CHAPTER 10

Exploring the Millimeter Sky

In 1962, Frank Drake recruited Texas Instruments physicist Frank Low to come to Green Bank to develop bolometer receiver systems for use at millimeter wavelengths. Under Low's leadership, NRAO contracted with the Rohr Corporation to manufacture a 36 Foot Telescope designed for use at wavelengths as short as 1 mm. To minimize the effects of tropospheric water vapor, NRAO located the telescope at the Kitt Peak National Observatory near Tucson, Arizona. Fabrication errors led to long delays, and before the 36 Foot Telescope was finished, Low left NRAO to join the University of Arizona, where he could pursue his interests in infrared astronomy. Low's bolometers never reached the anticipated sensitivity at 1 mm, and manufacturing errors limited the performance of the 36 Foot dish. However, the unanticipated discovery of powerful 2.6 mm radio emission from interstellar carbon monoxide (CO), and later from other molecular species, led to a greatly increased interest in millimeter astronomy. Despite many technical and administrative concerns, the 36 Foot Telescope became the most oversubscribed NRAO telescope. In 1983, NRAO replaced the faulty 36 Foot dish with a more precise 12 Meter surface. Arguably, the 36 Foot/12 Meter Telescope became the most productive instrument in the world for millimeter spectroscopy until it was eclipsed by more powerful facilities both in the US and abroad.

An ambitious plan to build a 25 meter millimeter wave telescope on Mauna Kea in Hawaii was never funded, and it would be another quarter of a century before the NRAO would return to the forefront of millimeter wave radio astronomy with the completion of the Atacama Large Millimeter/submillimeter Array (ALMA) as a joint NRAO-ESO-NAOJ facility in northern Chile.

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10.1 First Attempts

Although the 1961 Pierce Panel report (Keller 1961) emphasized high resolution radio imaging, the Panel also drew attention to the potential opportunities at millimeter wavelengths noting that “the exploitation of wavelengths from 3 cm down through the millimeter range should be encouraged and supported.” They also pointed out that “Such work can best be carried out at altitudes above 13,000 feet[1] with highly accurate dishes of moderate size (less than 100 feet).” But the Pierce Panel was primarily motivated by the drive for higher angular resolution, which they argued could be achieved with relatively small and therefore inexpensive dishes operating at millimeter wavelengths. Indeed, the highest resolution filled aperture radio telescope at the time was the Naval Research Laboratory’s (NRL) 50 foot dish, which had a 3 arcmin beam at 8 mm wavelength.

As a physicist working for Texas Instruments, Frank Low (Fig. 10.1) developed sensitive liquid helium cooled germanium bolometer detectors that promised greatly improved sensitivity at infrared and short millimeter wavelengths (Low 1961). Since bolometer systems respond to all incoming radiation, including the warm radiation from the ground and atmosphere, the challenge was to develop effective filters that could isolate the desired waveband and attenuate everything outside the reception band by at least a factor of a million, while, at the same time, not introducing significant noise. This meant that the filters as well as the bolometer needed to be cooled to liquid helium temperatures. Frank Drake became aware of Low’s work,[2,3] and

Fig. 10.1 Frank Low came to NRAO from Texas Instruments in 1962 to begin a millimeter astronomy program in Green Bank. Credit: NRAO/AUI/NSF

recruited Low to come to Green Bank to develop millimeter wavelength receiver systems. Following his short visit to Green Bank in March 1962, Joe Pawsey warmly endorsed Drake and Low's millimeter initiative and also noted that Low's bolometer was "an ideal instrument for infra-red spectroscopy."[4]

After arriving in Green Bank in 1962, Low worked on 1.3 mm and infrared bolometer systems. He and Drake set up a 5 foot plastic dish with a gold plated surface and began the first astronomical observations in the 1.3 mm band (Low and Davidson 1965). This was NRAO's first experience with liquid helium cooled receivers, and the bolometer contract with Texas Instruments included two weeks of training in cryogenic techniques for Observatory personnel.[5] However, with their limited sensitivity, all Low and Drake could observe at 1.3 mm was the Moon, and they began to develop plans to build a larger antenna on a mountain site to minimize the absorption due to atmospheric water vapor.

Dave Heeschen shared their enthusiasm, and expressed the opinion that "Millimeter wavelength observations constitute a vast unexplored region of radio astronomy," and said he did not believe the Observatory should leave the millimeter wavelength field to others because this work could be done effectively only by a strong balanced group such as was available at Green Bank.[6] Although still struggling to complete the 140 Foot construction, Heeschen boldly proclaimed that the millimeter wavelength telescope ranked third in priority for NRAO "after the very large dish [LFST] … and the interferometer array [VLA]."

10.2 The NRAO 36 Foot Millimeter Wave Telescope

As part of its 1964 budget submission to the NSF, NRAO included a request for \$600,000, later increased to \$800,000, to obtain a 36 foot diameter antenna designed to work at wavelengths as short as 1.3 mm. Frank Drake later recalled that it was a last minute thought, and that he added just a few paragraphs of explanation to NRAO's annual budget submission to support the request for a new millimeter wave telescope.[7] Prior to starting the 36 Foot project, Low and Drake embarked on a development program to build a series of smaller antennas ranging up to 12 feet in diameter (Fig. 10.2).[8] Although Heeschen was successful in the getting the NSF funds, it soon became clear that it was going to be a challenge to achieve the required surface accuracy of 0.002 inches (0.05 mm), less than the thickness of a sheet of paper, and 2 arcsec pointing accuracy, about the angle subtended by newsprint seen across a football field.[9] Moreover, in 1964, "in view of the relatively small initial cost and the scale of the operation," the AUI Board raised questions about whether or not a millimeter wave telescope was more appropriate for a university than for NRAO.[10] But Heeschen claimed that there were no universities prepared to invest in the technology development needed for observing at millimeter wavelengths.

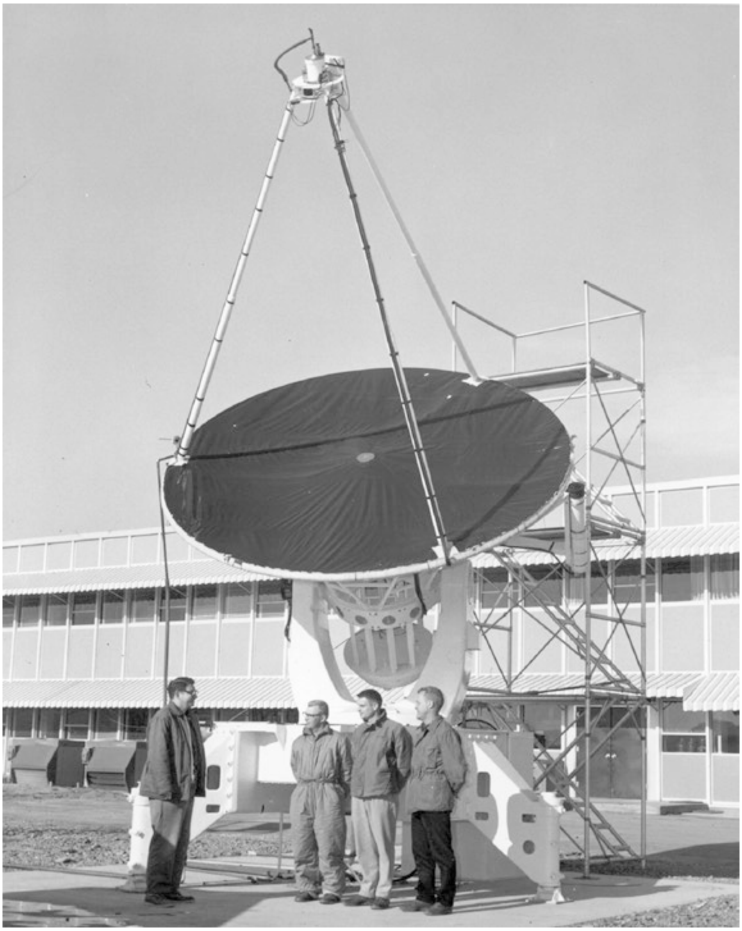

Fig. 10.2 Frank Low (on the left) supervises the installation of his 1 mm bolometer on a 12 meter diameter dish behind the Green Bank Jansky Laboratory. Credit: NRAO/AUI/NSF

In order to accommodate his 1.2 mm bolometer system, Low argued for an unusually long feed support structure. This made the optics for the conventional heterodyne receivers used at longer wavelengths more complex than would be the case for a more conventional *f/D* ratio of about 0.4, and was “the subject of prolonged discussion” within NRAO.[11] Also, as argued by Peter Mezger, the longer feed support legs were more subject to wind and thermal effects which compromised the pointing accuracy.[12] The controversy was finally resolved by adopting a compromise geometry, but as Mezger had anticipated, this still created problems in using the telescope at longer wavelengths.

After recruiting Low to start a millimeter program at NRAO, Drake left NRAO in 1963 to join the Jet Propulsion Laboratory. Two years later, after getting NRAO to agree to these unusual antenna specifications, Low left to join the University of Arizona Lunar and Planetary Laboratory. Low was already spending a lot of time in Tucson pursuing his interests in infrared astronomy, and suggested setting up an NRAO laboratory in Tucson to support the 36 Foot operation. Apparent in Low's request was his interest in remaining in Tucson instead of living in Green Bank or Charlottesville. Responding to Low, Heeschen firmly replied, "We do not intend to set up, instrument, and staff a lab in Tucson. This is a firm decision and applies to you and everyone else on the NRAO staff."[13] Later Heeschen added, "the Tucson site will always be—for the NRAO—purely an observing site. We will not have any appreciable staff there, no development lab there, and no scientists permanently in residence there…. It will not be possible for us to indefinitely maintain you in Tucson. At some time you should return to Charlottesville or affiliate with some other organization."[14] Low elected, instead, to join the University of Arizona, where he went on to have a very distinguished career as one of the pioneers of infrared astronomy. He also formed his own company to build and market infrared detectors for astronomical, industrial, and military use, and he liked to tell stories of dark-suited customers who would pay for bolometer systems with thousands of dollars in cash.

The departure of Drake and Low left NRAO with a novel but challenging millimeter wave telescope project, but without the two scientists who had initiated it. John Findlay took over as the project director, but he left in 1965 for a year's leave-of-absence to become director of the Arecibo Observatory in Puerto Rico, leaving Hein Hvatum, NRAO Assistant Director for Technical Services, in charge of the millimeter telescope effort. Peter Mezger, who was on the Green Bank Scientific Staff, assumed the role as the scientific leader of NRAO millimeter wave astronomy. In a thoughtful report,[15] Mezger noted that the few sources likely to be strong enough to study with the planned 36 Foot Telescope included the Sun, the Moon, and some of the planets. Although he noted that "there is some evidence of radio sources of very small apparent diameters with flat or increasing spectra which may become 'visible' at very short wavelengths," he commented, "it seems to be very doubtful if observations at 3 mm wavelength or shorter can contribute anything to the radio astronomy of galactic and extragalactic sources." He also went on to speculate on the possibility of observing atomic Radio Recombination Lines from high order electron transitions. In the same report, Mezger compared the short wavelength capabilities of the 36 Foot antenna with other facilities and reviewed the range of available millimeter wave amplifiers.

