognized as a possible problem, and a number of approaches were considered. By this time, there were sufficient uncertainties surrounding the 140 Foot project, which was about to become a contractual responsibility, that it did not seem feasible to simultaneously push the studies of the much larger (600 foot) telescope. Nevertheless, Berkner was confident that the construction of the 140 Foot Telescope would not take more than two years, and perhaps could be completed in as little as 18 months. However, some members of the AUI Board were already expressing concern over the lack of a firm cost estimate, so Berkner agreed that "commitments be limited to land acquisition, construction of essential roads, and installation of electric power."[54]

Under the guidance of the newly constituted AUI Advisory Committee on Radio Astronomy, in October 1956 AUI contracted with Ned Ashton for a "definitive" design of an equatorial mounted 140 foot radio telescope. Ashton was a structural engineer from the University of Iowa who had also designed the NRL 50 foot radio telescope, which was, when built, the largest in the world. A special ad hoc committee, including Howard Tatel and Merle Tuve from DTM, along with John Bolton and Bruce Rule from Caltech, was constituted in October 1956 to give "advice" to Ashton.[55] Bruce Rule was a Caltech structural engineer who had been involved in the construction of the Palomar 200 inch, and he was in charge of the design and construction of the new twin 90 foot equatorially mounted radio telescopes for Caltech's Owens Valley interferometer. Rule and Bolton offered to make the design of the Caltech 90 foot antennas available to Ashton and the Committee. The committee gave careful consideration to how both the polar and declination axes would be aligned and the methods by which the reflector surface would be fabricated, measured, and adjusted. But it was acknowledged that it would strain known optical or microwave procedures to adjust the surface to the needed accuracy.[56]

With an equatorial mount, there could be considerable cost savings by restricting the sky coverage, but "full sky coverage" was argued to be a fundamental requirement for a general purpose radio telescope. As a compromise between sky coverage and cost, the Advisory Committee initially agreed that the hour range would be restricted to six hours from the meridian. However, Donald Menzel, who carried a lot of weight with both AUI and the NSF, insisted that the telescope must be able to follow the Sun when it was above the horizon at any time of the year,[57] thus increasing the hour angle limit to seven hours. Tuve pointed out that this would seriously impact the performance and cost. Ashton denied that this was true (Heeschen 1996), although the increased range of hour-angle required longer yoke arms, which greatly increased the weight of the movable structure and the load on the polar bearing. Deciding to include the capability to observe the Sun at any time probably more than doubled the cost of the antenna and compromised both the surface and pointing accuracy, as well as being responsible for the long delay in its completion. According to Dave Heeschen, it was arguably the worst decision made in NRAO's long history.[58] Ironically, by time the 140 Foot Telescope was completed in 1965, solar studies with the limited resolution of filled aperture telescopes were no longer of great interest. As noted by Heeschen (1996), the 140 Foot Telescope had gradually "evolved from a quick-off-the-shelf instrument to one that pushed the state of the art of telescope construction and would become extremely costly and time consuming to build."

Without an NRAO director, management of the 140 Foot program remained in the hands of AUI. As discussed previously, when Otto Struve became NRAO director in July 1959, it was agreed that the "director's primary task will be to assemble a staff to operate the Observatory when it is completed,"[59] and the responsibility for the construction of the 140 Foot Telescope remained with Emberson and AUI. This unfortunate agreement, which removed the day-to-day management of the construction from Green Bank, was perhaps the most significant contribution to the series of miscalculations and mismanagements that resulted in multiple cost increases and schedule delays, and nearly led to the closing of NRAO before it even began any effective operation. According to Heeschen (2008), Struve apparently regretted the agreement and later unsuccessfully tried to transfer management of the telescope construction back to Green Bank. Only after both Struve and Berkner had resigned in 1961 did the project management shift from AUI in New York to NRAO in Green Bank. But by then millions of dollars had been wasted and five years had been lost.

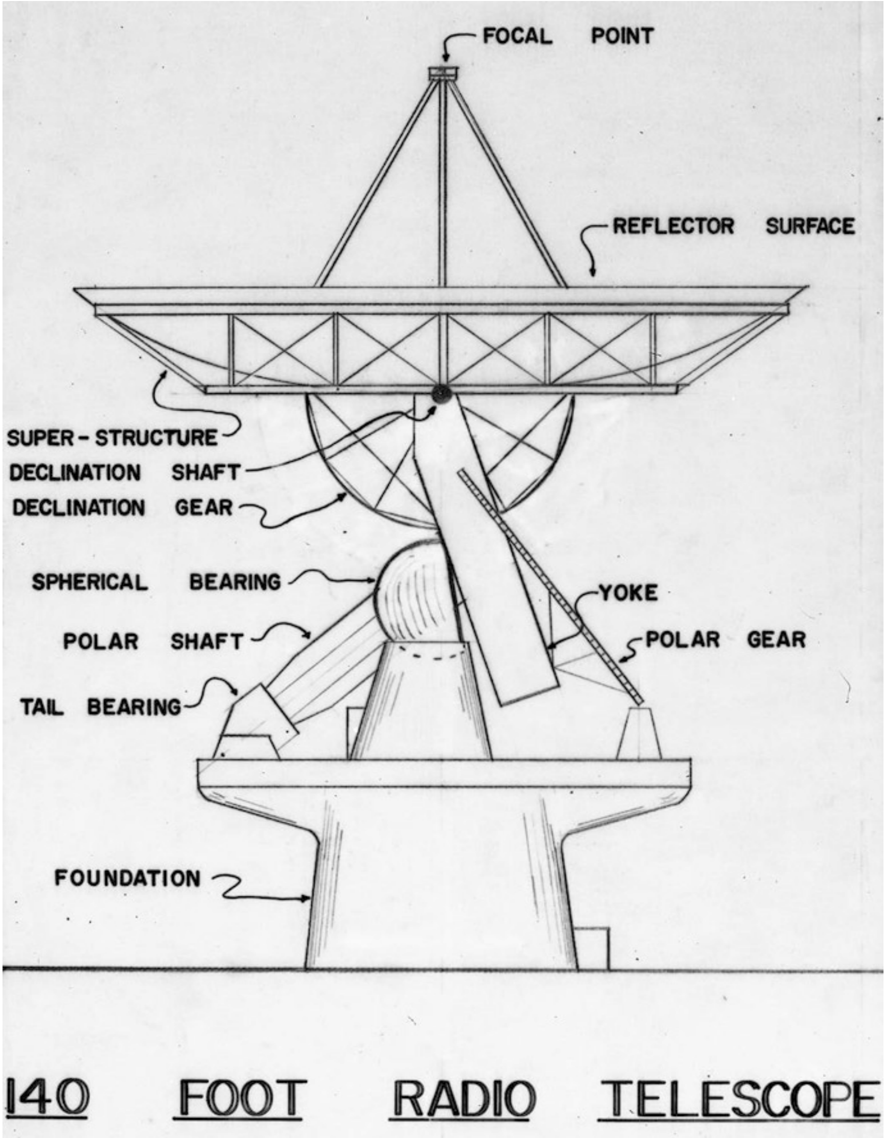

Fig. 4.7 Ned Ashton design for the 140 Foot Telescope. Credit: NRAO/AUI/NSF

Ashton's design called for a large yoke supporting the dish structure attached to the polar axis, which was supported by a large spherical bearing sitting on nine (later reduced to four) oil supported pads (Fig. 4.7). This was much like the iconic 200 inch Palomar telescope, but, of course, the 140 Foot was much larger and heavier, and also had more precise pointing specifications. The yoke, polar axis, and spherical bearing were to be made of steel, and the dish backup structure of aluminum. The surface was composed of 72 aluminum panels set in three concentric rings.

Planning for the development of the Observatory was based on an anticipated budget of $4 million for FY1957 and $1.13 million for 1958. At the time, AUI estimated the cost of building the 140 Foot Radio Telescope would be about $2.2 million.[60] But due to the uncertainty about the price of the 140 Foot Telescope, it was difficult with the limited budget to also commit funds for a control building, instrumentation, and operations. In January 1958, AUI issued "Estimated Costs of Construction" for NRAO that included detailed requirements for roads, water, electric power, buildings, housing, cafeteria, and staffing. By this time, due to the more ambitious requirements to work at short centimeter wavelengths, the increased appreciation of the impact of the remote location, and better understanding of the engineering problems, AUI's estimated cost for the 140 Foot Telescope had ominously increased to $6.8 million.[61]

Contracting for Construction An NSF suggestion for an independent review of Aston's design was dismissed by Emberson on the grounds that the AUI ad–hoc committee "had already accomplished this review."[62] While it was agreed that there should be a written record of the AUI review, there is no evidence that this ever happened. On 1 August 1957, AUI issued a Request for Proposals to construct the 140 Foot antenna following Ashton's design. At the 12 September 1957 Pre-Proposal Conference, AUI stated "AUI does not contemplate a re-design phase to precede construction; the objective is to build the present design."[63]

Ashton's design turned out to be incomplete and devoid of details. AUI received nine bids ranging from $3.96 million to $12.02 million to construct the antenna.[64] After negotiations with the four lowest bidders, the lowest acceptable bid of $4.75 million came from the E.W. Bliss Company of Canton, Ohio, an amount nearly twice the available funds, but the bid offered an attractive, if unrealistic, delivery time of only 14 months. However, the bid did not include another $1.2 million that AUI estimated would be needed for engineering, power, taxes, and cost escalation. In an emotional letter to the NSF on 12 February 1958, Berkner pleaded for the additional funds needed to accept the Bliss proposal.[65] At the subsequent NSF review on 13 March 1958, Emberson admitted that the original $2.2 million figure "was first used in almost casual conversation," and was for a "smaller less precise instrument." Struve kept up the pressure by pointing out to the NSF the ultimate need for "a very large antenna with a diameter well in excess of 1000 feet," and said that the "140 foot telescope should be regarded as merely a stopgap."[66] AUI was initially authorized to contract with Bliss for $145,000 for engineering (Phase I), with an option for fabrication (Phase II) which was contingent on upon an additional Congressional appropriation, and gave Bliss a letter of intent authorizing Phase I in December 1957. After Congress had passed a supplemental appropriations bill, AUI was able to let a fixed price contract to E.W. Bliss for

$4.75 million for fabrication of the 140 Foot Radio Telescope. Although not included in the contract, completion was promised in 24 months. On 9 June 1958, representatives from Bliss, AUI, and NSF gathered in Green Bank to sign the contract for the construction of the 140 Foot Telescope. Groundbreaking was two months later, on 14 August 1958 (Fig. 4.8).

The contract with Bliss was poorly formulated. There were no penalties for delay or incentives for early completion. AUI maintained that Bliss was responsible for completing the design, and would be free to depart from the Ashton design, provided that the stringent performance specifications were met. Nevertheless, Bliss repeatedly claimed that they were unwilling and unable to provide designs not covered by Ashton. As described by Heeschen (1996),

> The exact relation between Ashton's design and that of the contractor was never adequately spelled out, neither in the RP nor in the subsequent contract with the successful bidder, but it was clear that Ashton's concept was to be used. Ashton's detailed designs could be changed by the contractor, but only with the approval of AUI. The degree of responsibility for performance was also worded ambiguously.

Fig. 4.8 Groundbreaking for the 140 Foot Telescope, 14 August 1958. From left to right, Eugene Hallik (AUI), unidentified (Bliss Co.), Frank Callender (NRAO), Richard Emberson (AUI), and John Findlay (NRAO). Credit: NRAO/AUI/NSF

Signs of Trouble Apparently neither Ashton nor Bliss nor AUI had considered how the antenna was to be fabricated or erected, or how the large components would be shipped to Green Bank. From the beginning, Bliss had problems in completing the design and in fabricating the spherical bearing. As early as mid-1959, John Findlay reported that the completion date of the 140 Foot had slipped from early 1960 to the "fall of 1960," but that "construction on the site and in the contractor's shops is proceeding satisfactorily."[67] By the time the promised two year construction period had passed in mid-1960, fabrication of the spherical bearing, yoke, and polar shaft were proceeding in the Bliss plant, but already the project was nearly two years behind schedule (Heeschen 2007a). Due to design problems, work on the drive and control system, which had been subcontracted to the Electric Boat Division of General Dynamics, had not yet started, and Bliss also reported difficulty in developing a procedure for fabricating the surface panels.

On 5 May 1960, Bliss wrote to AUI that small cracks had developed in the spherical bearing, and that in cold temperatures, the type A-373 steel being used to fabricate the bearing and the polar shaft might be subject to what was called "brittle fracture." It was known that in North Atlantic winters during WWII, brittle fracture caused merchant ships constructed from A-373 steel to fracture and sink. Green Bank winters can be very cold, with temperatures reaching −30F (−34C). Since Bliss apparently had a supply of A-373 steel and experience in using it on other projects, they used it to fabricate the spherical bearing and the polar shaft. AUI was concerned that although the cracks in the bearing were minute, there was a slight danger that under cold weather the cracks might propagate, leading to failure of the bearing which supported the whole movable structure. An additional complication arose when neither Ashton nor Bliss were able to develop a procedure for welding the polar shaft to the yoke and sphere. Bliss wanted to bolt the pieces together, but this required modification of the components that already had been fabricated. Ashton argued that a bolted structure would not be sufficiently strong. Bliss maintained that the problem was due to the unsatisfactory Ashton design, and that AUI would be responsible for any additional costs and delay. AUI promptly responded that the problems were not due to design faults, but to unsatisfactory shop and welding procedures, and since, according to the contract, Bliss was responsible for the final design, they should be responsible for finding a solution and for any additional expenses involved.

Both AUI and Bliss hired consultants, but they disagreed on the optimum technical solution and on legal responsibility. On 24–25 May 1960, Lewis Burchill, the AUI Controller, and Emberson met with Bliss to discuss renegotiating the contract to provide a firm completion date, but they agreed that this would not be possible until the technical issues were resolved.[68]

Over the next months, AUI, the NSF, and Bliss discussed a number of possible solutions:

1) heating the enclosure surrounding the sphere, which could be risky if power were lost to the heating system during cold weather;

2) drilling small "mouse holes," or coating the sphere with epoxy to reduce stresses;
3) using a process known as "normalizing" to heat at least the spherical bearing, and perhaps all of the steel components, to a temperature of 1600 degrees F, which would change the structure of the steel and greatly decrease the possibility of brittle fracture;
4) scrap the sphere and start over with a new type of steel; or
5) do nothing and take a chance that brittle fracture would not occur. Meanwhile, the polar shaft, which had been fabricated with the same defective steel, had already been delivered to Green Bank.

On 30 August 1960, AUI and NRAO staff, along with consultants, met with the NSF to address the problems and discuss whether to terminate the contract with Bliss. Although Ned Ashton claimed that the chances of brittle fracture were negligible, and that the safety factor included in the design of the sphere excluded the possibility of catastrophic failure, Emberson maintained that this was potentially a very serious problem and he did not want AUI to take any chances, however small. The antenna was already way behind schedule and over budget. NRAO, and especially Struve, expressed concern that by time the 140 Foot Telescope was finished, it would no longer be cutting edge. They were well aware of the growing number of 85 foot radio telescopes around the world, as well as the Jodrell Bank 250 foot dish, and the Parkes 210 foot telescope then under construction. Struve contended that NRAO was not able to attract new staff members because the existing equipment was not sufficiently attractive or unique, and that there was a danger current staff would leave. Moreover, he argued that radio astronomy was progressing so fast that, after 1962, the 140 Foot would be "outdated." Perhaps somewhat irresponsibly, but no doubt with good intentions, he maintained that "the urgency of need" outweighed the "ideal technical or engineering solutions."[69]

Encouraged by Ashton's reassurance, recognizing that refabricating the major structural elements would be costly and introduce yet further delays, and concerned about minimizing the delay, Struve insisted that Bliss be allowed to continue with the erection of the antenna using the existing yoke, bearing, and polar shaft without normalizing. Although Emberson expressed dissatisfaction with the decision, the NSF agreed to proceed, and Emberson ordered that the spherical bearing and other fabricated components be shipped to Green Bank for integration and assembly. But the shipment was delayed by a railroad strike and by the continuing contention over who was responsible for the design faults and subsequent delays.[70] Lloyd Berkner, meanwhile, was on a two-month trip to Europe and the Middle East attending to some of his other national and international responsibilities. When NRAO and AUI met with the NSF on 30 August 1960, Berkner was in London as head of the US URSI delegation, and did not participate in this important discussion. After being updated by Emberson, three days later, Berkner telegrammed his agreement with Ashton and Struve to use the existing structures, and thus avoid further delay and cost increases which would "damage the health and effectiveness of the Observatory." But he encouraged Emberson to "investigate heating of the bearing house to prevent low temperatures that may induce brittle fracture."[71] By this time, although probably unknown to most of the principals, Berkner had already decided to resign as AUI President.[72]

After his return to the United States in late September 1960, Berkner, along with Emberson and Burchill, met with Struve and the Observatory staff in Green Bank to develop plans to either renegotiate the contract with Bliss or decide instead to give notice to terminate the contract.[73] Following a 22 September 1960 meeting between AUI and Bliss, with both sides backed by their respective legal teams, AUI asked Bliss to propose a contract revision that included a firm fixed price for completion and a firm date for final delivery, "preferably not substantially later than November 1, 1961."[74] As a prerequisite to any negotiation, AUI required that all finished parts be shipped to Green Bank, that work on the sub-contracted drive and control system be completed, and that assembly in Green Bank be resumed.[75] AUI was ready to assume responsibility for Ashton's design, provided that they had the opportunity to inspect progress and that Bliss agree to a price adjustment if they were not able to complete the telescope by the agreed date.[76] AUI appreciated that any renegotiation would require additional funds, which would need NSF approval, and that this would likely mean further delay, especially if the negotiations involved normalizing any of the steel components. By this time, Bliss was claiming over $1 million in excess costs they argued that they had already incurred, due, they claimed, to defects in Ashton's design. Burchill was confident that that they would settle for less, but the NSF agreed to "make additional funds available to you in such amount as may be necessary for a full settlement," and to provide up to an additional $100,000 for assembly of the telescope in Green Bank.[77] Meanwhile, at their 23 September 1960 meeting, the AUI Board authorized Berkner, at his "discretion," to terminate the contract with Bliss, although they recognized that this would be "fraught with difficulty."[78]

Finding a Solution Berkner's and Struve's apparent confidence was not shared by Emberson or the NSF. On 25 September 1960, Berkner and Emberson, along with Lewis Burchill and NRAO Business Manager Frank Callender, met with NSF Director, Alan Waterman, and other NSF staff, to review the deteriorating situation in Green Bank. After further review at the NSF, and probably influenced by Emberson's concerns, on 5 October, Waterman wrote to Berkner that while[79]

> we fully understand and sympathize with your desire, and that of the NRAO staff, to place the telescope in operation at the earliest possible date, … the interests of the Federal Government must be protected by assuring that sound procedures are followed in fabricating any part of the telescope whose failure might result in

> death or injury of personnel, severe financial loss and long delay in putting the telescope into operation.

After reviewing the options, Waterman went on to state

> Because of the complexity, the serious consequences of major mistakes, and the possibility that our judgements may be overly influenced by the pressures we are all under to complete the job rapidly, the Foundation feels it is desirable at this time to have the technical problems reviewed by a highly qualified committee of experts in order that AUI may have the best possible basis for a decision on this problem.

Waterman added that he had appointed Dr. Augustus B. Kinzel, an engineer and Vice President of Union Carbide, to chair a committee charged with addressing the apparent problems with the spherical bearing and polar shaft.[80]

Discouraged by the deepening problems surrounding the 140 Foot project, on 23 September 1960 Berkner quietly informed AUI that he was resigning as AUI President.[81] Berkner's resignation was officially accepted at the 20–21 October 1960 Annual Meeting of the AUI Board of Trustees.[82] Struve was also upset by the delays in the project. Citing ill health, frustration over the NSF reversal of the 30 August 1960 decision to continue construction with the existing bearing, which, he noted, "is a severe disappointment to me personally," and feeling that important decisions were being made without consulting him, Struve stated that he was unwilling to assume the responsibility for the success or failure of the 140 Foot Telescope unless he could be sure of control. Noting that he had previously taken the position that he would not continue as Director unless the telescope could be finished by 1 July 1962, and that "nothing had happened which gives him any confidence that this condition will be met," Struve told AUI that he "cannot continue to serve as director of the Observatory."[83] Although Struve's effectiveness as NRAO Director was questioned, in view of the worsening 140 Foot situation, AUI apparently did not want to deal with the potentially embarrassing, nearly simultaneous resignation of both the AUI President and the NRAO Director.

At their 18 November 1960 meeting, the AUI Executive Committee reassured Struve that the "Director should be in complete charge at the Observatory and that Dr. Struve could count on the unwavering support of the Trustees in his administration of the Observatory."[84] The Trustees noted that in the earlier absence of a full time director, "practices had grown up at Green Bank and had simply been continued without any thought of acting contrary to the wishes of the director." The minutes of the 18 November AUI Executive Committee reported that, following the unanimous vote of their "complete confidence in Otto Struve, their satisfaction at the progress of the Observatory under his direction, their hope that he will find it possible to continue as Director," Struve "expressed his pleasure at the action taken and emphasized that he had never felt any lack of confidence on the part of the Trustees, but on the part of the contracting agency, the NSF." Later Struve (1961) would write, "the Observatory does not yet fulfill its intended function of serving as a 'national laboratory.' This is due to several causes, the most important of which is the delay in completing the 140 foot telescope." Heeschen recalled that Struve "remained very upset," over the reversal, without consulting him, of the 30 August decision, and that "his growing dissatisfaction with his role in the project would lead to his departure just a year later."[85]

These were certainly the darkest days in the history of NRAO. There was no clear route to completing the 140 Foot Telescope without major redesign and refabricating most of the structure, which would be both costly and lengthy. The AUI President who had been the driving force behind the creation of NRAO had resigned, and the NRAO Director was threatening to resign. The AUI contract with the NSF to operate NRAO was coming up for renewal. The cost overruns and delays already incurred by the Green Bank 140 Foot antenna, as well as those surrounding the Navy's 600 foot antenna at Sugar Grove, West Virginia (Sect. 9.3), came to the attention of the White House.[86] The NSF and the American radio astronomy community were becoming increasingly disillusioned with the lack of progress in Green Bank, and NRAO was becoming the subject of scorn and ridicule. At Caltech, the two-element interferometer was already in operation and was making a wide range of exciting solar system, galactic, and extragalactic discoveries (Sect. 6.6), while NRAO and the 140 Foot were being dismissed by the Caltech staff and students. The situation was so serious that the Observatory was threatened with closure.[87] Annoyed at the likely delays that would be introduced by the NSF decision to appoint an external committee to review the 140 Foot situation, Berkner took matters into his own hands, and did not hesitate to make Kinzel aware of his concerns about introducing further delays in the completion of the telescope. Seemingly ignoring the fact that he had just announced his wish to resign as AUI President, or maybe recognizing that he had nothing to lose, Berkner boldly wrote to Kinzel that, "you will learn of the technical aspects of the problem in your forthcoming meetings with members of the AUI staff, representatives of the E. W. Bliss Company, and consultants."[88] Suggesting that there were more important issues at stake than just the metallurgy, Berkner, hinting that the urgent need to use the telescope was more important than dealing with the metallurgical issues, wrote, probably inappropriately, to Kinzel,

> It is important, however, that you and members of your committee understand the unique position the 140-foot telescope has taken in the life of the Observatory and why we believe completion at the earliest possible date is necessary even if some measure of perfection may have to be sacrificed.

Continuing, he added,

> Therefore, a 140-foot telescope has become a symbol for the staff of the observatory in generating the opportunity at a national institution which would keep the

U.S. in the forefront of radio astronomy development. It is moreover, a symbol in the eyes of the scientific community generally including members of the NSF Board and to Congress and the public which is of course the ultimate source of support for such an institution as the NRAO.

But on 31 October 1960, in a letter to Leeland Haworth, who was to succeed him as AUI President, Berkner made it clear that he was relinquishing immediately all responsibility for the 140 Foot to Haworth and Struve, and informed Haworth that "AUI has employed long-time Trustee, Ted Reynolds, as an independent business consultant to study the AUI-Bliss relations."[89]

In November 1960, Bliss wrote to Emberson and Waterman requesting that the contract be revised to "to incorporate the changes which have incurred to date and to restate the consideration to be paid Bliss for the contract, as amended, on a cost plus fixed fee basis."[90] Following a meeting between AUI and Bliss on 23 November, Bliss estimated that their cost to complete the telescope, including the "additional cost to alter the present sphere and to accomplish a bolted field joint between the sphere and the shaft," would be just over $7 million, and proposed a total price, including their 7% fee, of $7.558 million.[91] Aware that "the expedient completion of this project is of great importance," Bliss claimed that "erection could be completed by at least by November 1962," but only with the additional "judicious expenditure of $600,000 for overtime premium, shift differentials, multiple work areas, additional facilities, and extra supervision." Another half a million was needed to complete the design work. Haworth noted that allowance for contingency further increased the likely contract price to at least $9 million, but that this was still less than some of the original bids.[92] This meant that AUI would need to get another $3.7 million from the NSF, but apparently, as Haworth explained, because West Virginia was considered a "distressed area," it was "desirable to speed up shipments from Canton so that work can go forward in the field using local labor."[93] AUI had no confidence in the engineering capabilities at Bliss, and began to explore alternate arrangements to provide satisfactory engineering supervision for the remainder of the work.[94]

Not surprisingly, the appointment of the Kinzel Committee had delayed any further work on the telescope. At one of the Committee meetings, Ashton "strongly urged that the original plan for welding the sphere to the shaft be followed, and, indeed, insisted that no other plan was feasible."[95] The Committee refused to accept Ashton's position, and their January 1961 report concluded that the spherical bearing should indeed be normalized and that it should be bolted rather than welded to the polar axis.[96] Due to the ensuing contract renegotiations, redesign efforts would not get underway until April 1961, and construction did not begin again until autumn 1961. At least another year had been lost.

Although the NSF had appointed the members of the Kinzel Committee, by agreement, their report was advisory to AUI. But the AUI consulting engineers were concerned about bolting the polar axis to the spherical bearing, which had been designed to be welded, not bolted. Not only was there a danger that the bolts might become loose, but it would be necessary to heat both the sphere and polar shaft. Instead, AUI concluded that it would be better to redesign the polar axis and the yoke, along with the spherical bearing, and fabricate all of the components using steel not subject to brittle fracture. After a meeting at the Bliss plant in Canton, still unable to reach a consensus, AUI, the NSF, Bliss, and Kinzel agreed to pursue both concepts. Following several meetings in early 1961 between AUI and Bliss, the contract with Bliss was terminated with a lump sum settlement, and it was agreed that "all future work performed by the E. W. Bliss Company in connection with the construction of the 140-foot telescope will be covered by a cost-plus-fixed fee contract."[97] But according to the 20 April 1961 minutes of the AUI Executive Committee, "serious disagreement developed over the degree of control which AUI will have to exercise over procedures followed by Bliss in fabrication and erection, as well as over procurement, subcontracting, and other matters." Bliss maintained that AUI's position "violated the understanding arrived at … on March 1, 1961, … [and] threatened to bring suit for breach of contract."[98]

New Management and a New Contractor In April 1961, AUI hired the Stone & Webster Engineering Company (S&W) to manage the whole project, and in particular to act on behalf of AUI in dealing with Bliss on all technical, financial, and management issues.[99] AUI finally acknowledged that it did not have the expertise to manage the project with its limited in-house staff. In particular, AUI was seeking engineering advice on the "problems raised by the polar shaft and main bearing," and noted that "no power of decision was vested in the Kinzel Committee."[100] After reviewing the work to date, S&W concluded that Ashton had prepared only a conceptual design. Since Bliss had refused to accept any design responsibility, Ashton's drawings became the de facto design.[101] Consequently, in yet another decision reversal, S&W decided that it would be necessary to fabricate a new polar shaft, yoke, and spherical bearing, which would all be bolted rather than welded together, and would use steel not subject to brittle fracture. The S&W design maintained only the broad character of Ashton's design. Meanwhile all construction work had again ceased. With the assistance of S&W, AUI negotiated a new agreement, withdrawing work from Bliss, as well as transferring the Electric Boat sub-contract for the drive and control system from Bliss to AUI.[102] AUI finally assumed responsibility for the design, and S&W became the agent for AUI in all future dealings with Bliss.

NRAO's Frank Drake was particularly frustrated with the delays, and did not see any solution to the problems connected with the polar axis and spherical bearing. He also noted that the 140 Foot was already becoming obsolete at wavelengths longer than about 10 cm, and that Green Bank was not a very good site for short wavelength work. In a memo to Struve and the entire Green Bank scientific and senior technical staff, Drake made two radical suggestions:

convert the design to an alt-azimuth mount, and move the telescope to a better site near Tucson, Arizona.[103]

Following AUI's acceptance of Berkner's resignation in October 1960, AUI Trustee Edward (Ted) Reynolds was put in direct charge of the project. Nevertheless, relations between the NRAO Green Bank staff and AUI remained troublesome. Basically AUI didn't trust Struve, but was unwilling and probably unable to replace him. At the same time AUI leadership was evolving. BNL Director Leeland Haworth succeeded Berkner as AUI President, and was followed first by Ted Reynolds and then I.I. Rabi. Decisions based on recommendations from consultants and committees were being made in New York by AUI without involving or even informing Struve, Heeschen, and Findlay in Green Bank. Heeschen finally led a revolt of the entire NRAO Scientific Staff, spearheading a 9 May 1961 letter to Struve.[104]

> The situation with regard to the 140-foot telescope is of great concern to us. There has been essentially no progress whatsoever for at least a year, and there appears to be no basis for expecting progress in the near future. There is, we feel, valid reason for questioning whether the AUI-Bliss contribution will succeed in completing the telescope before it is obsolete.
>
> We feel very strongly that the principle [*sic*] source of the 140-foot troubles lies in the way it is being managed by AUI. The lack of action in the past year and the apparent inability to make decisions is appalling and inexplicable to us. The decisions that are needed to get the telescope completed cannot be based solely on technical considerations. The scientific needs of the Observatory are not being given sufficient consideration largely because there is virtually no contact between the Observatory and the management of the telescope project.
>
> We do not understand why the 140-foot telescope has not been placed under your direction, and we have been questioned repeatedly by other scientists as to why the Observatory and the Director are not more immediately involved. Everyone seems to agree that in principle the job should be run from Green Bank. We reject the argument that the job cannot be managed by NRAO because NRAO has an inadequate engineering staff. Engineering advice is available from many sources. Stone and Webster for example can report as easily to you as to anyone else. The real problem is in deciding which of the conflicting engineering opinions should be acted on.

The next day, Struve forwarded to Rabi the letters from both Heeschen and Drake, along with a strong note criticizing AUI management of the 140 Foot Telescope project. Struve wrote[105]:

> AUI has ruled that the project should not be directed from Green Bank, and I have accepted this decision, despite the fact that I am not personally in favor of it.
>
> During the past few months I have not been fully informed concerning the negotiations with the Bliss Company, the Stone and Webster Engineering Management

firm and the NSF. This creates an intolerable situation that cannot continue much longer.

It is perhaps appropriate to mention that the NRAO suffers from having had virtually no AUI president during the past six months or so. Mr. Berkner, though absent for considerable intervals of time, had a good grasp of the whole project and managed to accomplish a great deal and provide a stabilizing influence on the whole organization. Matters of vital importance to the Observatory have from time to time centered around persons who lack understanding of the scientific competence to make major decisions but whose advice and influence have been obviously accepted by those who have the authority to act.