NRAO solicited proposals from eight potential suppliers and received three firm bids to construct the complete telescope.[16] Following evaluation of the proposals under Findlay's leadership, including visits to the three finalists' plants, NRAO chose the Rohr Corporation in Chula Vista, California to build the 36 Foot telescope. This was not NRAO's first experience with the Rohr Corporation. In 1963, when NRAO and Rohr were discussing a possible design contract for a 400 foot transit radio telescope, Rohr engineer Bob Hall had casually remarked that Rohr had recently completed a 15 foot dish designed for operation up to 140 GHz.[17] In order to protect the antenna from the weather, Rohr proposed enclosing the telescope in a 95 foot diameter rotating astrodome, allowing observations to be made through a 40 foot slit, much in the manner typical of optical telescopes.

Although Low and Drake had succeeded in making millimeter observations in Green Bank, the 36 Foot Telescope clearly needed to be located at a better site with less atmospheric water vapor. Two sites near Tucson, Arizona were considered: one on Kitt Peak Mountain, home of the Kitt Peak National Observatory (KPNO) and located about 50 miles to the west of Tucson, the other on Mount Lemmon, northwest of Tucson, home of the University of Arizona optical and infrared telescopes. Other sites near Climax, Colorado and at the Los Alamos National Laboratory in New Mexico were also discussed, the latter being pushed by some of the AUI Trustees with their atomic physics backgrounds. The Mount Lemmon site was located at an altitude of 9,000 feet, about 2,000 feet higher than the Kitt Peak site, but there were powerful radio transmitters, as well as other activities, on Mount Lemmon, which were a potential source of interference to millimeter astronomy. NRAO chose Kitt Peak, as KPNO agreed to provide logistical and administrative support for NRAO's millimeter telescope. Interestingly, there was no attempt made to evaluate any of the other potential sites, as Heeschen argued that "the difference between a so called 'good' site and a somewhat better one from the water vapor point of view is so much less than the difference between a good site and a bad site [Green Bank] as to make it unnecessary in his judgment to embark on detailed studies."[18] However, in spite of Heeschen and Findlay's reassurances about the adequacy of the Kitt Peak site and the attraction of collaborating with the optical astronomers at KPNO, the AUI Board continued to press the issue of seeking a more favorable site. On the other hand, the NSF Director Leeland Haworth cautioned Heeschen about the difficulties of operating such a distant site but otherwise supported the project.[19] Heeschen acknowledged that "a split operation presents real difficulties," but pointed out that the planned large array would also involve an additional site for NRAO.

Construction Challenges Construction of the dish itself, which took place at the Rohr plant in Chula Vista, was a challenge. In order to meet the 0.002 inch rms accuracy required for operation at 1.3 mm, Rohr decided to fabricate the surface in one piece rather than use multiple panels as for the Green Bank antennas, and machined the surface from welded sections of aluminum plate. The precision cutting procedure was so sensitive to vibrations that to avoid the effect of passing trucks and the effects of ocean tides, the cutting could only be done at night and at low tide. Moreover, the welding process distorted the structure, so that to achieve the desired parabolic shape, the thickness of the dish surface would then be less than the "desired minimum surface thickness." To correct for this, Rohr engineers sprayed additional metal to the low areas of the reflector surface. But the sprayed areas contained contaminants that dam-

Fig. 10.3 The 36 Foot dish was transported by road from the Chula Vista factory to the base of Kitt Peak. Credit: John Hungerbuhler/NRAO/AUI/NSF

aged the cutting tool and probably contributed to the resultant poor thermal characteristics of the dish.[20]

The dish surface was finally complete in late February 1966 and the 13,000 pound 36 foot dish was transported by road from the Chula Vista factory to the base of Kitt Peak (Fig. 10.3), accompanied by California and Arizona State Police escorts. The 425-mile trip took ten days and the entire Rohr convoy included eight truckloads of telescope components. Due to problems and delays in completing the dome, concerns about the impact of inclement weather conditions on top of the mountain, and ongoing repairs to the road up the mountain, the dish structure remained at the bottom of Kitt Peak for many months—under guard lest it be stolen or used as target practice by Arizona locals. Even after the dish was mounted, difficulties with the drive system, the azimuth bearing, control of the dome motion, and the on-line computer control delayed the start of telescope operations for another year. The 36 Foot Telescope (Fig. 10.4) was finally turned over to NRAO in April 1967, although a variety of problems remained, including the flexure of the bi-pod feed support, which could be mitigated by tightening the cables securing the legs, but there was a concern that this would lead to dish distortions. On one occasion, the cables were inadvertently loosened and the feed legs crashed into the dish, but fortunately there was no serious damage to either the telescope or personnel, except perhaps for the great embarrassment of the senior engineer who caused the accident.[21]

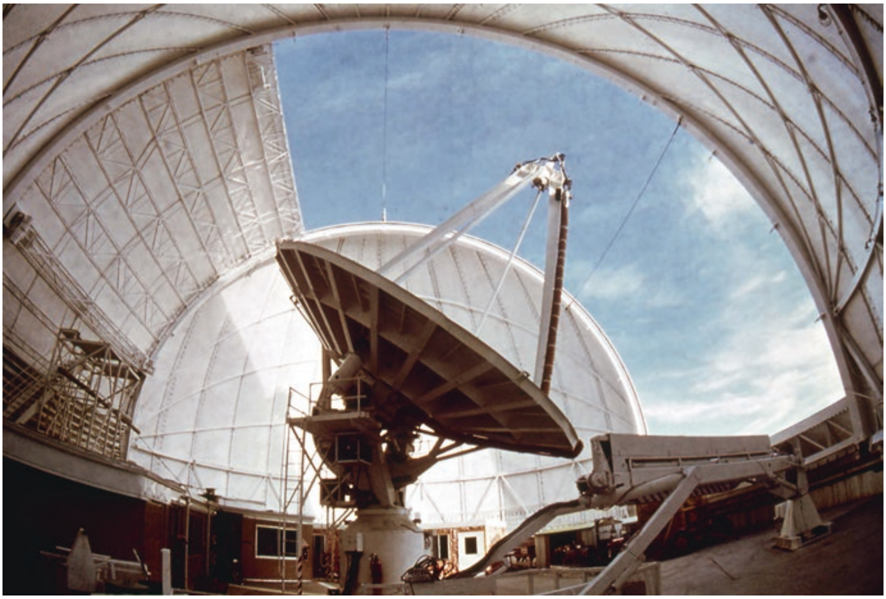

Fig. 10.4 The completed 36 Foot Telescope in its rotating dome enclosure on Kitt Peak

The 36 Foot millimeter wave telescope was novel for the time, as it was the first NRAO telescope to be designed from the start to be operated under the control of a digital computer. However, programing the computer introduced new challenges. Although the 85 foot, the 140 Foot, and the 300 Foot antennas all ended up being computer-controlled, it was only after years of experience with an operator interacting with analogue control systems. The 85 foot and 140 Foot telescopes were equatorially mounted and so needed no coordinate conversion, while the 300 foot was a simple transit telescope. The 36 Foot was NRAO's first alt-az telescope that required coordinate conversion between celestial right ascension-declination and altitude-azimuth, and indeed the concerns raised a decade earlier in the debates surrounding the design of the 140 Foot Telescope resurfaced (Sect. 4.4). Other alt-az radio telescopes such as those at NRL, Dwingeloo, Jodrell Bank, and Parkes used an analogue conversion system. The 36 Foot was one of the first telescopes anywhere to use a digital computer for the coordinate conversion. As a new experience, and due to errors in the operating system along with faulty hardware interfaces, it took several trips to Tucson by Green Bank engineers, and a new programmer, before the telescope was able to accurately point and track a celestial target. An interesting by-product of the later attempts to improve the computer control of the 36 Foot Telescope and real-time data analysis was the introduction of the FORTH[22] language developed by Charles (Chuck) Moore. After bringing FORTH to both Green Bank and Tucson, Moore left NRAO to form FORTH

Inc., which developed FORTH applications for a wide variety of end users including the space shuttle, medicine, oceanography, engineering, music, the San Francisco BART metro system, and the Boeing 777 avionics system.

Getting Going in Tucson The original scientific justification for the 36 foot millimeter wave telescope was marginal. It was not built to solve any specific scientific problem or to investigate any known phenomena, but rather to explore the opportunities for new discoveries that might be possible by working in this almost unexplored region of the electromagnetic spectrum, and in particular to exploit Frank Low's 1.3 mm bolometer system. A realistic estimate of what one might expect to observe with Low's bolometer and the 36 Foot telescope would have included the Sun, the Moon, the thermal emission from a few planets, and a few H II regions with thermal spectra. Only a few extragalactic sources were known to have spectra that when extrapolated to millimeter wavelengths might be detected with the 36 Foot. The class of compact "flat spectrum" radio sources were still unknown, and, ironically, there was no consideration of any spectroscopic observations.

Reflecting the anticipated nature of the 36 Foot operation as an experimental instrument, and perhaps realizing that the 36 Foot Telescope appeared to have limited attraction for outside users, Heeschen planned to keep the Tucson-based NRAO support staff to a minimum and the operation informal. After the telescope went into operation, George Grove, who had served in a variety of roles in Green Bank, transferred to be Head of Tucson Operations in August 1967 to support the 36 Foot operation and to provide some observing assistance. Initially, unlike at Green Bank, observers were for the most part expected to run the telescope and take care of the instrumentation themselves, but in 1968 Don Cardarella, who had been a Green Bank 300 Foot operator, moved to Tucson and became the first 36 Foot telescope operator.

When the telescope was finally placed in operation in the summer of 1967, there was no immediate rush of observers waiting to use the instrument. Drake and Low, who had started the project with great enthusiasm, were gone. Unlike the 140 Foot and 300 Foot Green Bank telescopes, the 36 Foot was conceived of as an experimental instrument and not a user facility. The telescope was scheduled informally, first by Heeschen and later by Bill Howard, then Assistant to the NRAO Director, with large blocks of time going to individuals or to small teams who would be in residence in Tucson for several weeks at a time. Much of the early observing was devoted to calibrating the pointing and learning how the focus and gain changed with elevation and temperature. However, the poor sensitivity resulting from the small antenna size, low efficiency, and high system temperatures made calibration challenging. Only the Sun and the Moon, and two planets, Venus and Jupiter, gave sufficient signal-to-noise ratio, and solar heating limited observations to the nighttime. When under computer control, the telescope moved very slowly, so large azimuth motions resulted in a lot of lost observing time. An adventurous and courageous observer knew how to unlock the computer and manually drive the telescope at high speed to a new position, hoping that the brakes would work, and risking tearing off the connecting cables if the telescope were not stopped in time.