Struve had clearly crossed the line with his censure of AUI and, by inference, criticism of Rabi, which may have led to Struve effectively being summarily fired by Rabi six months later (Sect. 4.6). Frustrated with AUI, Struve sent Heeschen to represent NRAO at the 19 May 1961 meeting of the AUI Executive Committee, where Heeschen continued his criticism of AUI's management of the 140 Foot project. Apparently of particular concern was the relative authority and responsibility of Struve and Emberson. Responding to Heeschen's criticism, Reynolds acknowledged the need to "improve communication with the Observatory." Although the Board reaffirmed that Reynolds was in overall charge of the 140 Foot project, "Reynolds explained that Dr. Emberson will continue to serve as Project Manager, but that, *as in the past,* he is responsible to the Director of the Observatory."[italics added][106] At Struve's suggestion,[107] Dave Heeschen was appointed as the "scientific project director," which Heeschen later described as "meaningless."[108] Apparently, at least three individuals, Struve, Emberson, and Heeschen, now had some authority and responsibility for the 140 Foot antenna construction, but there was no clear division of responsibility.

Meanwhile, the NSF was becoming increasingly concerned with the repeated reversals of decisions on how to deal with engineering problems surrounding the 140 Foot project, as well as the growing cost and apparent management issues. Faced with the emerging S&W report recommending that all of the components already fabricated by Bliss be scrapped, the AUI Trustees circled the wagons, and agreed "that the only sensible choice is to follow the conservative Stone & Webster recommendations in all proposals to the NSF. The responsibility for taking risks should be placed on the Foundation and not be assumed by AUI."[109] Heeschen suggested that a "radical alternative" was to instead scrap the whole project, and build a copy of the Haystack 120 foot antenna, which he initially estimated might be done for $2 million. However, following a visit to Haystack, Heeschen and Findlay concluded in their 17 July 1961 report that it would be better not to make an entirely new start, but to salvage what little they could from the Ashton-Bliss enterprise. According to the minutes of the meeting, "Mr. Reynolds emphasized the importance of avoiding any discussion of scrapping the 140' Telescope. This possibility should not even be mentioned unless there is an alternative which is clearly more desirable."[110]

At the 20–21 July 1961 AUI Executive Board meeting, Reynolds reported that "Ashton still insists that his design is entirely feasible and can be completed in less time and for less money than the one now being prepared by Stone and Webster," and that Ashton had gone to the NSF "objecting to what he claimed to be waste of time and money involved in the present plans."[111] At the same time, AUI was concerned that the S&W recommendations involved rejecting the recommendations of the Kinzel Committee, and that following a meeting with Kinzel on 17 July 1961, Reynolds reported that "Kinzel insisted that the solution his committee recommended is still satisfactory," although he agreed that the S&W design "was in some respects superior."[112] Closing his report, Reynolds wrote that he had informed the NSF that the total cost of the 140 Foot Telescope would be close to $11 million.

By September 1961, AUI had taken over from Bliss the contract with Electric Boat for the drive and control system, but it was becoming clear that Bliss was also having difficulty fabricating the surface panels, while Aston continued to be critical of S&W. To complicate matters, the AUI contract to operate NRAO was due to expire on 16 November 1961. AUI was concerned, as they probably should have been, that the NSF was likely to impose stricter controls on the operation of the Observatory, and was unwilling to agree to a long term extension of the contract until the NSF agreed to AUI's plan for completing the 140 Foot Telescope.[113]

At Bliss, the President and other senior management all resigned. AUI decided to terminate the contract with Bliss since "there is no work in connection with the newly designed components which Bliss is capable of doing satisfactorily."[114] Ending the contract with Bliss was no easy matter, and had to be justified to the NSF, the Bureau of the Budget, and to Congress. S&W was unwilling to help document the case, as it did not want "to place itself in the position of apparently profiting by taking work away from E.W. Bliss."[115] S&W was now estimating the cost to finish would be over $12 million, or about $2.5 million more than allocated by the NSF based on estimates made only six months earlier. Even this price was predicated on a November 1963 completion, and Reynolds emphasized that "if AUI and NSF want this instrument at the estimated price, unusual efforts will have to be made to prevent the construction schedule from going into an additional year."[116] At this point, the Trustees seriously debated "whether completing the telescope … was the best use of funds available for the support of the Observatory." They concluded, however, that, "the adverse effect, from the public relations point of view, of abandoning the project," and the instrument's promise "to be a very valuable research tool for many years to come," were sufficient motivation to complete the construction of the 140 Foot Telescope.

Following the resignation of Otto Struve as NRAO Director, and pending the arrival of the new Director, Joe Pawsey, Dave Heeschen became NRAO Acting Director on 1 December 1961 (Sect. 4.6). Maxwell Small, the BNL

Business Manager and former Construction Manager for Brookhaven's Alternating Gradient Synchrotron and High Flux Beam Reactor, was recruited as the 140 Foot Telescope Construction Manager. Small set up an office in his home in Boston near S&W, with an agreed goal of being the single point of contact between AUI and S&W. Ensuing discussions among AUI, NRAO, Bliss, S&W, and the NSF, led the new Bliss management to agree to terminate the contract with AUI.[117]

The NSF agreed to the AUI/S&W approach and on the level of financial support required to complete the telescope, in "an amount not to exceed $12,095,000."[118] However, the bids from Bethlehem Steel to re-fabricate and erect the polar axis and spherical bearing were significantly higher than the S&W estimates, as were the estimates from Electric Boat for the drive and control system. Meanwhile, the NSF was becoming increasingly concerned that they were not being fully informed about the negotiations with Bethlehem Steel, nor about the schedule and cost for completing the telescope, but AUI could only respond that these remained uncertain.[119] Unfavorable media coverage and confrontational correspondence with Ashton led to further anxieties at AUI and the NSF.[120] By time of the April 1962 meeting of the AUI Executive Committee, the cost estimated by S&W had risen to $13.3 million.

Completing the Job After S&W had completely redesigned the spherical bearing, the yoke, and the polar shaft, fabrication was subcontracted to various firms.[121] Ashton's 22 foot diameter spherical bearing design, which had been so controversial, had been reduced to 17.5 feet, the largest that could fit with three inch clearance through a rail tunnel near Droop Mountain, WV, on the way to Green Bank (Fig. 4.9). It was the largest nickel steel casting ever poured. A specially built railway car was used to transport the 167 ton bearing from Eddystone, Pennsylvania, where it was cast, to the Westinghouse foundry near Pittsburgh where it was machined to a precision of less than 0.003 inches (Heeschen 2007a, b). The spherical bearing, the polar axis, and the yoke were all shipped to Green Bank, first by rail to the nearby town of Durbin, and then by road over the last 13 miles to the telescope site. A small bridge over a creek near Green Bank needed to be rebuilt in order to bear the 55 foot long 90 ton load of the massive polar axis. Following the advice of Small, a contract for aluminum surface panels was let to the D.S. Kennedy Company, while Electric Boat continued as the subcontractor for the drive and control system. All that remained of the Ashton-designed, Bliss-fabricated telescope was the aluminum backup structure and the already completed 5800 ton concrete and steel foundation, which extended 30 feet below the ground level. The original Bliss polar shaft and yoke were discarded. Some pieces were sent to Brookhaven as shielding for BNL accelerators; the rest was buried in Green Bank where it remains as a memorial to the troubled 140 Foot Radio Telescope.

In planning for the assembly and erection in Green Bank, Heeschen and Small felt that since the ultimate responsibility for the project was with AUI, that AUI rather than S&W should assume more control. Furthermore, they

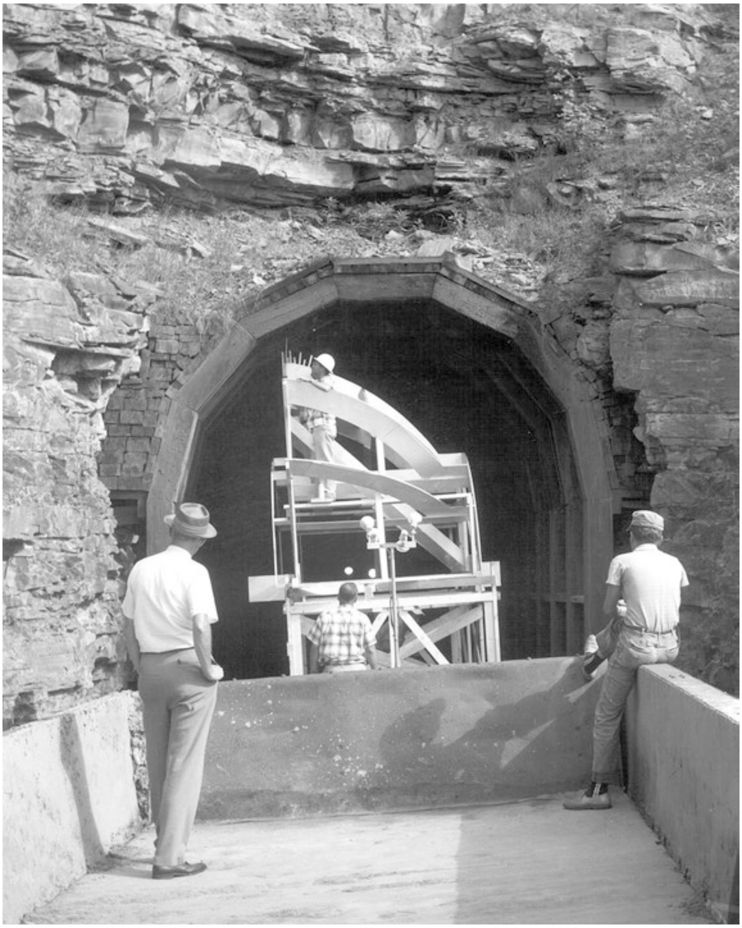

Fig. 4.9 Testing a model of the 17.5 foot spherical bearing for clearance in the rail tunnel through Droop Mountain, 1961. Credit: NRAO/AUI/NSF

argued, "much would be gained by having members of the Observatory staff actively working on the Telescope at the earliest possible date." Although the "Trustees doubted the desirability of diminishing in any way the responsibility of Stone & Webster,"[122] at the 15 February 1963 meeting, AUI decided to modify the contract with S&W to give AUI responsibility for all field operations.

Max Small moved to Green Bank in May 1963 to take charge of completing the fabrication of the backup structure on site, the assembly of the declination and polar shafts, and of the yoke and spherical bearing, all scheduled to arrive by rail from the various plants where they were being manufactured. An anticipated railway strike, which would further delay the construction schedule, threatened to interrupt shipments before the winter, but as it turned out, new problems in fabricating the major components ended up in delaying their shipment and erection in Green Bank.

In September 1963, authority for the 140 Foot project was transferred from the AUI President in New York to the NRAO Director in Green Bank, where the project was handled in the same way as other Observatory projects. Max Small hired two engineers and two clerks to facilitate interaction with S&W, as well as with the various manufacturers. At the 17 October 1963 meeting of the AUI Executive Committee, Small reported that the design was 95% complete, fabrication 70%, and construction 20%.[123] The polar shaft was finally delivered and on site, but due to delays in the receipt of the other major telescope pieces, Small was forced to renegotiate a new erection schedule with Pacific Crane and Rigging. The new contract, which assigned increased responsibility to Pacific Crane for "all work necessary to bring the telescope to completion after the components have been completed and delivered," included additional compensation of $1 million. But D.S. Kennedy reported "a wide variety of problems" in fabricating the surface panels, and stated that they were going out of business after delivering the panels.[124]

The spherical bearing was finally received in late April 1964. It was bolted to the polar axis and then lifted into place without incident. This was followed by separate lifts to hoist the two parts of the yoke into place. On 4 November 1964, a large crowd gathered to witness the final lifting of the telescope backup structure to fasten onto the yoke arms. Pacific Crane and Rigging company was in charge of the lift. However, the 266 ton structure proved too heavy, and when lifted just off the ground a cable snapped. There was no damage except to the cable. Five days later, after repairs and the revision of the lifting procedure (including cutting off a portion of one of the lifting cranes!), the backup structure was successfully lifted into place, and was bolted to the yoke the following day.[125] The 140 Foot major structural work was finally complete. All that remained was the installation of the 72 surface panels. Preliminary tests indicated that the panels distorted due to solar heating, but this was largely mitigated by the use of a special paint designed to scatter the incoming solar radiation and radiate strongly in the infrared, thus keeping the dish surface below ambient air temperature. By the end of 1964, all the surface panels were in place on the backup structure, and the two 167 foot tall cranes were dismantled. On 23 December 1964, the telescope was moved for the first time, and pointed to the zenith, with the entire 2700 ton weight of the rotating structure sitting on four oil pads, floating on a thin film of oil only 0.005 inches thick and under 3000 pounds per square inch pressure.

The 140 Foot Telescope (Fig. 4.10) construction was finally completed in the spring of 1965. The many delays and huge cost overrun of the project, which required unexpected additional funding for NRAO had challenged the credibility of the Observatory, and even the concept of a national federally funded facility. But this quickly changed with the introduction of a vigorous visitor program and the resultant flow of scientific results, particularly in the area of centimeter wavelength spectroscopy.

Fig. 4.10 Completed 140 Foot Radio Telescope. Credit: NRAO/AUI/NSF

The first astronomical observations with the 140 Foot Telescope were made on 22 May 1965 at 234 MHz (1.3 meters) and 405 MHz (74 cm) to study the Crab Nebula during a lunar eclipse. In July 1965, Bertil Hoglund, a visiting scientist from Sweden, and NRAO staff member Peter Mezger, detected a long sought hydrogen recombination line at 5 GHz (6 cm) (Sect. 6.2). Painting the telescope took place throughout the summer of 1965, while observations continued at 11, 6 and 2 cm. The aluminum panels were set during the summer nights to minimize the effect of solar heating and distortion.

The final cost of the 140 Foot Telescope was about $14 million. The dedication was held on 13 October 1965. Unlike the dedication of Green Bank eight years earlier, it was a beautiful sunny day. More than 150 visitors joined the NRAO staff by a podium erected under the telescope, surrounded by the splendid West Virginia fall foliage. One of the authors, (KIK) clearly recalls that in his speech at the dedication, Dave Heeschen remarked, "This isn't the largest radio telescope in the world, but it is the largest equatorial mounted radio telescope in Pocahontas County, West Virginia." Indeed, no radio telescope larger than 85 feet was ever again built with a polar mount, and since the late 1990s, starting with the Keck 10 meter telescope on Mauna Kea, all large optical telescopes now use the much simpler alt-az mountings which had been rejected by AUI for the 140 Foot Telescope.

By the end of 1965, the telescope had been used at wavelengths as short as 9 mm. However, due to large scale deformations when the telescope was tilted from the zenith, the aperture efficiency decreased substantially at wavelengths shorter than about 3 cm. Due to the nature of the equatorial mount, the efficiency changed differently with hour angle or declination. In 1976, as a test bed for the VLA antennas, the 140 Foot Telescope was modified so it could be used at the Cassegrain focus. Two years later, the fixed subreflector was replaced with a deformable subreflector whose surface was adjusted to partially compensate for the loss of gain at low elevations. The 140 Foot Telescope was originally designed to have a pointing accuracy better than 10 arcsec so that it could be used to determine accurate radio source positions (Struve 1960; Drake 1960), although by the time it was completed in 1965, it had become clear that radio source positions are best determined by interferometric means. In fact, 140 Foot pointing errors up to 30 arcsec, especially in the daytime, continued to plague observers, especially when observing at short centimeter wavelengths where the beamwidth was only a few arcminutes across.[126]

Until AUI relinquished control of the project to NRAO in September 1963, the 140 Foot Telescope was the first and only construction project managed directly by AUI, rather than by Brookhaven or NRAO. Throughout the project, maintaining that operation at short centimeter wavelength with a 140 foot diameter dish would provide unique opportunities, the NRAO staff had always argued against relaxing the performance specifications in order to limit the ever-increasing cost. The 140 Foot was smaller than the Jodrell Bank 250 foot, the Australian 210 foot, and Canadian 150 foot antennas, and had only a small fraction of the collecting area of the Arecibo 1000 foot dish (Sect. 6.6). Neither the pointing precision nor the surface accuracy were as good as either the Haystack 120 foot or the Canadian 150 foot telescopes, both of which were completed earlier and in routine operation well before the completion of the 140 Foot Telescope. By time the 140 Foot was completed in 1965, the Parkes 210 foot radio telescope was already in operation at wavelengths as short as 6 cm, and by 1972 at 1.3 cm. But as described in Sect. 6.2, as a result of the outstanding instrumentation and a competitive “open skies” access policy, until the completion of the VLA in 1980, the 140 Foot Telescope was arguably the most productive radio telescope in the world, with a growing oversubscription rate. Of particular interest was the use of the deformable subreflector and 1.3 cm maser radiometer for a wide variety of programs to study interstellar water vapor and ammonia. From 1967 until the completion of the VLBA in 1993, the 140 Foot Telescope was the backbone of the growing national and international VLBI effort.

In July 1999, for lack of operating funds, the 140 Foot Telescope was closed as an NSF-supported user facility for astronomical observations. For several years an independently funded MIT group used the antenna for ionospheric studies. Later, with financial support from the Russian Astro Space Center, it was resurrected in 2013 as a ground station for the Russian RadioAstron space VLBI mission (Sect. 8.9).

John Findlay later remarked, "no one with hindsight will deny" that "the choice of an equatorial mount was idiotic,"[127] and that the choice of a hydrostatic bearing which was copied from Palomar was foolish, while Bernard Burke described the 140 Foot Radio Telescope as having "served well, but its equatorial geometry is antique, its structural flexure is dreadful, its surface quality is inferior, its maintenance is expensive and man-power intensive, and its pointing is substandard."[128] Grote Reber was a bit more colorful in his appraisal of NRAO and the 140 Foot project. Writing to John Findlay, he remarked, "If such an affair had happened during the days of Elizabeth I, there would have been some public hangings."[129]

In 1992 Dave Heeschen summarized the 140 Foot project, by saying[130]

> The 140 foot is a classic example of how not to design and build a telescope. The design specs were set by a committee of outside consultants who had no responsibility or accountability for the final result, and who gave liberally of poor advice. The 140 ft project leader [Dick Emberson], a very nice gentleman who was [assistant] to the president of AUI and responsible for the entire feasibility study that led to the establishment of NRAO, uncritically accepted all this advice. The telescope was originally going to have an az-el [*sic*] mount because the consulting engineers thought that was the most feasible…. But the steering committee membership changed from time to time and finally had on it a prominent and outspoken scientist [Tuve] who insisted the mount should be equatorial…. Then the solar astronomer [Menzel] on the steering committee decided that the telescope should observe the sun from sunrise to sunset on Jun 22 each year.
>
> The errors made in bidding, contracting, and construction were even worse…. AUI wound up with a fixed price contract, for $4 million, with a company—E W Bliss—that really didn't want the job, except for one enthusiastic vice [president] who apparently bullied them first into accepting the final contract. He quit shortly afterward and AUI was left with a semi-hostile contractor.

Some important lessons were learned, or should have been learned, from the 140 Foot experience:

1) beware of the lowest bidder;
2) be sure the contract is clear about who is responsible for what;
3) finish the design before starting construction;
4) establish clear points of contact, authority, and responsibility on both sides;
5) have a firm understanding of when the antennas will be delivered, with penalties for late delivery;
6) don't take committee advice too seriously; and
7) have good in house expertise.

Regrettably, many of these same issues arose with the ill-fated 600 foot Sugar Grove antenna and resurfaced 25 years later with the Green Bank Telescope (Chap. 9).

4.5 The 300 Foot Transit Radio Telescope

By early 1958, the 140 Foot Telescope was no closer to completion, and it was not even clear if it would be completed (Heeschen 1996). While NRAO scientists were able to do some interesting observations with the Tatel 85 foot telescope, it was by no means a state of the art facility that would attract visiting observers in the way that had been expected for the US national observatory. Not only did the University of Michigan operate a similar, and indeed, a somewhat better 85 foot antenna, but competing facilities were coming on line throughout the world, even within the United States. Both Germany and the Netherlands were operating 25 meter class radio telescopes; Jodrell Bank had their 250 foot dish; and planning for the Parkes 210 foot radio telescope was well along. At Caltech, with financial support from the Office of Naval Research, John Bolton was building a novel two-element interferometer in the Owens Valley, capable of operating at centimeter wavelengths. With a modest budget that was dwarfed by the generous NRAO NSF budget, Caltech scientists would begin an ambitious radio astronomy program that would make the Owens Valley Radio Observatory the dominant radio astronomy facility in the US.

With only a modest radio telescope, essentially no visiting observers, and facing increasing concerns about when, or even if, the 140 Foot Telescope would be completed, John Findlay and Dave Heeschen thought a fixed 300 foot miniature Arecibo type antenna could be built for about $300,000. But their 1958 proposal was not well received by the NRAO Visiting Committee or by the NSF.

A year later, Findlay and Heeschen developed a bold plan to build the best antenna that they could for not more than about $1 million, which they thought to be the largest amount of money the NSF would approve without long delays. Following his appointment as NRAO Director in July 1959, Otto Struve was able to sell the project to the Visiting Committee and then to the NSF (Heeschen 2007b, 2008). A 300 foot transit antenna, movable only in elevation, thus simplifying its design and limiting the construction cost, seemed to offer the best compromise between opportunity for scientific returns and price. Funding was approved in the 1961 NSF budget. John Findlay became the project manager, and recruited Bob Hall to design the telescope.

Hall had just left Blaw-Knox for a new position at the Rohr Corporation, which was anxious to get into the antenna business. Between his jobs at Blaw-Knox and Rohr, with the aid of five Blaw-Knox engineers, Hall spent six weeks at the end of 1960 working for NRAO from his home in Chula Vista, CA, to design the 300 Foot antenna. Later, Ed Faelten was retained to complete the engineering drawings necessary for construction bids. To meet the limited construction budget, the design was kept simple. Specifically, the height of the supporting towers was limited, which constrained elevation motion to 60 degrees from the zenith and the corresponding observable declination range from the north pole to minus 19 degrees. The antenna was driven in elevation by a 230 foot long quadruple chain which wrapped around the antenna elevation wheel. The construction cost was further reduced by using standard steel members, simple joints and bearings, and constructing the reflecting surface from chicken wire rather than solid panels. It was anticipated that the future would see a large, fully steerable, radio telescope at NRAO, so the useful scientific life of the 300 Foot was expected to be not more than about five years. Emphasis was on getting it completed and on the air quickly, rather than longevity. The 3/8 inch chicken-wire holes would restrict the operation to wavelengths longer than about 20 cm, but the 300 Foot antenna nevertheless became a powerful facility for both galactic and extragalactic 21 cm H I research, as well as for continuum source observations.

In April 1961, NRAO contracted with Bristol Steel and Iron Works to construct and erect the antenna. Groundbreaking in Green Bank was on 27 April 1961. Under Findlay's leadership, construction took less than 18 months at a cost of about $850,000, a record construction time for any large radio telescope project. On 21 October 1962, the 300 Foot Telescope was handed over to the Green Bank operations staff and began its first astronomical observations. The next day, President John F. Kennedy announced the US naval blockade of Cuba in response to the discovery of Soviet missile bases a week earlier. Two days later, the US military went on the highest military alert since 1945, and the start of observations with the world's largest parabolic dish went relatively unnoticed by the nation.

The 300 Foot Radio Telescope, now one of the most powerful radio telescopes in the world, became an immediate success. For the first time, NRAO had a world class instrument that was attractive to both visitors and NRAO staff. The successful completion of the 300 Foot transit radio telescope probably saved Green Bank from a premature closing resulting from the continued debacle with the 140 Foot antenna project. From the start of 300 Foot observations, the Observatory operated as the first true visitor facility for radio astronomy. One of the earliest visiting observers was Bernard Burke who, with his colleagues from DTM, brought a 100 channel receiver for 21 cm spectroscopy in November 1962. Gart Westerhout, who had recently arrived in the US from the Netherlands to start a radio astronomy program at the University of Maryland, became a regular user of the 300 Foot Telescope. At the start of each summer, Westerhout would arrive in Green Bank with his family and a cadre of students to help observe and reduce data, and to escape the heat and humidity of the eastern Maryland summers. According to Heeschen (2007b), the 300 Foot taught NRAO how to manage an oversubscribed telescope, train operators, provide calibration and documentation, and, in general, deal with visitors. Unlike the 85 foot and 140 Foot antennas, the 300 Foot was the first of a series of antennas and arrays that would be conceived by NRAO staff and built under the direction of NRAO.

Initially, the rim of the 300 Foot antenna would hit the ground at low elevations, so the antenna could not be moved over the full 60 degree range of zenith angle allowed by the drive system. In October 1962, at Frank Drake's urging, the Observatory started to dig a pit at the south side of the structure in order to lower the antenna elevation limit. But the excavation reached bedrock after digging only six feet below the surface. The Green Bank site manager, Bob Elliot, suggested deepening the pit further by using dynamite, much to the chagrin of the conservative scientists who were concerned that the blast might destroy their new telescope. Indeed, the explosion sent rock and other debris more than 100 feet into the air, scattering the crowd that had assembled to watch the big event. Fortunately, no one was hurt, but one of the rocks put a one foot hole in the dish surface.[131] However, the exercise was successful in extending the southern declination limit to minus 19 degrees.

By the summer of 1966 several structural deficiencies had become apparent, and the backup structure was strengthened with the addition of 20,000 pounds of steel, 120 sections of rib structure were replaced, and welding added another 7000 pounds to the structure. The wire mesh surface, which was irregular to start with, further deteriorated as a result of staff walking on the antenna surface, and in October 1966 the surface was removed and flattened by laying sections on the ground and running over them with a steam roller (Fig. 4.11).

Although the 140 Foot antenna later became the NRAO workhorse, it was primarily used for centimeter wavelength spectroscopy. For continuum observations at longer wavelengths, the 140 Foot was limited by confusion,[132] while for 21 cm spectroscopy, observers preferred the greater collecting area and better resolution of the 300 Foot. The 300 Foot was designed to be used in a "drift-scan" mode, where the antenna would be driven in elevation to the declination of interest, shortly ahead of meridian transit, and the rotation of the Earth would allow the source or area of interest to drift through the antenna beam, typically in about one minute. To increase the available integration time, in 1969 a so-called "traveling feed" was constructed, which would allow the antenna beam to track equatorial sources for up to an hour depending on the wavelength of observation. The travelling feed was later replaced in 1980 with a unit that supported heavier cryogenically cooled receivers.

By 1970 it was becoming clear that the basic antenna structure and pointing were sufficiently precise to allow operation at a shorter wavelength than 21 cm, but the chicken wire surface was too porous and too irregular for this purpose. In 1970, NRAO replaced the original chicken-wire surface with perforated aluminum panels. The contract for the new surface was placed with a new, relatively unknown company, Radiation Systems Inc. (RSI) from Sterling, VA. Richard (Dick) Thomas, the president and principal owner of RSI, was anxious for business, and apparently underbid for the contract. NRAO Associate Director Ted Riffe recalled that Thomas realized that he was about to lose a large amount of money, and appealed to the NRAO to renegotiate the contract. Riffe, who had come to NRAO from the West Virginia coal mining industry, was a hard-nosed business man who sat quietly while Thomas explained where he had made an error, how his error would hurt his employees and the economy of Northern Virginia, how his family would be deprived, his children not able to go to college, and so on. Finally, Riffe looked Thomas in the eye and replied, "Bull shit!"[133] NRAO did not adjust the price, but RSI

Fig. 4.11 Working in vain effort to smooth the surface of the 300 Foot Telescope, October 1966. Credit: NRAO/AUI/NSF

weathered the storm and went on to become a major player in the antenna industry, including constructing the surface panels for the VLA (Chap. 7), and contracting to build the ten VLBA antennas (Chap. 8). But 20 years later, again in his anxiety to win the contract, Thomas would underbid for the GBT (Chap. 9), leading to a huge cost overrun and eventually the end of RSI.

Over the next years there were many minor 300 Foot repairs, including additional weldings and more reinforcing structures, and the structure was repainted multiple times. An unanticipated use of the 300 Foot Telescope, one that would later prove fatal, was to take advantage of the great sensitivity by rapidly moving the antenna in elevation to cover a wider area of the sky than possible with only Earth rotation drift scans. When first proposed by the Green Bank scientists, Fred Crews, head of telescope operations, was reluctant to introduce the unplanned stresses on the telescope that would result from nearly continuously driving the antenna and from the rapid reversals of direction which would occur at the end of each scan.[134] Naturally, the scientists wanted to limit the time wasted in turning the telescope around at the end of each scan. Following review by the cautious telescope operations staff, operators began the practice of slowing the antenna to a gradual stop before reversing its direction, thus minimizing any sudden decelerations or accelerations.

The 300 Foot antenna was built to withstand snow or ice loads up to 10 pounds per square inch (Lockman et al. 2007, pp. 103–105). While dry snow might fall through the chicken wire surface, wet snow or ice could become a serious problem. During the first few years, the dish was tipped during snowstorms, and most of the snow would fall out. But on two occasions, a small army of site personnel had to use brooms to sweep up the snow, and it was difficult to avoid damaging the surface by walking only along the ribs. On one occasion small fires were built under the dish to melt the snow, but the melting snow dripped down and extinguished the fires. At Findlay's semi-serious suggestion, NRAO acquired a surplus jet engine, which was used to blow snow off the dish. Needless to say, for nearby households, the sound of a jet engine running all through a snowy winter night was like trying to sleep next to an airport where the same plane was continuously taking off. The use of the jet engine to de-ice the dish was abandoned after a few years, in deference to residents of Green Bank and Arbovale, and because of the considerable maintenance required to keep the engine operational. Following the installation of the new more robust aluminum panel surface in 1970, snow accumulation was less of a concern.

4.6 Jumping Ship

Lloyd Berkner Resigns as AUI President Even while juggling the two simultaneous jobs as President of AUI and Acting Director of NRAO, Berkner assumed many other national and international responsibilities. In 1955, he became president of the International Council of Scientific Unions (ICSU), then president of the International Union of Radio Science (URSI), and was the leader of the 1957–1958 International Geophysical Year. From 1958 to 1962, he was Chair of the newly created National Academy Space Studies Board, and from 1956 to 1959 a member of President Eisenhower's Science Advisory Committee. In 1957 he became a member of the Board of Texas Instruments, and in 1958 he returned to Antarctica to prepare a report for Eisenhower that became the basis for continuing the US Antarctic program. Following his resignation from AUI in late 1960, in the midst of the 140 Foot construction problems and corresponding unrest among the Green Bank staff, (Sect. 4.4) Berkner went to Dallas, TX, to become the first president of the new Graduate Research Center of the Southwest. On 22 November 1963, Berkner was waiting to have lunch with President Kennedy, whom he had welcomed to Dallas earlier in the day before he began his fateful motorcade.

Although Berkner's resignation as AUI President did not become effective until 30 November 1960, as discussed in Sect. 4.4, AUI records show that the Board of Trustees had already accepted his resignation at their annual meeting on 21 October 1960, following his announced resignation on 23 September 1960 at a closed session of the Executive Committee.[135] Presumably, Berkner must have sometime earlier begun discussions with the group in Texas. At this same meeting on 21 October, the AUI Board appointed a selection committee chaired by Trustee Edward Reynolds, the Administrative Vice President at Harvard and a retired brigadier general, to "nominate one or more individuals" to succeed Berkner. At their 18 November meeting, probably recognizing the time required to recruit a new President, the Board appointed Brookhaven Director and AUI Vice President, Leeland Haworth as AUI President. Haworth served as President for only four months, until 30 March 1961 when he took a leave of absence from AUI to accept a position on the Atomic Energy Commission. During this entire period Haworth also continued in his demanding role as Brookhaven Director. He was succeeded as President by Edward Reynolds. Since Berkner's resignation, Reynolds had taken charge of the 140 Foot project, but, by previous agreement, he only served as AUI President for three weeks. AUI stayed inside in choosing their next president, and, on 21 April 1961, named I.I. Rabi, Trustee from Columbia, to be President.