Although Low continued to attempt 1.3 mm bolometer observations, the uncertain antenna pointing, poor aperture efficiency, and thermal distortions of the dish limited results. Scientific observing by NRAO staff, as well as by visitors, at 3 mm and 9 mm wavelength using simple mixer continuum radiometers to study extragalactic radio sources and thermal emission from compact H II regions were not productive. It was clear that the 36 Foot was not going to meet its design specifications, and, already, Heeschen was contemplating replacing the dish structure.[23] But AUI first called for a review to explain the increased cost, the delay in completion, and the failure to meet the anticipated specifications.[24]

The local oscillator systems for both the 3 and 9 mm receivers, were derived from klystron oscillators. Not only did they have limited lifetimes, but they were expensive, and not all of the klystrons lasted for their full 500-hour advertised lifetime. Since the klystrons were manufactured by the Canadian branch of the Varian Corporation, replacements were delayed by the need to get exemptions from the Buy American Act. More than one replacement klystron oscillator was hand carried across the border to minimize bureaucratic delays. Mark Gordon (2005, pp. 99–100) recalled the Charlottesville attempts to build a cooled parametric amplifier for millimeter spectroscopy. When finally delivered after years of development, it only worked over a narrow band around 49 GHz, where there were no spectral lines of interest, and where it was uncomfortably close to the atmospheric O_2 absorption feature. Gordon estimated that NRAO probably spent at least $500,000 on the amplifier project. NRAO also obtained a new bolometer system that was fabricated at the University of Oregon and designed to operate at 1, 2, and 3 mm by using different filters. The new bolometer also had limited success.[25]

By 1968, there were a few external users observing the Sun and planets as well as bright H II regions and the Crab Nebula. In spite of its limitations, the 36 Foot Telescope was probably the most productive millimeter wave radio telescope in existence. Even with its low 10–15 percent efficiency at 1.3 mm, the 36 Foot had more collecting area, and better resolution than the Palomar 200 inch. However, problems operating the telescope with limited staff, inclement weather, and power failures continued to plague millimeter observers. A not uncommon visitor experience was, “Our run was pretty frustrating but not entirely unproductive.”[26] Another observer asked for “some reasonable imitation of a working system.”[27] In October 1968, Heeschen decided to stop scientific observing and give priority to long neglected repairs and better calibration of the efficiency and pointing. As he informed one potential observer, “The 36-ft has many problems associated with it: pointing calibration is difficult, other calibrations are difficult, the receivers have been unreliable, there have been mechanical problems with the dome, dish parameters—focus, pointing, gain—are unknown functions of temperature.”[28] He finally realized that some of the problems in Tucson were the result of trying to manage the program from a distance and, in order to provide more effective local management, he hired Edward (Ned) Conklin in October 1969 as the first Tucson resident member of the NRAO scientific staff to act as the Tucson site manager. Conklin had received his PhD in electrical engineering at Stanford working with Ron Bracewell, and brought a new level of technical expertise to the Tucson group.

Local logistical support for NRAO's Tucson operations was provided by KPNO, which rented Tucson office and laboratory space and allocated several rooms in the KPNO mountain dormitory to NRAO. NRAO staff and observers on the mountain ate their meals at the KPNO cafeteria, which provided a pleasant opportunity to informally interact with observers using the KPNO optical telescopes, especially when poor weather prevented both radio and optical observing. However, with the introduction of spectroscopic capability in late 1969, there was growing pressure to use the telescope, even in the daytime, even if the gain and pointing were uncertain due to thermal deformations of the structure. As a result, the radio and optical astronomers kept different hours, and each complained of noise generated by those working at the other end of the spectrum. NRAO installed trailers, later upgraded to permanent buildings near the telescope itself, where the operators and observers were able to sleep in quiet, but instead of the noise, they then had to deal with the local scorpion and skunk population.

When Ned Conklin left NRAO in 1973 to join the Arecibo Observatory, he was replaced by Mark Gordon, who served as the first NRAO Assistant Director for Tucson Operations, with a charge to convert the 36 Foot from an experimental facility to a more user-friendly facility of the kind NRAO observers were familiar with in Green Bank. Gordon, who had spent a winter in Antarctica as part of the US Antarctic Research Project, brought a dynamic new leadership perspective to the 36 Foot operations. Soon the NRAO support staff in Tucson had grown to 20 people, including a full complement of telescope operators. However, the limited size of the Tucson Electronics Division, which perhaps reflected its original development as an experimental rather than a user facility, meant staff felt overworked maintaining the telescope and cryogenics, as well as the receiver instrumentation.[29] New receivers were built in Green Bank or Charlottesville, and a common complaint was that they would arrive untested only days before being scheduled on the telescope. However, the engineers in Charlottesville saw it differently, and complained about the misuse of their receivers by the Tucson engineers. The long commute between Tucson and Kitt Peak, especially in response to nighttime callouts, added to the low morale and likely contributed to the heavy turnover in the NRAO technical staff in Tucson.

Faced with growing tensions with KPNO and lack of adequate space resulting from the increased level of NRAO operations, Gordon moved the NRAO Tucson staff from their downtown KPNO offices to a free-standing facility in an industrial office complex some five miles away. But in October 1984, by agreement with the University of Arizona, the NRAO Tucson operations moved back to the university campus to occupy an upper floor of the new Steward Observatory building.

Interstellar Carbon Monoxide and Molecular Spectroscopy The possibility of observing narrow band radio emission from atomic and molecular transitions was discussed as early as 1955 by Charles (Charlie) Townes at the Jodrell Bank Symposium on Radio Astronomy (Townes 1957, p. 92). A few interstellar molecules, e.g., hydroxyl (OH), formaldehyde (H_2CO), water (H_2O), and ammonia (NH_3) had been detected at centimeter wavelengths (Sect. 6.2), but the transition probability of typical interstellar molecules increases rapidly toward higher rotational energy levels which occur primarily at millimeter wavelengths. Although there was no discussion of any spectroscopic capability when planning for the 36 Foot Telescope, by 1970 NRAO had installed a 40 channel spectrometer. However, in addition to the long-standing reliability and gain stability issues, spectroscopic observers were limited by the lack of any local data reduction capability at the telescope, and they had to wait until the next day to learn if they had discovered anything.

In February 1969, Arno Penzias from Bell Laboratories wrote to NRAO requesting eight weeks of observing time to search for "in descending order of our interest CN [cyanide], CO [carbon monoxide], and HCN [hydrogen cyanide]."[30] The CN observations were justified by the well-known detection of optical absorption lines (Field and Hitchcock 1966) but Penzias added that, "although CO has a much smaller dipole moment than CN, it is probably worth looking for." Heeschen granted Penzias only four weeks, but indicated that the other four weeks would likely follow. The Bell Labs group fully anticipated that any molecular lines would be weak and require long integration times to detect any signal. So in addition to bringing their own low noise front end to Kitt Peak, they also brought their own computer in order to average and display the results at the telescope. By this time, their main interests had shifted from CN to CO, but everyone was surprised when they pointed the telescope toward the Orion Nebula and saw a very strong CO signal in real time on the chart recorder. Robert Wilson et al. (1970) then went on to detect CO from a total of eight other Galactic sources including the Galactic Center.

The surprisingly strong CO emission discovered by Wilson et al. opened the door to the discovery of many other molecular species. Suddenly the 36 Foot Telescope was in heavy demand, and the competition to be the first to detect a new molecule or isotopic species was intense and not entirely cleanly fought. By this time Gordon had taken over the difficult task of scheduling observers with competing proposals. Although each proposal was sent to multiple referees for review, the referees were not always consistent in their comments, and there was considerable overlap between the referee pool and the observers. Complaints of unfairness or referee incompetence were not uncommon. With an oversubscription rate of about 5:1, only a small fraction of the proposals could be scheduled, but every proposer felt that their proposal was well above average. One group even threatened to go elsewhere to make their observations and thus deprive NRAO of the discovery of interstellar glycine (NH_2CH_2COOH).[31] But as Kellermann wrote to Heeschen, "the situation would be much worse if the available observing time exceeded the requested time by a factor of five."[32]

In order to search for a new molecule, observers needed to know the frequency, which could be calculated with some uncertainty, or in some cases determined from laboratory spectroscopy. Competing observers maneuvered to establish collaborations with theoreticians or laboratory spectroscopists to learn the correct frequencies needed to search for their favorite molecule; some then kept their search frequencies secret from other observers or even leaked false information. In principle, observers were supposed to follow their approved observing program, but some strayed into territory which had been staked out by other observers. Sometimes the frequency of a new line would become public, or at least known to competing groups. Whoever was the next observer could "discover" a new line. At least one observer was known to purposely enter an incorrect frequency in the telescope logbook in order to misdirect the next competing observer. Others misstated the sources they were observing or claimed that the reason they were observing a source not in their proposal was to use it as a calibrator. A particularly divisive situation arose in connection with the first detection of extragalactic CO. Competing observers argued among themselves and with NRAO that the other group had been approved for a different program and had acted unethically. Another observer recalled that, suspecting that someone was going through his desk at night, he invented a false molecule and a bogus observing proposal. Another observatory apparently spent considerable time looking for this molecule. When multiple groups discovered new molecules or new isotopes, there was a rush to publish before the other group, independent of who had actually made the first detection. These were arguably the most exciting times for millimeter astronomy but also perhaps the darkest days for millimeter astronomers.

As Mark Gordon (2005, p. vii) later wrote, molecular spectroscopy at Kitt Peak "revolutionized our understanding of the nature of interstellar gas, chemistry at extremely low temperatures, and how stars form and galaxies evolve." A whole new field of astrochemistry was largely born at the NRAO Kitt Peak millimeter wave telescope. Over one hundred different molecular and isotopic species had been detected, and NRAO was under considerable pressure to exploit this rapidly developing new field of astronomy. Moreover, millimeter astronomy was also being used to study the thermal radio emission from planets and other solar system bodies, as well as from stars and the energetic millimeter wave bursts from quasars. The 36 Foot Telescope had more than met the modest expectations of Drake and Low and was probably the most oversubscribed telescope in the world.

10.3 Replacing the 36 Foot Telescope

Although the 36 Foot Telescope had been responsible for many important discoveries, and, arguably, defined millimeter astronomy, it still had limited performance. The technical troubles remained, and observer complaints continued—along with a steady flow of advice on how to improve the 36 Foot operation. Not only did the surface distort due to differential thermal heating, but the pointing was erratic and non-reproducible, in part due to thermal distortions, but also to problems with the servo system. This made the telescope nearly useless for daytime observations. Even during nighttime, it was difficult to get quantitative results, although the competing astronomers were more interested in discovering a new molecule than in quantitative results that depended on accurately knowing things like the antenna gain and pointing. Various innovative attempts to shield the telescope from daytime heating proved less than effective (Gordon 2005, pp. 119–124). In 1973, the 36 Foot Telescope was converted to Cassegrain operation in order to facilitate the use of large cryogenically-cooled receivers and to permit beam switching using a nutating sub-reflector, but this did not address the more fundamental problems of telescope performance and safety. Perhaps the most serious issue arose in July 1972, when the 40 foot dome door jammed, driving the chief telescope operator to “declare the 95-foot radome housing the NRAO 36-foot radiotelescope [*sic*] condemned,” and “you can consider this my formal resignation if the situation described herein is not corrected to my satisfaction.”[33]

The 65 Meter Millimeter Wave Telescope In Sect. 9.4, we discussed how the growing interest in millimeter molecular spectroscopy led the LFST project to converge to a 65 meter antenna good to 3 mm under favorable observing conditions (Findlay and von Hoerner 1972). The proposed 65 meter telescope was designed to be homologous, although it was otherwise a conventional symmetric alt-az structure (See Fig. 9.7). Support for a major NRAO initiative in millimeter astronomy got a boost from the Greenstein (1973) Decade Review Committee, when it briefly appeared that there might be funds in the NSF FY1972 budget for a new millimeter wave radio telescope, but, as it turned out, the budget information was incorrect. Moreover, by this time, interest had moved to even shorter millimeter wavelengths, and there was no further attempt to fund the NRAO 65 meter telescope.