Rabi was known as a no-nonsense individual who demanded and accepted nothing less than excellence from his students and colleagues. He was well known for his 1944 Nobel Prize-winning discovery of nuclear magnetic resonance. In 1947, Rabi and his students were the first to make a laboratory measurement of the 1420 MHz hyperfine line in hydrogen, which led to his development of the hydrogen maser atomic clock. During WWII, he worked on microwave radar at the MIT Radiation Laboratory where he became Deputy Director, and later worked as a consultant to the Manhattan Project, which brought him to the 1945 Trinity test at Alamogordo, NM. In 1946, along with MIT and Harvard scientists, Rabi founded the Brookhaven National Laboratory, and became a founding Trustee of Associated Universities, Inc. He was later influential in the formation of CERN, and as a statesman for national and international cooperation in science (Ramsey 1993). Rabi served as AUI President until 19 October 1962, at which time he became Chairman of the AUI Board, a position which he held for a year. Rabi was succeeded as AUI President by Gerald Tape, who had been the AUI Vice President and Deputy Director at Brookhaven where he had oversight of the large reactors and accelerators. Like Rabi, Tape had worked at the MIT Radiation Laboratory during the War where he was an important liaison between the Rad Lab scientists and Army and Navy officers responsible for implementing these new instruments of electronic navigation. Tape left AUI on 10 July 1963 to become the US Ambassador to the International Atomic Energy Commission (IEAC), at which time Edward Reynolds again chaired a search committee for a new AUI President. AUI Trustees Curry Street, Frank Long, and Norman Ramsey all declined, so Reynolds assumed the position on an interim basis starting 10 July 1963. Expressing frustration over the rapid turnover of Trustees and lack of active participation of the Trustees in the affairs of the corporation, Reynolds notified Rabi that he did not want to continue as President after the October 1963 Board meeting,[136] but he was convinced to remain until 1 December 1964, when he was succeeded by Theodore Wright, who served from 1

December 1964 to 1 October 1965. Reynolds was succeeded by Theodore Wright (1 December 1964 to 1 October 1965), T. Keith Glennan (1 October 1965 to 30 June 1968), and then Franklin Long as Acting President (1 July 1968 to 1 May 1969), After completing his term as IEAC Ambassador, Jerry Tape returned to AUI as President from 1 May 1969 finally bringing much needed stability to AUI. Tape retired as AUI President on 10 October 1980 and was succeeded by Robert Hughes, a chemist from Cornell, and former NSF Assistant Director for Mathematical and Physical Sciences.

Dick Emberson, who had been so instrumental in leading the feasibility studies leading up to the 1956 establishment of NRAO, and then became director of the 140 Foot construction project, remained as 140 Foot project director and as NRAO Acting Deputy Director, but according to Dave Heeschen (1996) his role was diminished after S&W became involved. After Heeschen became NRAO Director in October 1962, Emberson left AUI to become Director of Technical Services, and then Executive Director and General Manager, of the Institute of Radio Engineers (IRE) later to become the Institute of Electric and Electronic Engineers (IEEE).

Otto Struve Resigns as NRAO Director In his Biographical Memoir for the National Academy of Science, Kevin Krisciunas (1992) described Struve as "both dedicated and demanding," and said "his physical appearance and demeanor" were imposing and intimidating. Although he was greatly respected by Dave Heeschen and the NRAO scientific staff, Struve's European background and somewhat conservative life style did not mesh well with the much younger and enthusiastic NRAO scientific staff or with life in rural Appalachia. He became frustrated by his inability to recruit scientists to the NRAO staff, a problem he recognized was due in large part to the lack of world class observing facilities, an absence which was exacerbated by the delays in the 140 Foot Telescope construction project and the isolated location of Green Bank. In addition to his demanding responsibilities as the NRAO Director, throughout his tenure Struve tried to maintain an active program of personal research and publication in areas unrelated to the NRAO mission, and became increasingly frustrated by the need to attend to administrative matters and by seemingly endless meetings.

Following Berkner's resignation and Struve's 1960 attempt to resign over the escalating issues surrounding the 140 Foot Telescope construction (Sect. 4.4), the NRAO Scientific Staff recognized that the reputation of the Observatory, as well as their relations with Struve, were being questioned. Led by Heeschen, the staff sent a very carefully worded letter to Struve expressing their confidence and their wish that he "continue as director as long as possible."[137] But recognizing both Struve's declining health and endurance, and his limited understanding of radio astronomy instrumentation, they suggested that AUI appoint a Deputy Director as soon as possible to assist Struve.

In January 1961, Haworth and the Trustees Committee on NRAO, went to Green Bank to personally assess the situation at the Observatory. The

Committee report recommended that "all engineering activities … be centered in Green Bank as rapidly as feasible," that a mechanical engineer be recruited to "participate in the completion of the 140' Telescope" and "become the leader of a permanent group which will have the responsibility for the design, construction, and maintenance of a continuing series of mechanical structure."[138] But they added that "for the present the negotiations with E.W. Bliss Company and the National Science Foundation regarding the 140′ telescope must of necessity be carried out by the officers of AUI." Finally, fearful of the adverse publicity and reaction of the NSF if Struve were to resign, they stressed "that the steady guiding hand of Dr. Struve is essential to the success of the National Radio Astronomy Observatory." Noting that "if certain conditions are met, Dr. Struve might reconsider his earlier announced wish to retire," the Committee urged "the President to explore with Dr. Struve the measures that would make it possible for him to continue." Struve responded to the Trustees that he would reconsider his request to be relieved of the Directorship in the summer of 1961, and, health permitting, to continue for at least one to two years more.[139] Prompted by Heeschen's letter and a proposal from Struve, AUI appointed John Findlay as Deputy Director of NRAO, and Dave Heeschen as Assistant to the Director replacing Findlay. At this point Findlay, who was ten years older, clearly outranked Heeschen, but the Board instructed Struve to explain to Findlay "that the appointment as Deputy Director should not be regarded as a stepping stone to the Directorship, because the Trustees believed that the director of the Observatory should be an astronomer."[140]

Although there appear to be no further questions about Struve's position as NRAO Director by either AUI or by Struve himself, Rabi had apparently concluded that he didn't want Struve to remain as Director of NRAO, and he began to work behind the scenes to find a replacement. In June 1961, during a visit to Green Bank, probably at Rabi's suggestion, Bart Bok wrote to Joe Pawsey to informally ask if he might be interested in the NRAO directorship.[141] Pawsey responded unenthusiastically, claiming that Green Bank was too "committed to big paraboloids," and that his "interest is in techniques," but he left the door open for possible further discussion.[142] Pawsey came to the United States during the summer and early autumn of 1961 to attend the August meeting of the International Astronomical Union that was held in Berkeley, CA, and also to visit various radio observatories and his brother-in-law, Ted Nicoll, who lived in Princeton, NJ. During a visit with Pawsey at the home of Pawsey's brother-in-law, Rabi discussed the Green Bank situation with Pawsey and asked him for his impressions of the situation there.

Following a three-day visit to Green Bank, Pawsey wrote to Rabi on 5 October 1961 that he "found the situation disappointing," and that none of the staff are "really first rate." But he was impressed by two visitors, T.K. Menon and Sander [Sandy] Weinreb, who was using the Tatel Telescope for his PhD research.[143] Pawsey reported that "the director's experience has not been in the field in which the staff is weak,—the technical radio and experimental physics side." Interestingly, and perhaps with some envy, he went on to say that, "Both

Greenbank [*sic*] and U.S. radio astronomy suffer from the same basic difficulty: a dearth of good radio astronomers and the too ready availability of elaborate equipment." Consistent with his earlier remarks to Bok, Pawsey only gave lukewarm support to the 140 Foot and 300 Foot antennas then under construction. However, he noted that for prestige and staff morale, both the 140 Foot and 300 Foot Telescopes "should be completed as soon as practicable." But the best he would say about the 140 Foot was that it will be "a thoroughly useful instrument." Pawsey stopped short of suggesting that the 140 Foot equatorial design should be abandoned in favor of the "master equatorial" idea used by Freeman Fox in designing the Parkes 210 foot or the Algonquin Park 150 foot dishes, but he did suggest that the Green Bank "engineers should be informed of the existence of the Freeman Fox design," as "there could be snags in the original Greenbank [*sic*] design and this could be a replacement." Citing the report of the NSF Pierce Committee (Keller 1960) Pawsey declared that "future emphasis should be directed toward instruments having a resolution of 1′ or less," and went on to suggest that NRAO might try to hire W.C. [Bill] Erickson and Sander Weinreb.

It is not clear what transpired between Rabi and Pawsey during their Princeton conversation and to what extent Pawsey's Green Bank visit was considered by either of them as being only in an advisory capacity, or whether either or both of them thought of it as a response to Pawsey's consideration of the possibility of becoming NRAO Director. Pawsey's use of phrases such as, "I should also like to encourage," or "My view is," and "I envisage" as well as "During my initial preparatory phrase," certainly suggests that Pawsey was responding to Rabi's overtures about the NRAO Directorship, and that he was seriously considering the possibility.

Three weeks later, the minutes of the 26 October 1961 meeting of the AUI Board of Trustees Executive Committee, reported that "the Committee held an executive session, at which it was directed that no report be made."[144] During a discussion of the renewal of the AUI contract with the NSF, Rabi expressed concern that if the contract were extended for only two years, that this might "impede the selection of a new director to replace Dr. Struve."[145] This was the first indication that changes might be forthcoming, although there was apparently no further indication from either Rabi or Struve that either might be aware of any imminent change. During his presentation to the Executive Committee, Struve commented that "the entire staff of the Observatory supported the continuation of AUI management of the observatory. The consensus of the Trustees was "that every effort should be made to obtain an extension of at least three and preferably five years." Struve reported on the good progress being made with construction of the 300 Foot dish (Sect. 4.5) and his concern about turnover in the scientific staff, while AUI Vice President Edward Reynolds gave a report on the status of the 140 Foot project (Sect. 4.4). After the formal adjournment, the minutes report that Trustees moved to another building to hear scientific presentations from Frank Drake on Venus observations, from Dave Heeschen on extragalactic radio source spectra, from MIT graduate student Sandy Weinreb on his attempt to detect the 327 MHz deuterium line and from T.K. Menon on H II regions. Following the formal signature of the Corporate Secretary, Charles Dunbar, attesting that the meeting was adjourned a note was added that,

> At the conclusion of the scientific presentation the Trustees met again in executive session. The Secretary was instructed to make the following report: The President informed the Trustees that Otto Struve had asked to be relieved of his responsibilities as Director of the National Radio Astronomy Observatory on December 1, 1961, or as soon thereafter as could be arranged. The choice of a successor to Dr. Struve was extensively discussed as well as interim arrangements to be made pending the appointment of a new Director. At the conclusion of the discussion, on motion duly made and seconded, all Trustees present voting, it was unanimously VOTED: That the President be and hereby is authorized to offer to Dr. Joseph Pawsey of Sydney, Australia, an appointment as Director of the National Radio Astronomy Observatory on such terms as the president deems appropriate. Dr. Rabi said that he would write without delay to Dr. Pawsey and report the result as soon as possible.

Unlike the frustrating three-year long search that preceded Struve's appointment, there was no search committee, and there is no evidence that Rabi sought the advice of anyone else. At this point, there apparently was no longer any agonizing over whether or not the NRAO director need be an American citizen. Merle Tuve must have been gratified when he heard the news that his 1956 question to the NSB, "Where will the staff come from? UK? Australia?" (Sect. 3.5) had been answered.

Interestingly, this important action was taken by only the AUI Board Executive Committee and not the full Board of Trustees. There is no indication from the agenda that was distributed to the Board on 4 October 1961 that there would be any discussion of Struve's successor, although it seems likely that this was the purpose of the executive session called at the start of the day. There was no statement of who moved and who seconded the motion to appoint Pawsey as the Director of NRAO. The only evidence that Struve had again asked to be relieved of his responsibilities was the announcement by Rabi at the late afternoon unscheduled session.

The next day, 27 October 1961, the full Board of Trustees met for what appeared to be a routine meeting primarily addressing corporate matters and business related to the operation of Brookhaven. Again, there was no scheduled discussion of Struve's successor, nor, according to the minutes, any announcement of the resolution passed on the previous afternoon by the Executive Committee to appoint Pawsey (Fig. 4.12). The only reference to Struve's tenure as Director came up during Struve's presentation of the NRAO Visiting Committee report, where the minutes recorded, "Dr. Struve said that since he is retiring as Director in less than a year, he would like to remind the Trustees of some of the problems he has encountered, in the hope that they

Fig. 4.12 Joseph L. Pawsey at IAU Symposium 4, Jodrell Bank, 1955. Credit: NAA-WTS Working Files, Interviewees

might be avoided in the case of his successor."[146] At the time Struve gave no indication that he expected to retire in only two months.

Apparently, Rabi informed Struve of the outcome of Executive Committee action and suggested that Struve resign on 1 December 1961, as, four days later, on 31 October 1961, perhaps in a face-saving move, Struve wrote to Rabi[147]

> to ask you whether my services at the National Radio Astronomy Observatory could be dispensed with about this December 1, either temporarily or permanently, in order to give me an opportunity to engage more actively in research than I have found it possible to do during the past two and a quarter-years. I feel that I must try to catch up with recent developments in astrophysics and I am unable to do so while I am compelled to spend nearly all of my time in non-scientific meetings and investigations by single persons and groups. These leave me in a state of continuous fatigue which is the cause of other health problems. A leave of absence for several months would of course be the most desirable arrangement from my point of view, if you feel that I deserve it. If this would not be possible, then according to our records I believe that I shall have 45 days of vacation pay due me if I leave by December 1. In either case the Observatory would not have to fear that the scientific staff would be left without guidance and protection, since I gathered from your remarks last week that the problem of my successor has virtually been solved. If you should wish it, I could return to Green Bank for a short time either before Dr. Pawsey arrives or soon afterward.

On 31 October 1961, the same day that Struve wrote to Rabi offering his resignation, Rabi wrote to Pawsey that the AUI Board had approved his nomination to be Director of the National Radio Astronomy Observatory, and that he had already obtained the approval of the NSF Director, Alan Waterman."[148] From the content of Rabi's letter, it is clear that he and Pawsey had previously discussed the matter in London, if not also in Princeton, although Rabi's formal offer letter was written the same day that Struve wrote his letter of resignation. Rabi did not disclose to Pawsey that he expected Struve to retire on 1 December 1961, but rather mentioned that "Dr Struve has asked for retirement as of October 1, 1962."

Pawsey promptly responded that before making a decision, he first wanted to talk with E.G. Bowen and CSIRO Chairman Fred White.[149] Two weeks later, on 17 November 1961, at an executive session of the meeting of the AUI Executive Committee, Rabi reported on the letter he had received from Struve, and the Committee voted unanimously, "pursuant to his own request," to relieve Struve of his duties as NRAO Director.[150] At the same time, David Heeschen was appointed as Acting Director of NRAO, effective 1 December 1961, in anticipation of Pawsey's arrival as the Director in October 1962. Immediately after the AUI Board meeting, Rabi wrote to Struve that the Trustees had accepted his resignation,[151] and also informed the NRAO staff that "at his request," Struve had "been relieved of executive responsibility" as Director of NRAO effective 1 December.[152] Fred White reluctantly agreed to Pawsey accepting the NRAO position, but was concerned that it should appear that Pawsey was accepting an invitation to help the Americans, and not that he was leaving due to any discontent with CSIRO or Australia.[153] Pawsey then accepted a three-year appointment at NRAO, "with the possibility of returning to my employment in Australia at the end of that time," but he made it clear that he wanted to maintain close ties with Australia and would seek increased cooperation between the US and Australia.[154] Since he was unable to take up the position until October 1962, he agreed that, as suggested by Rabi, he make a visit to Green Bank in the spring of 1962. Rabi responded that "your decision leaves us all rejoicing, Waterman, Scherer, myself, the whole board of AUI, the Staff of the Observatory, etc."[155] Heeschen was apparently losing patience with the situation and wrote to Rabi, "I do not intend to take care of all the administrative dirty work at the expense of my own radio astronomy interests and then be simply a rubber stamp to either the NSF or a distant director-to-be on the interesting things."[156]

Expressing his frustration with the 140 Foot situation, Rabi had no patience for Struve's complaining, and after receiving Pawsey's acceptance, Rabi sent a handwritten letter to Taffy Bowen, congratulating him on the recent dedication of the Parkes 210 foot antenna and commenting that "Pawsey is saving my life by coming as director of NRAO next year. The present incumbent although a great optical astronomer has no administrative talent and no knowledge of radio astronomy. We hope now we are off to a better start."[157] Rabi's rather disparaging remarks were clearly unfounded and inappropriate. The problems with Green Bank and the 140 Foot Telescope project preceded Struve's appointment and, in any event, AUI had barred Struve from any role in the 140 Foot project. Moreover, aside from his distinguished career in astronomical research, Struve had been the very effective director of the University of Chicago Yerkes Observatory. According to Osterbrock (1997, p. 159) "Otto Struve resurrected the Yerkes Observatory." He founded the McDonald Observatory in Texas and served simultaneously as a strong Director of the McDonald and Yerkes Observatories (Evans and Mulholland 1986). As mentioned earlier, he was a strong advocate of large astronomical facilities. Dave Heeschen (2008) later described Struve as a "fine person and a great astronomer," who had an important impact on NRAO, but that "his final years were made so stressful by the problems with the 140 foot telescope that he had inherited."