The Rise and Fall of the 25 Meter Millimeter Telescope Responding to the growing interest in the new field of astrochemistry, in 1974 Dave Heeschen established an NRAO committee to consider options for replacing the 36 Foot Tucson Telescope. He appointed Barry Turner as Project Scientist and chair of the committee, which included Findlay and von Hoerner as well as Mark Gordon and one of the present authors (KIK). Following a series of meetings, Turner’s committee concluded that NRAO should build a 25 meter diameter telescope capable of operating down to 1 mm wavelength.[34] Heeschen then

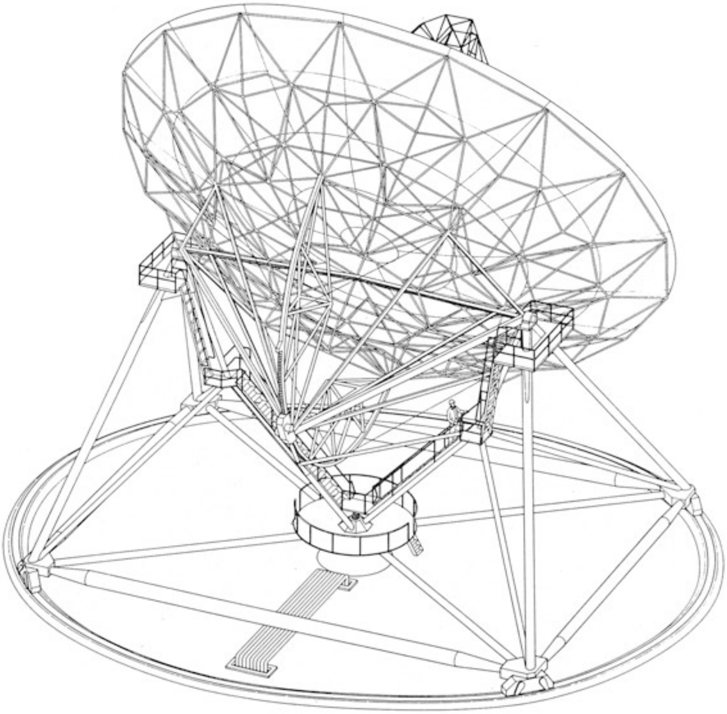

Fig. 10.5 Artist's conception of the 25 meter millimeter wave telescope. Credit: NRAO/AUI/NSF

established an external committee to give advice and to provide support for the new NRAO initiative.

By this time VLA construction was well underway, and in September 1975 NRAO submitted a formal proposal to the NSF to build and operate a 25 meter radome-enclosed telescope that would be good to wavelengths of 1 mm and shorter (Fig. 10.5). The main scientific motivations were for molecular spectroscopy to study star formation, the physical conditions (temperature, density) in interstellar clouds and in the atmospheres of cool stars, as well as tracers of galactic structure free of optical obscuration. Turner decided that his job was done and that he wanted to return to his research, and Mark Gordon replaced Turner as the 25 meter Project Manager and committee chair.

Discussions about where to site the 25 meter telescope became very controversial. Many committee members argued for a high altitude site with low water vapor content, important for the short millimeter and submillimeter wavelengths. The NRAO committee considered mountain sites in the continental US as well as the summit of Mauna Kea in Hawaii at nearly 14,000 feet elevation. A 12,470 foot high site on White Mountain, in the California Inyo Mountains near the OVRO appeared attractive, but access was limited, especially in the winter. The 9,000 foot high Mount Lemmon Observatory was a convenient, excellent observing site where the University of Arizona had many optical and infrared telescopes, but the radio and TV transmitters were a potential source of RFI. Mauna Kea has clear skies, low water vapor, and offered the best access to the galactic center and the southern hemisphere, but the projected construction and operations costs were much greater than for a continental site. One distinguished NRAO user commented that since the 2.6 mm CO transition was more important than the 1.3 mm band, a very high altitude site was not so important, and so it would be more cost effective to go to a less expensive site in Arizona.[35] However, citing the importance of low water vapor content to best exploit the capabilities of the telescope for observing near 1 mm, Gordon argued for Mauna Kea, and was supported by the NRAO Director, Mort Roberts, who felt that NRAO should provide the best possible instrument for the community.

After another two years of further design studies of the surface panels and the dome, as well as further analysis of potential sites, in 1977 NRAO submitted a revised proposal to the NSF to locate the telescope near the summit of Mauna Kea on the big island of Hawaii. The 1977 proposal differed from the earlier one in that NRAO now proposed an astrodome configuration, similar to that used for the 36 Foot or traditional optical telescopes, instead of a radome. The telescope would thus be protected from winds and inclement weather, but not suffer from the absorption characteristic of completely radome-enclosed telescopes such as Haystack (Sect. 6.6) and FCRAO (Sect. 10.4). But no rotating dome with an open aperture large enough to house a 25 meter diameter telescope had ever been built, and this added considerably to the estimated construction cost of $12.5 million and the annual operating cost of $1.35 million. The 25 meter antenna differed in an important way from all previous NRAO antennas which were "design and build" contracts based on performance specifications. Since the 25 meter specifications were so tight and difficult to measure, NRAO accepted the responsibility for the design and overall performance of the telescope, although William (Bill) Horne later noted that "while [NRAO] may possess the engineering capability, [it] certainly does not possess the engineering capacity … for the required design work."[36] Six months later, Horne became the Project Manager for the 25 meter construction project.

As was the practice for all telescopes on Mauna Kea, the University of Hawaii, which operated the Mauna Kea site, expected that ten percent of all observing time would be given to University astronomers. However, there were no radio astronomers at the University of Hawaii, and NRAO was unwilling to compromise its Open Skies policy, especially in this very competitive field of millimeter spectroscopy. Instead, NRAO agreed to provide a one-time contribution toward a buried power line to the summit, as well as an annual contribution equivalent to the salary of a University of Hawaii Associate Astronomer to support the mountain astronomical infrastructure. This added another $2 million to the already expensive proposal. Later, when the University appeared to renege on the deal reached between Gordon and the U of H Institute for Astronomy Director, John Jefferies, Gordon threatened to reopen negotiations to locate the telescope in Arizona.[37] To complicate the situation, local environmental and cultural advocates, who by then opposed *all* astronomical facilities on Mauna Kea, especially objected to the 25 meter telescope because of its very large size and visibility compared with the Mauna Kea optical telescopes.

As described by Gordon (2005, p. 140), the university millimeter astronomy community was somewhat ambivalent about the 25 meter telescope. On the one hand, it promised a powerful new observing opportunity. But unlike the situation at longer wavelengths where there were no viable university facilities, university millimeter astronomers perhaps saw the proposed NRAO 25 meter telescope as competition to existing and planned university facilities at Berkeley, Harvard-Smithsonian, Caltech, and the Universities of Arizona, Massachusetts, and Texas. Typical of the university astronomers, Peter Strittmatter, Director of the University of Arizona Steward Observatory and Chair of the NSF Astronomy Advisory Committee, wrote, “I also believe that the committee will need to discuss how long the 25 m should remain as astronomy’s No 1 new start priority if it is effectively blocked. Should other smaller projects be slipped in ahead of it?”[38]

Then, in 1979, Cornell’s Frank Drake proposed a low cost 35 meter fixed spherical reflector alternative to the NRAO 25 meter telescope. By this time the 25 meter cost had risen to between $22 and $27 million, depending on the funding schedule. To advise them on deciding between the NRAO and Cornell proposals, the NSF appointed a sub-committee chaired by Alan Barrett to review the two projects. Following their meeting on 16 and 17 July 1979, the sub-committee unanimously and unambiguously “recommended without reservation that the NSF fund immediately the 25-meter millimeter wave telescope, as proposed by NRAO,” and that “It is the unanimous judgment of the committee that the 35-meter fixed spherical telescope … is not a realistic alternative to the 25-meter fully steerable telescope.”[39]

The 25 meter project was saved, but it would only be a temporary reprieve. Bill Howard, now at the NSF as Astronomy Division (AST) Director, anticipated that with the ending of the VLA construction in 1980, the VLA funding level of about $10 million per year would remain in the AST budget and he could use these funds for the 25 meter telescope. Unfortunately, AST did not get to keep the VLA funding level, so AST proposed the 25 m telescope as a new start with new money in FY1981. As was described in Sect. 8.7, following the OMB cut to the proposed FY1981 NSF budget, the NSF director dropped the 25 meter telescope. It was included again in Jimmy Carter’s final FY1982 budget proposal, but was killed when Ronald Reagan became president and froze all new starts for the new fiscal year. The 25 meter millimeter wave radio telescope then fell victim to the VLBA following the selection of the VLBA over the 25 meter telescope, first by the Decade Review Field (1982) Committee and then by the NSF Astronomy Advisory Committee. Lew Snyder at the

University of Illinois initiated a last desperate effort to save the telescope by sending the NSF a petition signed by many of the prominent workers in the field.[40]

It is a matter of speculation whether or not the telescope might have actually been built, if, instead of opting for the best site, NRAO had chosen one of the less expensive and more accessible sites in Arizona or New Mexico. Mark Gordon (2005, p. 146) later made a valiant effort to resurrect the 25 meter telescope by suggesting a less expensive surface structure and dome, and siting the telescope in the Santa Catalina mountain range near Tucson instead of on Mauna Kea. But it was too late; the millimeter astronomers had moved on to consider arrays. In stark contrast to the easy funding of the 36 Foot Telescope in the early 1960s, the level of effort that went into the 25 meter project was enormous. Over a decade of time NRAO staff had prepared dozens of funding plans and more than 150 internal reports dealing with everything from structural analysis to the electromagnetic properties of various paints, as well as detailed site and tropospheric water vapor studies; numerous contracts were negotiated but never implemented. Doing business at the NSF as well as at NRAO had changed, and would become even more complex during the long and difficult international negotiations leading to the construction of ALMA (Sect. 10.7).

The 12 Meter Upgrade Discouraged by the lagging progress with the proposed 25 meter telescope and the anticipated competition from the new millimeter telescopes being constructed by Caltech, Harvard-CfA, UC Berkeley, the University of Massachusetts, the Nobeyama Observatory, and IRAM, Gordon urged that the 36 Foot dish be replaced with a better reflector.[41] As Gordon (1984) later noted, “the popularity of the 36-foot was being killed by its very success.”