As discussed in Sect. 4.5, after Heeschen and Findlay's proposal to build the 300 Foot dish had been rebuffed in 1958 by the AUI Visiting Committee and the NSF, it was Otto Struve who was able to convince both AUI and the NSF to fund the construction during the depths of despair about the lack of progress with the 140 Foot Telescope. It was also Struve who obtained the money and solicited donations of privately held books and journals for the NRAO library, which today arguably holds the largest collection of any radio astronomy library in the world, including complete runs of many journals such as *Nature*. Before the days of the Internet, the presence of a comprehensive scientific library had an immeasurable impact on scientific life in isolated Green Bank. In 1961, during a time of widespread global tensions, Struve also organized a US-USSR conference on radio astronomy that was held in Green Bank, opening a door which led a few years later to the decades-long NRAO-USSR collaboration in very long baseline interferometry (Sect. 8.2). After leaving NRAO, Struve held visiting positions at Princeton and Caltech, then returned to Berkeley, where he continued to work at the University of California until his death on 6 April 1963.

Joe Pawsey Appointed NRAO Director Although Joe Pawsey had been the founder and leader of the very productive radio astronomy group at the CSIRO Radiophysics Laboratory, he, Bernard Mills, and Wilbur (Chris) Christiansen were irritated with Bowen's focus on the large expensive programs to build the Parkes 210 foot telescope and Wild's solar heliograph at Culgoora (Robertson 1992, p. 198) at the expense of the more traditional Radiophysics innovative programs that had been pursued by the small groups. Two years earlier, fearing that Mills might leave Radiophysics, Pawsey had written to Struve to suggest a joint program to build a Mills Cross at Green Bank, noting that Sydney had the expertise and NRAO had the money.[158] However, in 1960, both Mills and Christiansen left Radiophysics to accept professorships, in physics and electrical engineering departments respectively, at the University of Sydney. Pawsey was particularly angered by the decision, which was made without consulting him, to appoint Bolton as head of the Parkes radio telescope. Pawsey had been made irrelevant by Bowen (Robertson 1992, p. 200; 2017, p. 227) and was open to Rabi's offer. Dave Heeschen (2008) and the NRAO staff were pleased with the selection of Pawsey and were looking forward to his coming to Green Bank as the NRAO Director.

As agreed, after stopping off in Pasadena to meet with Struve, Pawsey met with Rabi at the Princeton home of his brother-in-law, then attended the 16 March 1962 meeting of the AUI Executive Committee, after which he traveled to Green Bank with AUI Vice President Gerald Tape. One morning, about a week after he had arrived in Green Bank, Campbell Wade observed that Pawsey was dragging his foot,[159] and Frank Drake (Drake and Sobel 1992, p. 26) saw that Pawsey "was partially paralyzed on the left side of his body." Following medical evaluation in Washington, Rabi reported that Pawsey appeared to improve, and "there was every reason to suppose that his recovery will be sufficient to permit him to assume full-time duty at the Observatory on October 1 as planned."[160] However, at the 18 May 1962 meeting of the AUI Executive Committee, Rabi reported that Pawsey's illness "had taken a decided turn for the worse," and, "he is now at the Massachusetts General Hospital under the care of [AUI Trustee] Dr. William Sweet, and that on May 16 he was operated on for a brain tumor. The result of the operation is still uncertain."[161] In an executive session, Rabi expressed the opinion that "The chance that Dr. Pawsey's health will ever get to be sufficiently good to permit him to assume the duties of Director appears to be negligible," and "it will be necessary to find a new Director for the National Radio Astronomy Observatory." Rabi's sober appraisal of Pawsey's condition was confirmed the following month by Dr. Sweet.[162]

Pawsey remained optimistic. While still recovering from the surgery at Massachusetts General Hospital, he wrote a letter for Tape to read and deliver to Rabi following up on their earlier March discussion about his ideas on achieving high angular resolution.[163] Although he had hoped to return to Green Bank to discuss his plans for the Observatory, after his discharge from the hospital on 12 July 1962 Pawsey went to Princeton to recuperate with his sister and brother-in-law. Pawsey and Tape met in Princeton on 18 July, together with Pawsey's wife Lenore and his brother-in-law. Dave Heeschen was also present, and they all agreed that Pawsey should not undertake the NRAO Directorship, but while in Australia, Pawsey would "keep a hand in NRAO programs," and in particular, "the possibility of a cooperative program with CSIRO."[164] Before leaving for Australia, Pawsey prepared a short report outlining his 'general objectives in coming to Green Bank.[165] In his report, Pawsey outlined the following priorities for NRAO:

a) Develop a first-class scientific team
b) Provide extremely powerful radio astronomy equipment
c) The stimulation of US research in radio astronomy

Pawsey discussed two major Green Bank projects: completion of the 140 Foot Telescope, and a project which he said "is not well defined," but which he described as "the high resolution project" with the specific objective of "furthering the study of radio galaxies."[166] Interestingly, Pawsey gave higher priority to the high resolution project than to completing the 140 Foot antenna, but he also commented on a possible future solar program and, with great insight, he endorsed the plans by Frank Drake and Frank Low to develop a millimeter wavelength capability, as well as noting the opportunities for low-frequency radio astronomy.

Accompanied by his wife, Lenore, and Paul Wild from the Radiophysics staff, Pawsey returned to Australia on 27 July 1962.[167] Wild had been in the US for the previous two weeks and had visited Green Bank. Before their departure Rabi tried to recruit Wild to come to Green Bank as the NRAO Director but Wild declined, citing his opportunities and obligations at CSIRO.[168] AUI also considered Robert Hanbury Brown and Henk van de Hulst as possible NRAO directors. But it was recognized that Hanbury Brown was committed to building his intensity interferometer in Australia, and that van de Hulst would not be an effective director at an American national observatory.[169] In November 1962, both Heeschen and Tape made a long planned visit to Australia, where they reviewed the Australian radio astronomy and nuclear research programs, especially the work with the newly completed Parkes radio telescope, and they were able to visit with Pawsey before his death in Sydney on 30 November 1962.

Dave Heeschen Becomes NRAO Director There was little option left for Rabi but to appoint David Heeschen as the Director of NRAO, effective 19 October 1962. Again, there was no search committee or consultation within the community, although Rabi's selection was strongly supported by the AUI Board. Heeschen was only 36 years old, but had been involved with NRAO from the very beginning, first as a consultant, then as an employee of AUI, later as Head of the NRAO Astronomy Division, and finally, since 1 December 1961, as Acting Director of NRAO. In 1960, he received tenure from AUI, but was almost drawn away from NRAO by an attractive offer from the University of Virginia as a Full Professor, Chairman of the Astronomy Department, and Director of the University of Virginia Observatory.[170]

But Rabi had appointed Heeschen over the older and more senior John Findlay, who had originally been recruited by Berkner. Findlay was furious, and never forgave Rabi, who apparently disliked Findlay, and the relationship between Findlay and Heeschen became strained. Findlay developed a drinking problem, and although he continued to take a leadership position in the planning for the long-awaited, large fully steerable telescope (Sect. 9.4), and in the initial planning for the 36 foot millimeter telescope (Sect. 10.2), he was gradually relieved of his responsibilities as Deputy Director, although Heeschen later claimed that he never had the nerve to fire or replace him.[171]

4.7 Exodus from Green Bank

The site chosen for NRAO is actually situated between Green Bank and the even smaller village of Arbovale. From the earliest years, NRAO has used a Green Bank postal address, but the telephone exchange was in Arbovale. For reasons which remain lost to history, the Observatory came to be associated with Green Bank rather than Arbovale. Perhaps "Green Bank" sounded more colorful than "Arbovale," or perhaps AUI was trying to draw an analogy with "Jodrell Bank." Located in Pocahontas County, only about five miles from the Virginia border, local loyalties during the American Civil War were mixed, and the sympathies of the two villages leaned in opposite directions. The local churches were the center of political debate and, as a result of the allegiances founded in the Civil War, there remain today separate United Methodist Churches in Green Bank and Arbovale, located less than two miles apart and sharing the same pastor.

According to the Pocahontas County Historical Society, there is no evidence that "Pocahontas ever set foot in present-day Pocahontas County," but when the then-Virginia county was established in 1821, the Governor of Virginia was Thomas Randolph, who was a direct descendant of Pocahontas. In the early part of the twentieth century, during the heyday of the lumber industry, the small town of Cass, located about ten miles from the Observatory, was a thriving town with a population of more than 2000, which, by the late 1950s had declined to less than 400. The local sawmill was once the largest double band sawmill in the world, producing 1.5 million board-feet of lumber per week. In 1911, West Virginia had more than 3000 miles of logging railroad line, more than any other state in the country. By 2010, only the 11 mile long Cass Scenic Railway line remained. Although remote by almost any measure, a local business proprietor once boasted that half of the people in the United States lived within a day's drive of Cass. Nearby were the colorfully named communities of Clover Lick and Stony Bottom. At the time NRAO arrived in 1956, there were no bars in West Virginia. Alcohol could not be served in public except in restaurants and private clubs. Each county was allowed a liquor store, but the hours were kept limited. Frank Drake later recalled asking a Cass local if he knew where the liquor store was and being told, "Yup, but I ain't gonna tell ya." (Drake and Sobel 1992). On another occasion, after a party at his home, an NRAO scientist had put the empty bottles out in the trash, only to find them removed the next morning. After some investigation, his local cleaning lady confessed that she was so embarrassed that his neighbors might find out that there had been drinking in his house that she hid the bottles. There were no secrets in Green Bank. All telephone calls had to go through an operator in Cass, who, if she wished, could, and probably did, listen in to phone calls going through her exchange; those who shared one's multi-party telephone line undoubtedly listened as well.

In 1996, Dave Heeschen (1996) gave the following colorful description of life in Green Bank when he arrived in 1956 with his wife, Eloise, and their young children.

> In 1956, Green Bank and Arbovale were small villages relatively isolated from the outside world by the mountains and the poor roads. The local residents were almost all descended from a few original families, and spoke a form of English that had been frozen in time by the isolation of the area. That and their distinctive accent made them difficult to understand at times. Like all true Americans anywhere in the world, when they weren't understood they simply spoke faster and louder. Farming and hunting were the only activities, the latter carried out with much more enthusiasm than the former, and with almost total disregard for formal hunting seasons and the laws. In fact, about the only recognition of the existence of hunting laws was that the local schools closed on the opening day of deer season. Green Bank consisted of two small stores, a post office, an Oldsmobile dealership, and a few homes. Arbovale was smaller, having one store with a post office in the store. With a few exceptions the locals were very friendly and welcomed the coming of the Observatory. Many looked at it as a potential source of badly needed jobs.

As most of the NRAO scientific and technical staff came from more urban environments, they, and particularly their families, often did not easily fit into the Green Bank culture. Shopping, medical, and dental facilities were a 40- to 60-minute drive from the Observatory, although a local Arbovale general store carried a wide, yet limited, range of supplies, from food to hardware to equipment needed to castrate bulls. AUI provided funds to help subsidize a local doctor by contracting to provide annual physical exams for all of the resident staff. However, it was even more difficult to recruit physicians than scientists and engineers. At one point a married physician pair were recruited from Norway, but they only lasted a few years. There were long periods when the only local doctor was an osteopath (DO) rather than an MD. More than one child was born on the way to the nearest hospital in Elkins, 50 miles distant over a sometimes treacherous Cheat Mountain.

Winters in Green Bank were cold and the ground could be covered by snow for many months. The only guaranteed frost-free month was July. Opportunities for employment for observatory wives were limited, although some spouses found satisfying work teaching in the local schools.[172] Some parents felt that the local school system was inadequate for their ambitious children, although in fact many of the discipline problems common in larger city school systems were not found in Green Bank. Particularly in the primary grades, there was strong emphasis on the fundamentals. However, owing to the relatively small fraction of the local children that went on to universities, the opportunity to take the advanced level courses thought to be needed for acceptance to elite universities was limited. Many of the local children, when legally allowed, left school to raise families and work. Most of the local children were on reduced-cost lunches, reflecting the generally low income levels in the community.

When she was the Green Bank site director from 1981 to 1983, Martha Haynes frequently told colleagues that the nearest McDonald's was an hour away—over a mountain. The nearest TV stations were also very distant, and the Observatory site had been specifically chosen because it was shielded by the surrounding mountains. Even when using the largest Radio Shack antennas, picture quality from Roanoke and Pittsburgh TV stations was at best marginal.

If incoming staff were required to build or buy homes, it could be a dangerous investment, particularly for scientific staff on term appointments. Unlike most areas of the country where the population was growing, the population of Pocahontas County was decreasing due to the lack of employment opportunities. NRAO reluctantly built 24 houses on the site, mostly in an area that became known as "the rabbit patch"[173] and provided them for staff at a very modest rent. Although intended in principle for young scientists on term appointments, in practice they were also occupied by tenured scientists, engineers, and administrative staff on indefinite appointments. AUI also shared the financial risk with those who chose to build their own homes, and partly guaranteed the mortgages so that local banks could provide low interest loans. In an effort to compensate for the limited medical support in the area, AUI purchased an ambulance and trained staff to serve as EMTs. But even with this additional support, it remained difficult to recruit or retain scientific, and particularly engineering, staff.

In some respects, Green Bank could be an attractive place to live and work, especially if one enjoyed outdoor recreation activities. Opportunities for hunting and fishing were excellent. NRAO families often got together for weekend hikes in the surrounding mountains. A small group of scientists and engineers became active spelunkers and enjoyed investigating the local limestone caves. As in many small towns, local school sports were very popular and often the focus of community activity. One could walk, bicycle (and in the winter, ski) to work if you lived in one of the nearby Observatory houses. Observatory rents were attractive, and maintenance was readily available from the Observatory maintenance staff. Children were free to play and ride bicycles on Observatory grounds without any concerns by them (or their parents) for traffic or other urban dangers. Starting in 1962, NRAO operated a kindergarten on the site. Costs were shared by the NSF, AUI, and the parents.

Nevertheless, the lack of social, medical, and educational opportunities soon became apparent. Staff members, and especially their families, were not happy. Some, like John Findlay, chose to live elsewhere and make the long commute home on weekends. Others, such as Frank Drake, left NRAO to pursue opportunities elsewhere. Interestingly, although there were a few hardy Americans (including one of the present authors—KIK), it was particularly hard to hire American scientists and engineers, who wanted the ambiance of universities and cities. In the mid-1960s, the resident scientific staff in Green Bank had come largely from Germany, the Netherlands, Sweden, Poland, Norway, France, India, and Iraq. By 1962, NRAO was beginning to plan for the design and construction of the VLA and the 36 foot millimeter telescope, and it did not make sense to have either the engineering staff for these projects, or the growing administrative staff, isolated in remote Green Bank. Dave Heeschen made the difficult decision that if NRAO were to maintain its viability, it would be necessary to move the NRAO headquarters from Green Bank to a more desirable location. But who should move and where should they go?

One of the successes of the Green Bank operation was the close collaboration between the scientists and engineers, facilitated, at least in part, by virtue of the fact that they and their families lived, worked, and played together. In particular, the NRAO scientists and engineers worked closely together designing and commissioning new instrumentation. In principle, the scientists might be able to live away from the telescopes in Green Bank, but then they would lose contact with the engineers. There was no distinction at NRAO between design engineers and those who maintained the equipment. An engineer who designed and constructed a piece of equipment was responsible for its operation. If it failed in the middle of the night, the engineer was expected to show up at the telescope and fix it. So there was no obvious way to keep some engineers in Green Bank and not others. Moreover, it was the engineers more than the scientists that motivated moving from Green Bank. The scientific opportunities for research with the unique NRAO facilities in Green Bank might have been sufficient to attract members of the scientific staff, but the same was not true for engineers. Although there were attractive opportunities for engineering research and development at NRAO, salaries were not competitive with the rapidly expanding, attractive opportunities in the military-industrial complex characteristic of the Cold War period.

In May 1962, while still only the Acting Director, Heeschen raised with AUI the idea of moving the NRAO headquarters from Green Bank. Trying to minimize the impact of a split operation, he looked for nearby possibilities, and considered Charlottesville, VA, home of the University of Virginia (UVA) and Morgantown, WV, home of West Virginia University. Both cities were about a two and a half-hour drive from Green Bank. Charlottesville seemed to offer better living conditions and had the stronger university.[174] Moreover, the West Virginia University did not have an astronomy program. Although UVA had one of the oldest Astronomy Departments in the country and operated a 26 inch telescope that had been the gift of Leander McCormick, the department languished for many years while the university pursued excellence in the humanities and related areas. In 1960, Heeschen had seriously considered the offer from UVA to head the astronomy department, so he was familiar with UVA and with Charlottesville.

After a long search, UVA had finally hired Larry Fredrick in 1962 to rejuvenate the Astronomy Department and the McCormick Observatory. Shortly after Fredrick arrived at UVA, Heeschen called him on the phone to ask if “they could chat.”[175] When he arrived in Fredrick’s office, Heeschen closed the door and hesitatingly asked if Fredrick would object if he brought the NRAO headquarters and the scientific staff to UVA. Fredrick was enthusiastic and set up a meeting with UVA President Edgar Shannon, who indicted that UVA could provide the land and attractive financial conditions to construct a building for NRAO on the UVA Grounds. A local bank indicated they would finance mortgages for staff purchasing homes in Charlottesville. Everything was set, but Heeschen needed to first convince AUI, who five years earlier had gone out on a limb with the NSF and Merle Tuve to "build an extensive community in the deep woods." (Sect. 3.3).

Heeschen's recommendation to move the NRAO headquarters from Green Bank turned out to be very controversial. At its 17 May 1963 meeting, the AUI Executive Committee debated the arguments pro and con for moving the NRAO headquarters to Charlottesville. The Trustees were split on whether or not to move, and those who did support a move were split on the relative merits of remaining close to Green Bank or locating at a prestigious university. Some Trustees considered easy access to Green Bank as the strongest factor in determining the best location; others argued that "a congenial and stimulating environment for the scientific staff … should be the primary consideration." AUI President Gerald Tape expressed concern that if the new headquarters became part of a university "there would be little reason for the AUI-NRAO mechanism," and that the Observatory might "easily deteriorate into simply one more radio astronomy laboratory," and lose its identity as a National Observatory. The Trustees concluded their meeting with a request to Heeschen "to prepare for consideration by the Trustees a detailed statement of operating plans under a split location arrangement," saying that "considerations should be given to several possible headquarters locations."[176]

Although his presentation to the AUI Executive Committee was scheduled for the afternoon of 18 July 1963, a small subgroup of Trustees asked Heeschen to be available in the morning for "a full discussion" and "following that distribute his memorandum with whatever revisions the morning discussion has produced."[177] The formal presentation and discussion stretched over two days. Instead of presenting several possible locations as instructed, Heeschen opened his four page report with, "I recommend that NRAO establish offices in Charlottesville, Virginia and that scientists and certain other members of the staff be transferred there."[178] After summarizing the need to move, his report weighed the advantages of a "stimulating and intellectual environment" against "closeness to Green Bank," and argued that it was essential to be close to Green Bank. He also noted that the planned VLA and 36 foot millimeter telescopes would mean that Green Bank would be less important as the administrative, technical, and scientific headquarters for a broadly geographically dispersed Observatory. After extensive discussion among the Executive Committee, Ed Reynolds, who had taken over the AUI Presidency from Tape, appointed a committee to guide a detailed study of the proposed move. The committee was chaired by Carl Chambers and included three members of the Board plus Emanuel R. (Manny) Piore from IBM.

The committee supported Heeschen's suggested move to Charlottesville, and there was a general consensus among the committee members and the Trustees to accept Heeschen's recommendation, although "some Trustees still voiced objection to making any move from Green Bank."[179] Of those that agreed to the move, many favored a location where the staff would find the intellectual stimulation that they felt was lacking in Green Bank. Princeton and Cambridge were touted as providing "all the social amenities and also the intellectual stimulation to be derived from close association with a major university maintaining a vigorous program in astronomy," and it was suggested that, by comparison, Charlottesville lacked "a congenial intellectual environment, … and might seem a rather isolated site intellectually."[180] Rabi, who on his last day as AUI President, had appointed Heeschen as NRAO Director, was particularly adamant about the merits of Princeton or Columbia as the best location for the NRAO headquarters. Heeschen, while fully cognizant of the advantages of co-locating at a university, particularly one with vibrant physics and astronomy departments, was more concerned about how to keep the staff engaged in Green Bank activities, and looked for a home for the NRAO Headquarters closer to Green Bank. But some Trustees maintained that "modern transportation greatly diminishes the importance of geographical proximity."

Fed up with the debate and procrastination, Heeschen characteristically pointed out the need for an "immediate decision," but a motion and second to approve the move from Green Bank was withdrawn after further discussion. Instead the Executive Committee decided unanimously "that the question of establishment at Charlottesville, Virginia of a headquarters for the scientific staff of the Observatory and the approval of the Director's proposal for carrying out this plan be referred to the full AUI Board of Trustees at its annual meeting to be held on October 18, 1963."[181]

The full AUI Board continued the debate when they met in Green Bank on 18 October. Reynolds, Chambers and Manny Piore spoke in favor of the move, but others argued against the move, which they felt would be "a dissolution of the Observatory as an institution." Finally, the Trustees voted to move the headquarters to Charlottesville, but the minutes recorded that the decision was made only by majority vote, and unlike most AUI Board actions, was not unanimous.[182] According to Heeschen, Rabi was so upset with Heeschen's insistence on moving to Charlottesville rather than Princeton or Columbia that he walked out of the meeting before the critical vote to wander around the Observatory, and that Rabi did not speak to Heeschen or Piore again for two years. Heeschen also described his experience with AUI over the move, as the most disagreeable dealing he ever had with AUI during his 17 years as the NRAO Director.[183]

In trying to understand Rabi's dogmatic opposition to locating the Observatory Headquarters at Charlottesville's University of Virginia, it might be noted that at the time, the University of Virginia was essentially all white and all male. Moreover, only three years earlier, the city of Charlottesville, as part of Virginia's broader "Massive Resistance," had closed the city's public schools to protest the 1954 Brown v. Board of Education Supreme Court decision against school segregation. As seen by Rabi, a Jewish immigrant from

Eastern Europe, Virginia was part of the still-segregated South. The records do not indicate which of the other Trustees also spoke in opposition to Charlottesville, but many of the AUI Trustees of that period shared a similar background with Rabi.

Having persuaded AUI, Heeschen still had to deal with the NSF, which in turn had to deal with the WV Congressional delegation. Fortuitously, the NRAO budget included a $600,000 item to build a new laboratory building, and the Foundation agreed to a proposal from UVA to divert this sum toward the new Charlottesville building. UVA then built a 25,000 square foot building, which was leased to AUI at a yearly rental rate so that the construction cost was amortized over a period of five years, and that after this period, the rent was reduced to a level covering only maintenance. The new headquarters building, which became known at UVA as Stone Hall, was finished in December of 1965, and most of the tenured and tenure track scientific staff, along with many engineers, technicians, and administrative staff, moved from Green Bank to Charlottesville (Fig. 4.13). With the large staff increase associated with the VLA, and growing technical, administrative and human resources staff, NRAO soon had outgrown the new UVA building and in November 1972, NRAO had to rent additional space in Charlottesville to house the technical staff. Although the engineers were located only a few miles away, the sociological impact of the separation of the scientific and technical staff became an increasing concern. Historically, there had been close collaborations between the

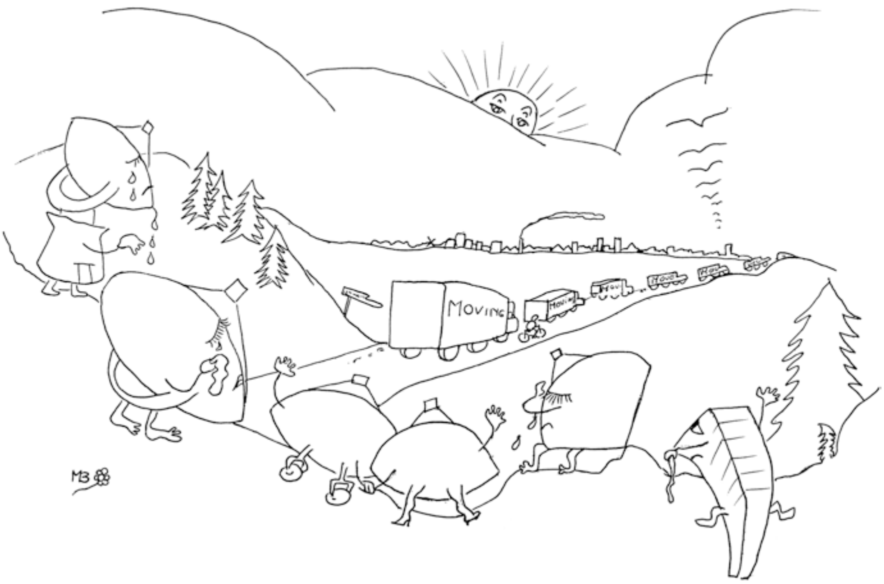

Fig. 4.13 In this cartoon from the December 1955 *Observer*, the Green Bank telescopes are weeping and waving as the moving vans head east to the big city of Charlottesville. Credit: NRAO/AUI/NSF

NRAO scientists and engineers in developing and testing new instrumentation, and in the design of new telescopes. In April 2005, with the intention of bringing the engineers and scientists back together, the capacity of Stone Hall was doubled by adding a new wing. But soon after construction began in 2003, it was apparent that even the addition could not accommodate the growing number of new staff involved with Atacama Large Millimeter/submillimeter Array, and the technicians and engineers of the Central Development Laboratory, as it was then named, remained in a separate location.

Notes

1. Sunderlin to diary, 23 January 1956, LOC-ATW, Box 26.
2. Bok to Pawsey, 31 July 1956, NAAustrl, C3830 Z3/1/VII. Miffed that he had been passed over as Director of the Harvard College Observatory, Bok had resigned his faculty position at Harvard (DeVorkin 2018). It isn't clear if his forceful "NUTS" reply to Waterman was based on the famous WW II reply of General Anthony McAuliffe to the German army general who demanded the American surrender in December 1944.
3. Berkner to Menzel, 21 September 1956, AUI-BOTXC, 21 September 1956. The other members of the committee suggested by Berkner were Ira Bowen, C. D. Shane, W. W. Morgan, Otto Struve, and J. B. Wiesner.
4. Menzel to Bowen, 3 October 1956, HLA-IB, Box 34.
5. Menzel to Search Committee, 18 October 1956, HLA-IB, Box 32.
6. Menzel to Search Committee, 22 October 1956, HLA-IB, Box 32.
7. Bok to Tuve, 3 July 1956, NAA-NRAO, Founding and Organization, Correspondence; CITA-JLG, Box 111, Folder 5.
8. Bok to Pawsey, 23 October 1956, NAAustrl, C3830 Z3/1/VII.
9. Report of the Ad Hoc Committee to Nominate the Director of the National Radio Astronomy Facility, 18 October 1956, HLA-IB, Box 34.
10. Goldberg to Berkner, 30 November 1956, HUA, Papers of Leo Goldberg, HUGFP 83.20.
11. Greenstein to Menzel, 6 March 1957, CITA-JLG, Box 23, Folder 4.
12. e.g., AUI-BOTXC, October 1958.
13. DSH, 31 July 1995, unpublished notes prepared for 140 Foot Birthday Symposium, September 1995, NAA-DSH, US Radio Astronomy History, Talks.
14. Minutes of AUI Board Meeting, 19 February 1960.
15. Struve to DSH, 9 February 1960, NAA-NRAO, Founding and Organization, Antenna Planning, Box 1.
16. The initial members were A.J. Deutch (MWPO), W.E. Gordon (Cornell), F.T. Haddock (Michigan), A.B. Meinel (NOO), J.B. Wiesner (MIT), E.L. McClain (NRL), G.C. McVittie (Illinois), D.H. Menzel (Harvard). Merle Tuve graciously declined to participate (Tuve to Berkner, 18 December 1956, CITA-JLG, Box 113, Folder 1).
17. Sullivan interview with Findlay, 14 August 1981, NAA-WTS, Individuals. https://science.nrao.edu/about/publications/open-skies#section-4
18. Jack Campbell only came to NRAO in 1972 as an Electronics Engineer to work on the VLA in Socorro. All of the other former Harvard students started

out on the NRAO Scientific Staff in Green Bank, but in 1965 most moved to the new NRAO headquarters in Charlottesville, VA.

19. KIK, ENB, and David Hogg interview with DSH, 31 May 2011, NAA-KIK, Oral Interviews. https://science.nrao.edu/about/publications/open-skies#section-4
20. Minutes of the Meeting of the AUI Advisory Committee on Radio Astronomy, 16–17 October 1956, NAA-NRAO, Founding and Organization, Meeting Minutes.
21. Both the official program for the dedication and the NSF press release included the words "National Radio Astronomy Observatory" in their titles.
22. DSH to Berkner, 12 November 1957, NAA-NRAO, Founding and Organization, Correspondence.
23. Undated 1957 report from DSH, "The Research Programs of the NRAO," NAA-NRAO, Founding and Organization, Planning Documents.
24. National Radio Astronomy Observatory, Site Development Program, December 1957, NAA-NRAO, Founding and Organization, Planning Documents.
25. Emberson to DSH, 21 April 1958, NAA-NRAO, Green Bank Operations, 85 Foot Tatel Telescope, Box 1.
26. Emberson to file, 8 July 1958, NAA-NRAO, Green Bank Operations, 85 Foot Tatel Telescope, Box 1.
27. DSH, NRAO Internal Symposium, 12 June 1992, NAA-DSH, US Radio Astronomy History, Talks.
28. DSH to Observers, 30 June 1960, NAA-NRAO, Green Bank Operations, 85 Foot Tatel Telescope, Box 2.
29. The possibility of detecting the Zeeman splitting of the 21 cm hydrogen line due to the galactic magnetic field was first discussed by Bolton and Wild (1957).
30. Technical and popular accounts of the planning and early history of the NRAO 140 Foot Radio Telescope are given by Emberson and Ashton (1958), by Emberson (1959), and by Small (1965). Personal accounts of the complex story surrounding the design and construction of the 140 Foot Telescope are given by Heeschen (1996, 2007a, b, 2008). Much of this section is adopted from Heeschen's 31 July 1995 unpublished notes prepared for 140 Foot Birthday Symposium, September 1995, NAA-DSH, US Radio Astronomy History, Talks. The story of the 140 Foot construction is portrayed in a movie which can be seen at https://vimeo.com/120155652
31. Letter written by Grote Reber, 7 October 1957, cited by Emberson and Ashton (1958).
32. DSH to Keller, 2 December 1957, NAA-DSH, Radio Astronomy History, NRAO.
33. DSH, 31 July 1995, op. cit.
34. AUI-BOTXC, 17 June 1955.
35. AUI-BOTXC, 14 July 1955.
36. These numbers are contained in Appendices A-1, A-2, and A-3 to the 11–12 July 1955 AUI Steering Committee report, AUI-BOTXC, 14 July 1955.
37. *Plan for a Radio Astronomy Observatory*, p. 34, NAA-NRAO, Founding and Organization, Planning Document. https://science.nrao.edu/about/publications/open-skies#section-4