Following a hastily called meeting in Charlottesville,[42] John Findlay was given the responsibility of replacing the 36 Foot dish structure. Instead of just matching the size of the existing 36 Foot (11.0 meter) diameter dish, Findlay elected to increase the size to 12 meters (39.4 feet), which he felt was the largest size compatible with the 12.5 meter (40 foot) dome slit (Fig. 10.6). As it turned out, this was probably a bad decision, as the telescope sidelobes did “see” the dome structure, limiting the performance, especially for sensitive continuum observations. Perhaps more important than the increase of 19 percent in collecting area, the focal ratio was changed to the more conventional value of 0.42, greatly facilitating the design of high efficiency feeds for millimeter wavelengths. After rejecting the possibility of obtaining a dish from Caltech (Sect. 10.4), NRAO solicited bids from 16 commercial sources, and awarded a contract to Central Fabricators, Inc. for $71,145 to fabricate a new reflector structure.[43] At the same time, the feed/subreflector bipod support was replaced by a quadripod to give better pointing stability. Unlike the solid 36 Foot dish, the 12 Meter reflector consisted of 72 aluminum petal-shaped panels manufactured by the ESSCO Corporation. When the new 12 Meter telescope went into operation in early 1983, it finally met the specifications originally set out

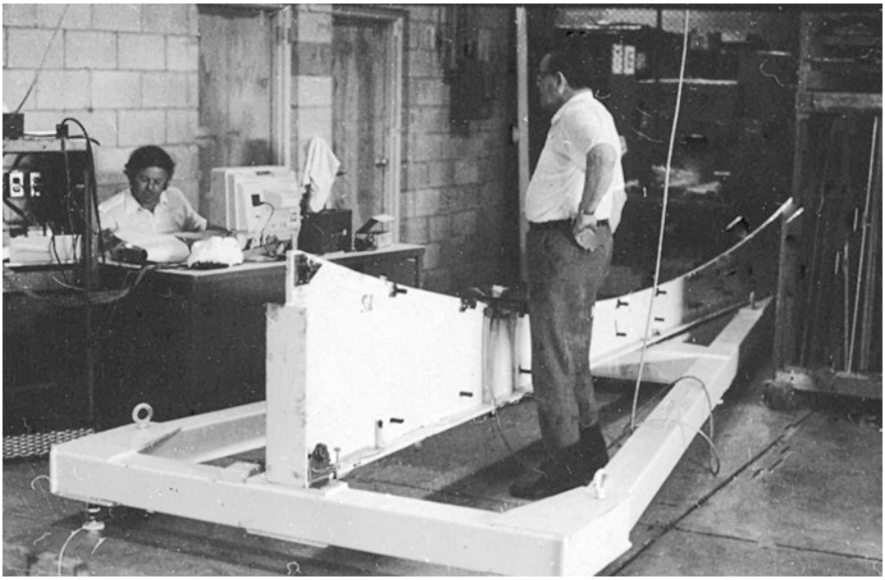

Fig. 10.6 John Findlay (right) and John Payne (left) discuss using the template to fabricate accurate surface panels for the 12 Meter Telescope

for the 36 Foot telescope and gave NRAO a badly needed competitive telescope with a surface that could support observations down to wavelengths as short as 0.8 mm.

Gordon stepped down as head of Tucson Operations in 1984 to return to full time research. He was followed as Tucson site director by Bob Brown, then Dave Hogg in 1985, and Darrel Emerson in 1986. But now a new cloud appeared on the horizon. For five consecutive years, NRAO had absorbed budget cuts and many of the new costs of operating the VLA by applying the budget cuts uniformly across all parts of NRAO. Everyone suffered and everyone complained, leading the new NRAO Director, Paul Vanden Bout, to announce that NRAO could no longer continue to do everything and that he might need to close the NRAO 12 Meter Telescope. Nearly fifty letters of protest from the user community as well as from NRAO staff were fired off to the NSF and to Vanden Bout.[44] Graduate students complained that their dissertation research was being arbitrarily terminated midway. But no one suggested any viable money-saving alternative, although some NRAO users suggested that there would be no loss if the Charlottesville headquarters were to be closed.

Fortunately, as described later by Gordon (2005, p. 187), Gordon was able to convince Arizona Senator Dennis DeConcini to use his influence to get sufficient funds restored to the NRAO budget. The NSF was not pleased with this political intervention, but as a result NRAO was able to keep the 12 Meter in operation until July 2000 when it was turned over to the University of Arizona to be used in their radio astronomy program. Some members of the NRAO

Tucson staff relocated to Charlottesville and become involved in the planning for ALMA; others retired, joined the University of Arizona program, or left NRAO to pursue other opportunities.

10.4 US Industrial and University Millimeter Wave Astronomy Programs

The NRAO 36 Foot/12 Meter telescope had opened up the new area of millimeter astronomy with its rich content of molecular transitions. Unlike other areas of radio astronomy, which were dominated by the large expensive telescopes and arrays, millimeter spectroscopy was much like optical spectroscopy, and limited more by observing time than by access to the most powerful facilities. It attracted not only traditional radio astronomers, who wanted to get away from their dependence on national facilities, but also laboratory spectroscopists such as Charlie Townes and Patrick (Pat) Thaddeus who saw opportunities to apply their skills in new ways.

Unlike centimeter to meter wavelength radio astronomy, states such as California, Illinois, Maryland, Massachusetts, and Texas, and at least two industrial groups, contributed to the construction and operation of a wide range of millimeter dishes and arrays, sometimes with additional support from the NSF. Perhaps motivated by their inability to fund the proposed NRAO 25 meter millimeter telescope and the recognition that the US was falling behind Europe in this emerging new area of astronomy, the NSF was particularly generous in supplementing both private and state funding for millimeter astronomy. But the NSF support came at a price: up to half of the observing time had to be made available to outside users.

Aerospace Corporation 15 Foot Millimeter Wave Antenna One of the first millimeter wave radio telescopes in the US was the 15 foot diameter dish operated by the Space Radio Systems Facility of the Aerospace Corporation. The antenna was located on top of the Aerospace building at the Los Angeles Air Force Station a few miles from the Los Angeles Airport and the Pacific Ocean, and had a surface accuracy of 0.09 mm rms. William Wilson, Robert (Bob) Dickman, and other Aerospace staff designed and built both continuum and spectroscopic receivers. In spite of the less than optimum location for millimeter observing, they, along with Eugene Epstein, used the telescope over a number of years for some of the first millimeter observations of quasars and planets, as well as for observing CO in the interstellar medium. (Stacey and Epstein 1964; Epstein 1977; Sargent 1979).

Bell Laboratories 7 Meter Millimeter Wave Antenna The Bell Labs Crawford Hill 7.5 meter millimeter wave antenna was built for propagation studies using the COMSTAR satellite beacons and for radio astronomy at frequencies up to 300 GHz. It was used over a period of years by Tony Stark, John Bally, and others, including many visitors. Highlights were studies of the Galaxy including a ^{13}CO survey of the plane (e.g., Stark et al. 1988), the Galactic Center region, and also studies of the structure and chemistry of molecular clouds. At the time it was probably the largest off-axis antenna ever built and remained so until the construction of the GBT (Chu et al. 1978).

University of Texas Millimeter Wave Observatory (MWO) The University of Texas 16 foot millimeter wave telescope was built in the early 1960s primarily for continuum studies of the planets and bright radio sources such as the Crab Nebula, the galactic center, and the Orion Nebula (Tolbert and Straiton 1965; Tolbert et al. 1965; Tolbert 1966). Although originally erected on the University of Texas campus in Austin in 1971, the antenna was moved to a better site at 2070 meters on Mt. Locke, the site of the University's McDonald Observatory. Motivated by the discovery of CO by Wilson et al. (1970), Paul Vanden Bout led an effort to bring the resources of the University of Texas, Harvard-CfA, Bell Laboratories, and the Columbia University/Goddard Institute for Space Studies to the MWO, and with support from NASA and the NSF, the MWO became a major player in millimeter wave spectroscopy. As described by Vanden Bout et al. (2012), "the amicable relations at the MWO stood in contrast to the NRAO 36-ft Radio Telescope where astronomers engaged in a vigorous competition to gain what was typically a few days of observing time, often to search for a new interstellar molecule." Rather than try to compete with NRAO observers in the race to discover new molecules, the MWO observing programs were largely devoted to using the strongest molecular lines to probe the physical conditions of their environment and to address questions posed by the discovery of an entirely new phase of the interstellar medium, including the nature of molecular clouds. Many of the future leaders of millimeter astronomy in both the US and Europe were trained at the MWO either as students or postdoctoral workers. In 1985, Vanden Bout left Texas to become the Director of NRAO, where he oversaw the construction of the VLBA and the GBT, and then spearheaded the US participation in ALMA.

Columbia University/Goddard Institute for Space Studies Shortly after the discovery of interstellar carbon monoxide (CO) by Wilson et al. (1970), Columbia University Professor Pat Thaddeus built a small 1.2 meter radio telescope which he placed on the roof of the Columbia physics building. In 1982 he installed a second telescope at the Cerro Tololo Observatory in Chile. When Thaddeus moved to Harvard-CfA in 1986, he took the Columbia instrument with him and placed it on top of a Harvard building. Over a period of many years, Thaddeus, together with numerous colleagues and students, used these two small radio telescopes to map out the 2.6 mm CO emission in the entire Galactic plane (e.g., Dame et al. 2001).

University of Arizona Steward Observatory Millimeter wave astronomy at the University of Arizona started with Frank Low's 1965 move from NRAO to Tucson, but stagnated as Low turned his attention toward infrared astronomy. In 1978, Peter Strittmatter, the Director of the UofA's Steward Observatory, spent a year at the MPIfR and began a discussion with Peter Mezger about millimeter and submillimeter wavelength astronomy. Mezger had hoped to build a submillimeter telescope on the summit of Pico Veleta above the 30 meter IRAM telescope, but access to the summit was hazardous, and Mezger was unable to gain permission for a summit site. Moreover, the Max Planck Gesselschaft (MPG) made it clear that they would not provide the additional annual funds which would be needed to operate the telescope. Strittmatter and Mezger then agreed to build and operate a 10 meter diameter submillimeter wavelength telescope at an altitude of 3180 meters on Mount Graham in eastern Arizona. The MPIfR—UofA Submillimeter Telescope (SMT), later renamed the Heinrich Hertz Telescope (HHT), has a surface accuracy of 0.015 mm rms and tracks to better than 1 arcsec. The HHT pioneered the use of carbon fiber reinforced plastic (CFRP) to minimize thermal effects in precision telescope structures (Baars et al. 1999) and operates at wavelengths as short as 0.35 mm.

Five College Radio Astronomy Observatory (FCRAO)[45] In 1976, FCRAO inaugurated a 14 meter diameter radome-enclosed antenna built by the ESSCO Corporation on the shores of the Quabbin Reservoir in central Massachusetts. Support for the construction and operation of the telescope came from a combination of NSF, private, and Commonwealth of Massachusetts funding. Until it closed for lack of operating funds in the spring of 2006, the FCRAO antenna was one of the largest millimeter wave telescopes in the US. During this period FCRAO scientists, engineers, and students designed and built a variety of innovative instrumentation, including a 16-element (QUARRY), then 32-element (SEQUOIA), MMIC arrays. The FCRAO receivers were among the best in the world, at times perhaps a factor two more sensitive than NRAO's 36 Foot/12 Meter receivers, and for many years FCRAO had a near-monopoly on structural studies of nearby galaxies. Many of the subsequent leaders in US millimeter wave science and instrumentation worked at or were trained at the FCRAO, and went on to distinguished careers in radio astronomy. Starting in the late 1990s, the FCRAO staff devoted their efforts toward building the LMT in Mexico. A 144 element bolometer 1.1 and 2.1 mm array known as AzTEC was developed at FCRAO in collaboration with others, and was used first on the James Clerk Maxwell Telescope (JCMT), then on the Japanese ASTE 10 meter submillimeter wave telescope in Chile, before being installed on the LMT in Mexico.