38. Engineering Design Objectives for a Large Radio Telescope, Vol. 1 pg. 1, CAMROC, NAA-JWF, LFST.
39. A contract let with the MIT Servomechanisms Laboratory and inquiries to commercial suppliers such as Goodyear Aircraft did not provide any encouragement that an alt-az mount and mechanical coordinate converter could provide the desired precision.
40. Tuve to Seeger, 23 February 1956, CITA-JLG, Box 111, Folder 6.
41. AUI-BOTXC, 17 February 1956.
42. Greenstein to Tuve, 6 March 1956, CITA-JLG, Box 111, Folder 6.
43. Seeger to Berkner, 22 March 1956, LOC-ATW, Box 26.
44. Minutes of the AUI Advisory Committee Meeting, 26–27 March 1956, NAA-NRAO, Founding and Organization, Planning Documents.
45. It was widely suspected that the obvious ripples in the 250 foot antenna surface were caused by the heat generated during the welding process, which caused a thermal deformation of the dish surface.
46. The radio emission from planetary nebula and H II regions is due to thermal processes and is typically stronger at shorter wavelengths.
47. Emberson to Sheppard, 16 April 1956, NAA-NRAO, Founding and Organization, Correspondence.
48. Tuve to Emberson, 14 March 1956, NAA-NRAO, Founding and Organization, Correspondence.
49. KIK interview with Frank Drake, 14 September 2010, NAA-KIK, Oral Interviews. https://science.nrao.edu/about/publications/open-skies#section-4
50. Tuve to A. H. Jackson, Vice President, Blaw-Knox, 25 July 1956, NAA-NRAO, Founding and Organization, Correspondence; CITA-JLG, Box 111, Folder 5.
51. Bok to DSH, 8 June 1956, NAA-NRAO, Founding and Organization, Correspondence.
52. Emberson to Haddock, 1 August 1956, NAA-NRAO, Founding and Organization, Correspondence.
53. AUI Advisory Committee on Radio Astronomy, Minutes of 16–17 October 1956, NAA-NRAO, Founding and Organization, Meeting Minutes.
54. AUI-BOTXC, 18 October 1956.
55. Minutes of the AUI Advisory Committee on Radio Astronomy, 16–17 October 1956, NAA-NRAO, Founding and Organization, Meeting Minutes. See also Emberson to Ad Hoc Committee, 31 October 1956, NAA-DSH, Radio Astronomy History.
56. AUI-BOTXC, 16–17 October 1956.
57. DSH, 31 July 1995, op. cit.
58. KIK, ENB, and David Hogg interview with DSH, 31 May and July 2011, NAA-KIK, Oral Interviews. https://science.nrao.edu/about/publications/open-skies#section-4
59. AUI-BOTXC, 21 September 1956; Minutes of Meeting of the AUI Advisory Committee on Radio Astronomy, 16–17 October 1956, NAA-NRAO, Founding and Organization, Meeting Minutes.
60. Minutes of 28 June 1957 meeting at the NSF, NAA-NRAO, Founding and Organization, Meeting Minutes.
61. Estimated Costs of Construction, 3 January 1958, NAA-NRAO, Green Bank Operations, Site Selection and Development.

62. Ibid.
63. Minutes of Pre-Proposal Conference on 140 Foot Equatorial Radio Telescope, 25 September 1957, NAA-NRAO, Founding and Organization, Meeting Minutes.
64. AUI-BOTXC, 15 November 1957; See also Condensed History of the 140-Foot Radio Telescope Project, 5 January 1961, NAA-DSH, Radio Astronomy History, NRAO.
65. Berkner to Bronk, 12 February 1958, appended to AUI-BOTXC minutes, 14 February 1958.
66. Record of Meeting at the NSF, 13 March 1958, appended to minutes of AUI-BOT, 18 April 1958.
67. Findlay undated 1959 memo, NAA-NRAO, Founding and Organization, Correspondence.
68. AUI-BOTXC, 14–15 July 1960.
69. Struve memo, 12 September 1960, appended to AUI-BOTXC minutes, 23 September 1960.
70. Berkner memo to file, 2 September 1960, appended to AUI-BOTXC minutes, 23 September 1960.
71. Ibid.
72. As reported in the minutes of the 20–21 October meeting of the AUI-BOT, Berkner had announced his resignation at an executive session of the 28 September meeting of the AUI-BOTXC. As instructed by the Chairman, the Secretary did not record the results of the 28 September executive session.
73. AUI-BOT, 21 October 1960.
74. AUI-BOTXC, 23 September 1960.
75. Berkner to Burchill, 22 September 1960, appended to minutes of AUI-BOTXC, 23 September 1960.
76. AUI-BOTXC, 23 September 1960.
77. Luton to Burchill, 1 September 1960, appended to minutes of AUI-BOTXC, 23 September 1960. Luton was the NSF Assistant Director for Administration.
78. AUI-BOTXC, 23 September 1960.
79. Waterman to Berkner, 5 October 1960, appended to minutes of AUI-BOT, 21 October 1960; also found in NAA-DSH, Radio Astronomy History, NRAO.
80. Other members of the Committee included metallurgical experts from Chicago Bridge & Iron Co., Bethlehem Steel, Battelle Memorial Institute, and US Steel. Bruce Rule from Caltech later joined the committee after several members resigned following the first meeting.
81. AUI-BOT, 20–21 October 1960.
82. Ibid.
83. AUI-BOTXC, 18 November 1960.
84. Ibid.
85. DSH, 31 July 1995, unpublished notes prepared for 140 Foot Birthday Symposium held September 1995, NAA-DSH, Talks.
86. D.R. Lord to President Eisenhower's Science Advisor, G.B. Kistiakowski, 8 September 1960, DDE, Radar and Radio Astronomy, Box 5, Records of the U.S. President's Science Advisory Committee.
87. DSH, 31 July 1995, op. cit.
88. Berkner to Kinzel, 17 October 1960, appended to minutes of AUI-BOT, 21 October 1960; also found in NAA-DSH, Radio Astronomy History, NRAO.

89. Berkner to Haworth, 31 October 1960, appended to AUI-BOTXC, 18 November 1960.
90. Lindberg to Emberson, 14 November 1960, appended to AUI-BOTXC, 18 November 1960.
91. Lindberg to Haworth, 6 December 1960, appended to AUI-BOTXC, 6 December 1960.
92. AUI-BOTXC, 16 December 1960; 19 January 1961.
93. AUI-BOTXC, 17 February 1961.
94. Haworth to Waterman, 29 December 1960, appended to minutes of AUI-BOTXC, 19 January 1961.
95. AUI-BOTXC, 18 November 1960.
96. Ibid.
97. AUI-BOTXC, 17 February 1961; Luton to Haworth, 23 February 1961, appended to minutes of AUI-BOTXC, 17 March 1961.
98. AUI-BOTXC, 20 April 1961.
99. Reynolds to Lindberg, 6 April 1961, appended to minutes AUI-BOTXC, 20 April 1961.
100. AUI-BOTXC, 20 April 1961.
101. Design Responsibility 140 ft. Radio Telescope, N. Cleveland to C. Davis, 18 February 1963, NAA-DSH, Radio Astronomy History, NRAO.
102. AUI-BOTXC, 19 May 1961.
103. Drake to Green Bank staff, 2 May 1961, NAA-DSH, Radio Astronomy History, NRAO.
104. DSH, Frank Drake, Roger Lynds, Kochu Menon, and Campbell Wade, all signed the letter to Struve, 9 May 1961, NAA-DSH, Radio Astronomy History, NRAO.
105. Struve to Rabi, 10 May 1961, NAA-DSH, Radio Astronomy History, NRAO.
106. AUI-BOTXC, 19 May 1961.
107. Struve to Rabi, 10 May 1961, op. cit.; Struve to Chambers, 16 May 1961, NAA-DSH, Radio Astronomy History, NRAO.
108. DSH, 1995, op. cit.
109. AUI-BOTXC, 16 June 1961.
110. Ibid.
111. AUI-BOTXC, 20–21 July 1961.
112. Ibid.
113. AUI-BOTXC, 14 September 1961.
114. AUI-BOTXC, 26 October 1961.
115. AUI-BOTXC, 17 November 1961.
116. AUI-BOT, 27 October 1961.
117. AUI-BOTXC, 15 December 1961.
118. Ibid.
119. AUI-BOTXC, 16 February 1962.
120. AUI-BOTXC, 16 March 1962.
121. The sphere was poured by General Steel Industries. Westinghouse fabricated the polar and declination shafts and also machined the spherical bearing. The critical spring-actuated brakes were fabricated by the Goodyear Tire and Rubber Company, and gear segments by the Philadelphia Gear Company.
122. AUI-BOTXC, 21 September 1962.
123. AUI-BOTXC, 17 October 1963.

124. AUI-BOTXC, 16 January 1964; AUI-BOTXC, 21 February 1964.
125. *The 140 Foot Telescope Construction Story*, a 1965 film made for NRAO/AUI by Peter B. Good, describes the lift in detail. https://vimeo.com/120155652
126. The half power beamwidth of the 140 Foot Telescope is given approximately by θ (arcmin) ~ λ (cm) so at 1.3 the half power beamwidth was only a little over a minute of arc, and the pointing errors up to half a minute of arc made observations difficult.
127. Findlay notes for a 29 April 1988 invited talk at Ithaca, NY that apparently was not presented. NAA-NRAO, GB-GBT, Planning and Design, Box 1.
128. Burke to Vanden Bout, 21 July 1987, NAA-NRAO, Green Bank Operations, GBT Planning and Design.
129. Reber to Findlay, 2 April 1965, NAA-NRAO, Green Bank Operations, LFST, Box 7. https://science.nrao.edu/about/publications/open-skies#section-4
130. DSH after dinner talk on 12 January 1992, op. cit.
131. Drake to KIK, 4 May 2018, private communication.
132. Due to their limited angular resolution, especially for filled aperture instruments, the sensitivity of radio telescopes to detect weak sources can be limited due to the blending of separate sources contained within the antenna beam. This is commonly called "confusion." See Condon and Ransom (2016, p. 121) for more details on how confusion varies with angular resolution and observing frequency.
133. TRR to KIK, private communication.
134. Pauliny-Toth et al. (1978) were the first to exploit this previously unanticipated use of the 300 Foot antenna. A decade later the antenna collapsed while Jim Condon (2008) was using the same technique.
135. AUI-BOT, 21 October 1960.
136. Reynolds to Rabi, 23 August 1963, LOC-IIR, Box 36. Rabi at this time was Chair of the AUI Board.
137. KIK interview with DSH, 31 May 2011, NAA-KIK, Oral Interviews. https://science.nrao.edu/about/publications/open-skies#section-4
138. Report of the Trustees Committee on the National Radio Astronomy Observatory, 18 January 1961, appended to the minutes of AUI-BOTXC, 19 January 1961.
139. AUI-BOTXC, 19 January 1961.
140. AUI-BOTXC, 17 March 1961.
141. Bok to Pawsey, 16 June 1961, J.L Pawsey private papers, courtesy of Hastings Pawsey and Miller Goss.
142. Pawsey to Bok, 21 June 1961, J.L. Pawsey private papers, courtesy of Hastings Pawsey and Miller Goss.
143. Pawsey to Rabi, 5 October 1961, LOC-IIR, Box 36. When the Rabi papers at the LOC were first examined by one of the authors (KIK) in April 2011, this letter had been replaced by a pink sheet of paper stating that "The following item(s) have been removed from the collection because they contain security classified information." A handwritten note said "Confidential (Australia)." Nearly two years later, following a FOIA request and the intervention of Virginia Senator Mark Warner's office, the letter was finally declassified and released. Pawsey had probably typed the letter himself, as evidenced by the large number of typographical errors, and because he had made personal comments about the quality of various people, he had typed at the top of the letter

"CONFIDENTIAL," underlined and in capital letters. Pawsey was travelling at the time, so he typed and mailed letter from the Australian Scientific Liaison Office in London, using their stationary with the official letterhead of the Office of the High Commissioner for Australia. Thirty years later, an LOC staff member processing Rabi's papers apparently saw the "CONFIDENTIAL" and the official Australian stationary and, knowing that Rabi dealt with highly classified material, unwittingly had the letter classified. It took nearly three years to get it unclassified.

144. AUI-BOTXC, 26 October, 1961.
145. Ibid. AUI Vice President T.E. Reynolds had been in contact with the NSF concerning the length of the contract renewal (Reynolds to Scherer, 30 September 1960, attached to the minutes).
146. AUI-BOT, 27 October 1961.
147. Struve to Rabi, 31 October 1961, Papers of Otto Struve, UCB Bancroft Library.
148. Rabi to Pawsey, 31 October 1961, J.L. Pawsey private papers, courtesy of Hastings Pawsey and Miller Goss.
149. Pawsey to Rabi, 9 November 1961, J.L. Pawsey private papers, courtesy of Hastings Pawsey and Miller Goss.
150. AUI-BOTXC, 17 November 1961, Report of the Executive Session.
151. Rabi to Struve, 17 November 1961, NAA-NRAO, Founding and Organization, Correspondence. https://science.nrao.edu/about/publications/open-skies#section-4
152. Rabi to NRAO Staff, 17 November 1961, NAA-NRAO, Founding and Organization, Correspondence. https://science.nrao.edu/about/publications/open-skies#section-4
153. White to Pawsey, 22 November 1961, White to Rabi, 28 November 1961, J.L. Pawsey private papers, courtesy of Hastings Pawsey and Miller Goss.
154. Pawsey to Rabi, 26 November 1961, NAA-NRAO, Founding and Organization, Antenna Planning. https://science.nrao.edu/about/publications/open-skies#section-4
155. Rabi to Pawsey, 5 December, 1961, NAAustrl, C3830 Z1/14/A/1.
156. DSH to Rabi, 21 December 1961, NAA-NRAO, Fiscal and Business Services, Budgets, Box 1.
157. Rabi to Bowen, 2 December 1961, NAAustrl, C3830 Z1/3/1/VIII; quoted in Robertson (1992, p. 202).
158. Pawsey to Struve, 25 September 1959, NAAustrl, C3830 Z3/1/IX.
159. KIK interview with C. Wade, 29 December 2003, NAA-KIK, Oral Interviews.
160. AUI-BOTXC, 19 April 1962.
161. AUI-BOTXC, 18 May 1962.
162. AUI-BOTXC, 15 June 1962.
163. Pawsey to Rabi, 27 June 1962, J.L. Pawsey private papers, courtesy of Hastings Pawsey and Miller Goss.
164. G. Tape, Notes on Pawsey for Discussions with Wilde [*sic*], 25 July 1962, NAA-NRAO, Founding and Organization, Antenna Planning, Box 2.
165. J.L. Pawsey: Notes of Future Program at Green Bank, 17 July 1962, NAA-NRAO, Founding and Organization, Antenna Planning, Box 2. https://science.nrao.edu/about/publications/open-skies#section-4
166. Ibid.

167. AUI-BOTXC, 19/20 July 1962.
168. Wild to Rabi, 31 July 1962, NAAustrl, C4660/1 Part 9.
169. Notes on the NRAO Directorship—for I. I. Rabi, Summary of Ideas from Conversations with Trustees and Discussions at the AUI Executive Committee Meeting on 7/20/62. G. Tape, NAA-NRAO, Founding and Organization, Antenna Planning, Box 2.
170. AUI-BOTXC, 19 February 1960.
171. KIK interview with DSH, 13 July 2011, NAA-KIK, Oral Interviews. https://science.nrao.edu/about/publications/open-skies#section-4
172. At the time, the NRAO scientific and technical staffs were essentially all male.
173. The name presumably derives from the large number of small children living in the NRAO housing complex.
174. KIK interview with DSH, 31 May 2011, op. cit.
175. KIK unrecorded interview with L. Fredrick, 1 May 2014; see also AIP Fredrick interview by David DeVorkin. https://www.aip.org/history-programs/niels-bohr-library/oral-histories/31235
176. AUI-BOTXC, 18–19 July 1963.
177. Dunbar to Reynolds, 8 July 1963, LOC-IIR, Box 36.
178. DSH to AUI Trustees, 18 July 1963, appended to minutes of AUI-BOTXC, 18–19 July 1963.
179. AUI-BOTXC, 15 October 1963.
180. Ibid.
181. Ibid.
182. AUI-BOT, 18 October 1963.
183. KIK interview with DSH, 31 May 2011, op. cit.

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