The Large Millimeter Telescope (LMT)[46] Planning for the 50 meter (164 foot) Large Millimeter Wave Telescope (LMT) on a high altitude site in Mexico as a joint effort between the University of Massachusetts and Mexico was already underway at the time of the 1990 Decade Review of Astronomy, but there were a number of competing proposals for what were considered “Moderate Programs.” NRAO had proposed to fill the gap between the VLA and VLBA by constructing four new antennas in New Mexico. The Bahcall Committee Radio Panel was sensitive to the need to maintain viable university-based radio astronomy facilities in the US, and reluctant to allocate too much of the NSF’s limited resources to NRAO, so it identified “A Large Millimeter Radio Telescope Working to at Least 230 GHz” as the highest priority for moderate sized projects. The expected federal share of the LMT cost was claimed to be only $15 million dollars, representing about half of the total cost (Kellermann 1991, p. I-9).

Normally, the parent committee of a Decade Review is tasked with interweaving the recommendations coming from the various wavelength panels, and it is rare for the parent committee to overturn the panel’s ordered recommendations. However, in this case, the parent committee was apparently not impressed by the proposed LMT. The VLA extension proposed by NRAO appeared sixth and last among the recommended “Moderate Programs” (Bahcall 1991, p. 17), but the LMT was not mentioned at all in the Bahcall Committee report. The proposed VLA expansion was never funded, although an extensive refurbishing and modernization of the aging infrastructure, correlator, and other VLA instrumentation was later supported by the NSF, leading to the upgraded Karl G. Jansky Very Large Array (Sect. 7.8).

The reports of the Astronomy and Astrophysics Survey Committee Wavelength Panels have no formal status as recommendations of the NAS. However, based on the Radio Panel Report (Kellermann 1991), the University of Massachusetts working with the Mexican Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) was able to obtain funding from Massachusetts and Mexican resources to build the LMT on the summit of Volcán Sierra Negra at an altitude of 4,600 meters (15,000 feet) in the Mexican state of Puebla. Following a series of technical and administrative disputes, compounded by funding delays, the LMT was finally completed in 2018 (Baars 2013). It operates at wavelengths as short as 0.85 mm on an excellent site. It is the world’s largest filled aperture steerable telescope operating at such short millimeter wavelengths and is the largest, most complex, and most expensive scientific instrument ever built in Mexico.

Harvard-Smithsonian Sub-Millimeter Array (SMA) Planning for the SMA began in 1983. Motivated in part by the Field (1982) Committee recommendation, the new CfA Director Irwin Shapiro appointed a committee to study the feasibility of submillimeter interferometry. The committee, chaired by James (Jim) Moran, recommended the construction of an array of six 6 meter diameter dishes on a high dry site (Moran et al. 1984), but there were technical challenges in developing low noise receivers and movable antennas with sufficient precision to operate at submillimeter wavelengths. In 1987, CfA set up a laboratory for the development of submillimeter receiver technology and investigated potential sites in Arizona, Chile, and Hawaii. Under Moran's leadership, construction of a six element array of 6 meter diameter dishes near the summit of Mauna Kea at 13,350 feet elevation began in 1999. Two additional elements were added by the Taiwan Academia Sinica Institute of Astronomy and Astrophysics (Ho et al. 2004), and the eight element SMA with up to 172,000 spectral channels, 2 GHz of continuum bandwidth, and angular resolution up to 0.1 arcsec was completed in 2003. In 2008, the SMA was linked with the JCMT and California Submillimeter Observatory (CSO) to form a 10 element interferometer with baselines up to about 800 meters.

The SMA was the first imaging array to operate at sub-millimeter wavelengths. It made the first resolved radio images of the thermal emission of the Pluto-Charon system, of CO and HCN in the atmosphere of Titan, of the unscattered polarized continuum emission from Sgr A*, and of the extremely high velocity and low velocity collimated SiO outflows from a low luminosity proto star (Ho et al. 2004; Moran 2006). Unlike many of the other millimeter facilities, the SMA follows an Open Skies policy and observing time is available to all qualified scientists based on peer-reviewed proposals.

The Hat Creek Radio Observatory and the Berkley-Illinois-Maryland Association Millimeter Array (BIMA) Starting in the 1970s, University of California Professor Jack Welch built what was probably the world's first millimeter wave interferometer at the Hat Creek Radio Observatory in northern California. Under Welch's leadership, the initial two-element variable spacing interferometer was first expanded to three, then six dishes, each 20 feet in diameter. Starting in 1987, the array was operated by the Berkeley-Illinois-Maryland Association (BIMA). In 1993, the 85 foot diameter telescope at the Observatory collapsed during a violent wind storm. Instead of replacing the 85 foot telescope, Welch used the University insurance money to build new 20 foot diameter antennas to form a ten-element array that could be reconfigured to give angular resolutions up to 0.4 arcsec at 100 GHz (Welch et al. 1996). BIMA used cooled SIS mixers to operate up to 270 GHz or 1.1 mm. Data analysis was based on the MIRIAD (Multichannel Image Reduction, Image Analysis, and Display) software package developed by the BIMA group (Sault et al. 1995). Financial support for BIMA came from the states of California, Illinois, and Maryland, as well as from the National Science Foundation and the Taiwan based Academia Sinica Institute for Astronomy and Astrophysics (ASIAA). Thirty percent of the observing time at BIMA was made available on an Open Skies basis to users from outside the BIMA collaboration.

The Hat Creek interferometer and later BIMA were used to study H_2O masers, the HCN emission surrounding the galactic center, SiO masers in Orion, for a survey of CO in normal galaxies, for observations of the Sunyaev-Zelodvich effect, and the first millimeter VLBI observations (Plambeck 2006). BIMA also pioneered the use of mosaicked observations where observations based on hundreds of array pointings were combined to image a large extended area. In 2004, the BIMA antennas were moved to Cedar Flats to form part of CARMA (see below).

Caltech Submillimeter Observatory (CSO) and the Owens Valley Millimeter Array When it became clear in the early 1980s that they would not have a major role in the construction or operation of the VLBA, Caltech turned its attention to millimeter and submillimeter astronomy. Led by Professors Robert (Bob) Leighton, Alan Moffet, and Thomas (Tom) Phillips, Caltech developed two major facilities for millimeter/submillimeter astronomy. The Caltech program in millimeter wave astronomy was based on a novel antenna design by Leighton used to construct a series of 10.4 meter diameter dishes. Leighton's dishes were fabricated using 84 hexagonal aluminum honeycomb tiles which were figured after mounting on a steel backup structure using a custom-designed cutting machine installed at the same facility that was used to grind the Palomar 200 inch mirror. After surfacing, the dishes could be disassembled and reassembled in the field with a typical accuracy better than 0.035 mm rms.

A total of seven dishes were fabricated by Leighton and his colleagues. The most precise dish was the basis of the CSO located just below the summit of Mauna Kea at an altitude of 13,350 feet. The Mauna Kea antenna was mounted in a rotatable dome to provide protection from wind and weather. Under the direction of Phillips (2007), the CSO went into operation in 1987. It was used at wavelengths as short as 0.35 mm using a variety of bolometer arrays and coherent SIS mixer receivers to exploit the relatively high transition probability of molecules at higher frequencies, as well as the increased thermal emission from cold dust which peaks at infrared and submillimeter wavelengths. Due to a lack of operating funds from the NSF, the CSO was closed in 2015.

The other six dishes were erected in the Owens Valley to form a versatile imaging millimeter array operating in the 1.3 and 2.6 mm bands using cooled SIS mixers with an angular resolution of 1 arcsec at the shorter wavelength (Scoville et al. 1994). The Owens Valley millimeter array was used for a variety of spectroscopic observations ranging from studies of planetary atmospheres, evolved protostars, protoplanetary disks, nuclear starbursts, and luminous and ultraluminous high redshift galaxies, and was later absorbed into CARMA.

Combined Array for Research in Millimeter-Wave Astronomy (CARMA) It had been clear for some time that the BIMA and Caltech Millimeter Arrays would be much more powerful if they were combined into a single array, but both Caltech and BIMA resisted any change which threatened their independence. However, threatened by the potential loss of NSF funding, Caltech and the three BIMA institutions finally agreed to combine their facilities to form a more powerful 15-element array consisting of the six OVRO antennas plus nine BIMA antennas. Tony Beasley was recruited from NRAO to serve as the project manager to build CARMA at Cedar Flats in the Inyo Mountains east of the Caltech Owens Valley site at an altitude of 7,200 feet. An innovative aspect of CARMA was its use of the eight 3.5 meter antennas of the former Sunyaev-

Zeldovich Array, which were placed close to the CARMA antennas and used to simultaneously observe phase calibration sources. Beginning in 2007, CARMA provided a powerful northern hemisphere complement to ALMA, but it was closed in 2015 as the NSF concentrated its support for millimeter wave astronomy on ALMA.

10.5 INTERNATIONAL CHALLENGES

The James Clerk Maxwell Telescope (JCMT) Starting in 1983, the UK, together with the Netherlands and Canada, built a 15 meter diameter antenna near the summit of Mauna Kea close to the CSO. The JCMT is enclosed in a rotatable dome and observes through a slit covered with a membrane that is nearly transparent at millimeter and submillimeter wavelengths. With a surface accuracy about 0.025 mm rms, the JCMT had good efficiency at wavelengths as short as 0.3 mm. For many years the main instrument on the JCMT was the powerful Submillimetre Common-User Bolometer Array (SCUBA) which gave high sensitivity in both the 0.45 and 1.3 mm atmospheric windows with arrays of 91 and 37 pixels respectively, and was supplemented by single pixel bolometers at 1.1, 1.3, and 2 mm for photometry (Holland et al. 1999). SCUBA was used for both deep imaging and wide field mapping, and discovered the important new population of star forming galaxies (Barger et al. 1998). A 16-pixel SIS heterodyne receiver array was used for spectroscopy at 350 GHz. In 2011, SCUBA was replaced by SCUBA-2, with a 10,000-pixel bolometer camera cooled to 0.1 K and operating at the same 0.45 and 0.85 mm atmospheric windows as SCUBA (Holland et al. 2013). SCUBA-2 was able to map the sky about 100 times faster than its SCUBA predecessor.

SEST and APEX When Roy Booth became Director of the Onsala Space Observatory in Sweden, he combined forces with IRAM millimeter wave astronomers and Peter Shaver at ESO to build the Sweden ESO Submillimetre Telescope (SEST). SEST was an open air 15 meter diameter telescope located at the ESO Observatory on La Silla in northern Chile at an altitude of 7,550 feet. The Cassegrain telescope was similar to the IRAM interferometer antennas, but was mounted on a fixed base, and was designed and built by IRAM in collaboration with French and German industrial partners (Booth et al. 1989). The antenna had a surface accuracy of only 0.07 mm rms and pointing accuracy of 3 arcsec. The construction and operating costs were shared equally by ESO and Onsala. Onsala was responsible for the technical operation and provision of the receivers and other instrumentation, while the operation on La Silla was managed by ESO along with their optical telescopes on the mountain. Starting in 1988, the SEST telescope was used primarily in the 1.3, 2.6, and 3.5 mm bands for spectroscopic observations of extragalactic interstellar molecules, especially CO, as well as for continuum observations of quasars. Observing time was shared equally between Swedish astronomers and ESO's European user community. The operation of SEST was ESO's first involvement with millimeter astronomy, and opened the door for ESO's later participation as a partner in ALMA. SEST was closed in 2003 when it was superseded by the Atacama Pathfinder Experimental Telescope (APEX).

APEX is a 12 meter diameter modified North American ALMA (Sect. 10.7) prototype antenna located at 16,500 feet altitude on the Chilean Atacama desert on the site of the ALMA telescope (Güsten et al. 2006). With its more precise surface of 0.017 mm rms and high altitude location, it replaced SEST, and operates primarily in the wavelength range between 0.2 and 1.5 mm, or between the radio and infrared parts of the electromagnetic spectrum. APEX was built as joint collaboration of the MPIfR, the Onsala Observatory, and ESO and, like SEST, is operated by ESO. NRAO was invited to join APEX, but declined due to the need to concentrate its limited resources on the MMA. Due to the high altitude location, the antenna is routinely operated from San Pedro de Atacama via a radio link. A particularly notable feature of APEX is its 295-element 345 GHz liquid helium cooled bolometer array known as LABOCA (Large Apex Bolometer Camera) (Siringo et al. 2009). LABOCA is the latest in a series of bolometer cameras developed by the MPIfR radio astronomer Ernst Kreysa, and has been used primarily to investigate star formation in the Milky Way Galaxy and in nearby galaxies.

The Institut de Radio Astronomie Millimétrique (IRAM) As early as the mid-1960s, Emile Blum began in France to develop plans for a millimeter wavelength interferometer (Encrenaz et al. 2011). During his 1967 visit to NRAO, he met Peter Mezger, then still on the NRAO scientific staff, but about to leave to become a Director at the MPIfR, where he would be in charge of the new Effelsberg 100 meter telescope. Perhaps based on his early exposure to the embryonic attempts in Green Bank by Frank Drake and Frank Low to experiment with millimeter wavelength astronomy in the early 1960s, Mezger had a long-time ambition to build a precise radio telescope to work at short millimeter wavelengths. With the support of the French Centre National de la Recherche Scientifique (CNRS) Director, Bernard Gregory, and the MPG President Reimar Lüst, Mezger, and Blum respectively, developed plans for a 30 meter antenna and a multi-element interferometer as parts of a joint observatory known as SAGMA.[47] The MPIfR group found an attractive site on Pico Veleta in the Spanish Sierra Nevada for their 30 meter antenna, while Blum and colleagues located a flat site on the Plateau du Bure in the French Alps suitable for an interferometer. But the Plateau de Bure site was only at an altitude of 2,550 meters, 300 meters lower than the proposed 30 meter site on Pico Veleta, and, more important, was further north, limiting access to the Galactic center.

Mezger was unyielding, arguing that the Plateau de Bure site was unacceptable for the 30 meter telescope, while Blum was equally firm that Pico Veleta could not accommodate an interferometer, especially if the baseline were to be expanded. Meanwhile, Gregory and Lüst were adamant that there would be no funding from CNRS or the MPG unless the two instruments were built as part of a joint French-German project. The issue was not so much a matter of saving money by a joint project, but a strong desire on the part of both CNRS and the MPG Max Planck Gesselschaft (MPG) in this post-World War II era to establish firm evidence for French-German collaboration. A radio astronomy project was perceived to be more straightforward than, for example, an agreement on agricultural subsidies. But Blum and especially Mezger were obstinate and held firm to their positions. Mauna Kea, on the big Island of Hawaii, was mutually acceptable to both Mezger and Blum, but was considered logistically unreasonable unless NRAO joined the project to provide local support and if significant funding came from the US.[48] The NRAO staff debated the idea of joining SAGMA on Hawaii and concluded that it would compromise its own plans for the 25 meter millimeter wave antenna (Sect. 10.3), and rejected the European proposal.[49]

Faced with an impasse, in early 1977 Gregory and Lüst convened an international committee of three so-called "wise-men" to adjudicate the siting issue. One of the present authors (KIK) served on the committee, along with Bernard Burke from MIT and Paul Wild from CSIRO in Australia. After meeting with MPG and CNRS and visiting the proposed sites, the committee met at the Paris CNRS headquarters to prepare their report and to deliver it to Gregory. Recognizing that the Plateau de Bure was by far the better of the two sites to locate the interferometer even though the latitude was higher than ideal, and that the Pico Veleta was by far the better of the two sites to locate the 30 m telescope, the committee noted that it would be inappropriate to favor one site over the other and recommended that the common center of the cooperative program should be located in an observatory headquarters in Grenoble, France. Recognizing the need to ease tensions and maintain the delicate balance between the French and German interests, the committee refrained from suggesting that the Director of the new joint observatory be German and that the chef be French. Following the Paris meeting, Burke and Kellermann traded in their first class plane tickets plus $50 each to purchase tickets for an unforgettable flight to Washington on the Air France Concorde.

The MPG Max Planck Gesselschaft (MPG) and CNRS accepted the recommendation, which led to the formation of IRAM, with headquarters in Grenoble, the three- (later expanded to six-) element interferometer on the Plateau de Bure and the 30 meter telescope on Pico Veleta (Baars et al. 1987). Peter de Jonge became the first director of IRAM, and established IRAM as a more independent and self-standing organization than either Mezger or Blum anticipated or found comfortable. In 1990 Spain became a full member of IRAM. Unlike in the US, where the NSF was not able to provide operating funds for CARMA at the same time as ALMA, IRAM, starting in 2014, constructed four more antennas with a goal of reaching a total of 12 by 2020 as part of the NOrthern Extended Millimeter Array (NOEMA), thus providing a powerful northern hemisphere complement to ALMA.

Both the 30 meter telescope and the Plateau de Bure interferometer operate up to 350 GHz (0.85 mm). The 30 meter is equipped with both multifeed spectrometer and bolometer cameras and, due to careful thermal control, operates well even in the daytime. A fatal accident with the cable car to the Plateau in 1999 killed 20 people, limiting access to the plateau to foot or helicopter, but was followed six months later by a helicopter crash which took the lives of another five people. Since then the rebuilt lift has been used only for transporting equipment, while IRAM staff and observers use a newly built road.

Japanese Millimeter Astronomy Under the leadership of Masaki Morimoto, Japanese radio astronomers built two world-class facilities at their Nobeyama Observatory, 150 km from Tokyo. The 45 meter dish is used at wavelengths down to 2.6 mm, and until the completion of the GBT (Sect. 9.7) was the largest telescope in the world operating at short millimeter wavelengths. A broad band 16,000 channel acoustical optical spectrograph was the heart of the 45 meter spectroscopic system. The millimeter interferometer, which contained six 10 meter diameter movable dishes operating between 1.2 mm and 1.3 cm, was closed for astronomical observing in 2007 as Japan devoted its resources to ALMA. The performance of both the 45 meter dish and the interferometer was limited by the modest 1,350 foot elevation and correspondingly high water vapor content.

As a prototype for their Large Millimeter and Submillimeter Array (Sect. 10.7), Japanese radio astronomers have also built the precision 10 meter diameter Atacama Submillimeter Telescope Experiment (ASTE) located near the ALMA site on the Atacama Desert in northern Chile. With its 0.02 mm rms precision surface and excellent site, ASTE is used (Kohno 2005) at frequencies up to 850 GHz (0.35 mm). Until it was moved to the LMT, ASTE used the FCRAO 144-element AzTEC bolometer for 1.1 mm continuum observations.

10.6 THE NRAO MILLIMETER ARRAY (MMA)

The millimeter wavelength facilities described in Sect. 10.4 brought new life to the US university radio astronomy programs, but the developing ambitions in Europe and Japan threatened US leadership in millimeter and submillimeter astronomy. Although the NRAO 36 Foot dish on Kitt Peak may have opened the field of millimeter astronomy, even after the 12 Meter upgrade it was no longer competitive with many of the other emerging millimeter wave facilities, which were larger, worked to shorter wavelengths, and were located on better sites. With the demise of the 25 meter project, NRAO was no longer a major player in this rapidly developing and promising field of millimeter astronomy.

The 1982 Astronomy Survey Committee (Field 1982) had assumed that the 25 meter telescope would be built, so they did not make any recommendations for any other major millimeter facility. Thus, following the April 1982 NSF Astronomy Advisory Committee decision to abandon the 25 meter telescope, there were no US plans to exploit this rapidly growing area of astronomy that had been pioneered in the US. The US millimeter astronomy community was not happy with NRAO's leadership, or perceived lack thereof, in selling the 25 meter to the NSF or to the broader astronomical community. Although many millimeter wave astronomers had gotten their start as a result of NRAO's pioneering efforts in millimeter wave astronomy, they now held NRAO responsible for the fall of the 25 meter telescope, in part due to what some felt was a stubborn insistence on sticking to the expensive Mauna Kea site, and in part for apparently abandoning the millimeter wave telescope in favor of the VLBA.

The Barrett Report In order to develop a strategy for moving forward after the collapse of the 25 meter project, Robert (Bob) Wilson (Bell Labs), Phil Solomon (Stony Brook), and Lewis Snyder (Illinois) convened a small meeting at the Crawford, New Jersey offices of Bell Laboratories on 28–29 October 1982 "to discuss future U.S. national instruments for mm-wave astronomy."[50] No one from NRAO was invited. The meeting participants acknowledged that the 25 meter telescope "would have been a world leading instrument when first proposed," but in view of "similar large instruments being built overseas in Europe and Japan, the time for the 25 meter telescope had passed."[51] The eighteen participants all signed a strong letter to NSF AST Director Pat Bautz and NSF Assistant Director for AAEO Frank Johnson presenting the case for building a "millimeter wave aperture synthesis instrument" based on a scaled down VLA and consisting of about 30 roughly 6 meter-sized antennas with a maximum baseline less than 3 km.[52] There was no mention in the letter of who should build the array or where it should be located.

Previously unaware of the Bell Labs meeting, and also concerned about the future of US millimeter astronomy, Bautz "convened a Subcommittee of the NSF Astronomy Advisory Committee [chaired by MIT's Alan Barrett] to advise on the future needs of millimeter and of submillimeter wavelength astronomy."[53] Barrett called an open meeting of the Subcommittee at the NSF on 3 December 1982. The Subcommittee heard reviews of existing mm wavelength interferometry and single dish facilities, as well as possibilities for future developments. The Bell Labs and NSF groups agreed to work together and met again at Bell Labs on 9–10 February 1983, primarily to review and formulate the scientific case for millimeter interferometery.[54]

The April 1983 report of the NSF Subcommittee, which became known as the "Barrett Report," recognized the advanced millimeter wave facilities already operating at IRAM and Nobeyama, and noted that the more modest interferometers at Caltech and Hat Creek were "unsuitable for general visitor use by a large segment of the mm-wave astronomers."[55] The first recommendation of the committee was the initiation of a design study of a millimeter wavelength aperture synthesis array with a minimum useable wavelength of 1 mm, an angular resolution of 1 arcsec or better at a wavelength of 2.6 mm, and a total geometric collecting area of 1,000–2,000 square meters. The NSF Subcommittee also did not specify who should build the array, but noted, "A project of this magnitude would be a national facility," and that, "It may well be that such an instrument would be situated with the present VLA in New Mexico in order to take advantage of the great expertise of the VLA staff."

Planning for the Millimeter Array The first serious discussions about building a millimeter array at NRAO took place at an internal workshop on future instrumentation held in Green Bank in October 1982. As input to the workshop, Frazer Owen prepared a memo calling attention to the millimeter wave dishes and arrays around the world "in the late planning or the construction stage," arguing that "the single dishes being planned seem likely to supersede the capabilities of the NRAO 12 meter fairly quickly," and that the time had come for NRAO to take the initiative.[56] Owen argued that the infrastructure already available at the VLA and the moderately high and fairly flat VLA site made it an ideal location for millimeter interferometry. He also pointed out that, in addition to the obvious drivers for spectroscopic imaging, interferometers were more effective than large single dish telescopes in suppressing the effects of ground and tropospheric emissions. Mort Roberts was impressed by Owen's presentation, and after the workshop asked Owen to form a small internal committee to review the scientific justification for millimeter interferometry,[57] but Owen was more concerned about the technical challenges of the array configuration.[58]

Encouraged by the Barrett report, Roberts formed a series of technical review committees to examine the configuration, siting, and antenna structures for a millimeter array. Potential sites in Antarctica, Arizona, Chile, Colorado, Hawaii, and Utah, were studied, along with the existing Owens Valley, Hat Creek, and VLA sites, as well as the nearby South Baldy site in New Mexico's Magdalena Mountains at 10,600 feet. A regular Millimeter Array Newsletter was issued, with Frazer Owen as Editor, and separate Millimeter Array technical and scientific memo series were begun.[59] NRAO Scientist Edward (Ed) Fomalont spent six months at the Nobeyama Observatory to implement AIPS on their interferometer and also to bring back to NRAO experience learned from working with the Nobeyama millimeter array. Following traditional NRAO procedure, a Millimeter Array Technical Advisory Committee, chaired by Bob Wilson, was established to solidify support from the university community.

Millimeter Array design work continued throughout the 1980s, with NRAO Associate Director Bob Brown as MMA Project Director, and included site testing in New Mexico, Arizona, and Hawaii. During this period, NRAO held a series of scientific and technical workshops to address a variety of technical issues and to tighten the scientific case for a Millimeter Array.[60] Interestingly, when asked about South America as a potential site, the MMA Advisory Committee responded, "This is not an attractive idea."[61] However, Mark Gordon expressed concern that in view of planned expansions of existing millimeter arrays in Japan, at IRAM, Caltech, and Hat Creek, the proposed NRAO Millimeter Array would not be sufficiently unique, and would be more attractive if located in Chile close to the CTIO facilities near La Serena.[62] NRAO staff also met with a group from the Smithsonian Institute to discuss possible collaboration between the MMA and the SMA. Joint Working Groups dealing with science, antennas, site selection, receivers, and management were formed. However, other than NRAO support for testing the Mauna Kea SMA site, the proposed collaboration did not materialize.

In January 1988, NRAO issued a two volume MMA Design Study. Volume I, *Science with a Millimeter Array* (Wootten and Schwab 1988), contained the Proceedings of the Green Bank Workshop held in October 1985 to define the scientific goals which a millimeter array might address. Volume II, *MMA Design Study* (Brown and Schwab 1988) discussed the design principle for a forty-element array using 7.5 meter antennas, instrumentation, and computing requirements. The estimated construction cost, including a 20% contingency, was $66 million.

Following another workshop, held in Socorro from 15 to 18 January 1989, to assess the scientific progress in millimeter wave astronomy, and after six years of planning, design, and prototyping, in July 1990, AUI/NRAO finally submitted a proposal to the NSF for the construction of a Millimeter Array (Brown 1990). The proposed MMA consisted of 40 transportable dishes, each 8 meters in diameter, to give a total collecting area of about 2,000 m^2 (Fig. 10.7). The planned frequency bands were 30–50 GHz, 70–115 GHz, 120–170 GHz, and 200–350 GHz. At its highest frequency of 350 GHz (0.85 mm) and in the largest 3 km diameter configuration the resolution was 0.06 arcsec. No site was specified, but the proposal reviewed the search for a suitable high dry site sufficiently large to hold the 3 km sized array. The attraction of a site in Chile was

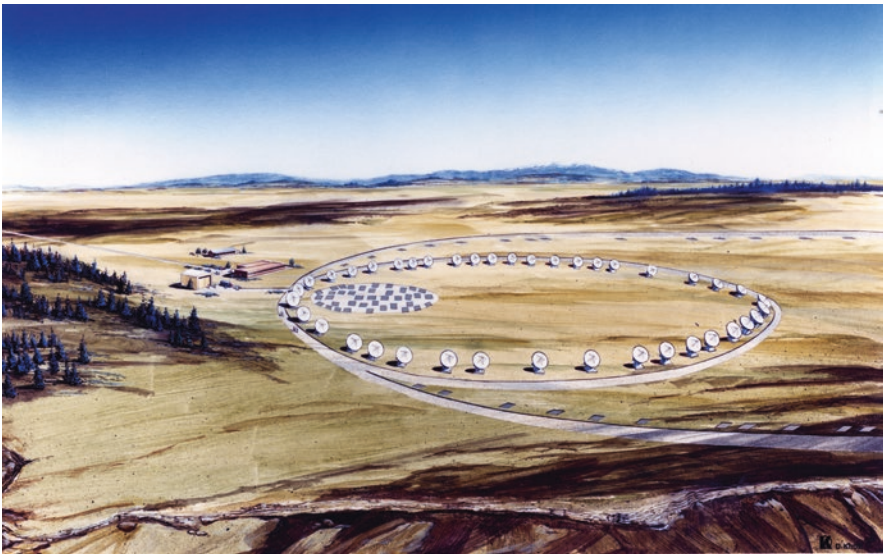

Fig. 10.7 Artist's conception of the Millimeter Array, with 40 transportable 8 meter dishes. Credit: NRAO/AUI/NSF

discussed but, due to the much greater construction and operating costs that would be involved, it was dismissed in favor of sites in Arizona and one in New Mexico, close to the VLA.

By this time, the anticipated MMA construction price had risen to $120 million, including 15% contingency. Annual operating costs were estimated as $6.5 million. However, there were still many unanswered questions. The NRAO's MMA proposal to NSF was reviewed by 20 US and foreign scientists, who recommended that NRAO proceed with the MMA, but raised concerns about the site selection process and the estimated costs of construction and operation. Several reviewers noted that NRAO had no experience in millimeter interferometry.[63] In April 1991 the NSF brought a committee to Socorro to assess the project. The proposal reviews, the site visit, and the long range planning committee of the Advisory Committee for the NSF Division of Astronomical Sciences (ACAST) all "overwhelmingly endorsed the NRAO Millimeter Array,"[64] but ACAST raised concerns about where the operating funds would come from.[65]

The Bahcall Committee Responding to the growing threat from IRAM, the MMA also received the important blessing of the 1990 Decade Review of Astronomy (Bahcall 1991) in order to "recapture the once dominant position of the United States in millimeter astronomy."[66] There were no other "large" radio astronomy proposals competing with the MMA, so, unlike the earlier bitter battles over the VLA and VLBA which occurred in the 1970s and 1980s Decade Reviews, the 1990s Radio Panel quickly reached a consensus to recommend "as the highest priority for new construction a Millimeter Wave Array with sub-arcsecond resolution, comparable to that of the VLA, and having good image quality, a sensitivity adequate to study faint continuum and line emission, and a flexible spectroscopic capability in all of the millimeter wavelength windows between 30 GHz and 350 GHz." (Kellermann 1991, p. I-9).

In the parent Survey Committee, the MMA faced competition from the two 8 meter optical telescopes recommended by the OIR Panel, one located on Mauna Kea, optimized for infrared astronomy, and the other to be built in the Southern Hemisphere, optimized for optical and near ultraviolet wavelengths. Although there was a broad consensus that after the VLA, VLBA, and then the GBT, it was time to support other wavelengths, after vigorous debate within the Committee, the MMA was still given second priority, following the Mauna Kea infrared telescope, but far ahead of the Southern Hemisphere telescope (Bahcall 1991, p. 11). However, even during the Committee deliberations, before any decisions had been reached, NSF Director Erich Bloch reported that he had negotiated a deal with the UK Science and Technologies Facilities Council (STFC) to jointly build both of the 8 meter telescopes with the US and the UK each paying for half the cost. John Bahcall, the Survey Committee Chair, was incensed and argued that since the Committee had not yet reached any conclusions about the relative priorities of the various projects under consideration by the Committee, such an agreement was premature. But Bloch, not to be intimidated, retorted that if he had to wait for committees to decide anything, nothing would ever get built.[67]

NSF Approval In response to the issues raised by the reviewers, NRAO submitted a new proposal for a "Millimeter Array Design and Development Plan," requesting $22.3 million over three years to continue site evaluation, to provide final engineering design for the antennas and instrumentation, and for algorithm development.[68] As usual, things moved slowly in Washington, and it was not until November 1994, at the request of NSF Director Neal Lane, that the National Science Board (NSB) approved a project development plan for the MMA. In May 1995, the NSB authorized the expenditure of $26 million for a three-year MMA design and development program. To jump start the development program, NSF AST Director Hugh Van Horn added $1 million to the NRAO 1995 budget from AST funds to begin site studies and further planning. The three-year MMA Design and Development Program began in 1996 and included a prototype antenna, configuration studies, SIS mixer, and HFET amplifier design. By this time, the antenna concept for the MMA had evolved from a conventional on axis design to an offset configuration with an unblocked aperture constructed of carbon fiber instead of steel to reduce the effects of thermal deformations.[69] An additional requirement, which was to lead to increased cost, was the need to be able to quickly slew the antennas between the region under study and a nearby reference source.

As with the 25 meter telescope, community support was ambivalent, particularly from Caltech, Berkeley, Illinois, and Maryland, who saw the MMA as not only an exciting scientific opportunity, but also as a threat to their own ambitions. Recognizing the concern about the lack of millimeter interferometer experience at NRAO, and the opportunity to better engage the university community, Vanden Bout invited Caltech and BIMA radio astronomers to join an MMA Development Consortium (MDC). This was perhaps NRAO's first use of an embedded acronym. Meanwhile, in 1998 the NSF established their own MMA Oversight Committee (MMAOC) to provide further advice and oversight of the MMA project. NRAO scientists and engineers were spending more time writing reports and attending meetings than they were in designing the MMA, but it would get worse.

Just like the previous radio telescope projects we have discussed, a particularly challenging and controversial aspect of the MMA was choosing a site. With the growing interest in sub-millimeter wavelengths, the primary criterion was for a high dry site, but like the VLA, the MMA required a large flat area within which the antennas could be moved to different array configurations. The most desirable locations appeared to be in the Atacama Desert in northern Chile, which seemingly offered unmatched opportunity for low water vapor content, large flat areas, and unrivaled views of the southern sky. In fact, it was claimed that the Atacama Desert had the lowest precipitable water vapor of anywhere in the world. Unsubstantiated (and untrue) stories circulated that the proposed site received only 1 cm of precipitation each century.

NRAO recognized that a Chilean site would come with many practical logistical challenges and at a greater cost of construction, and especially operation. However, following an exhaustive study by Mark Gordon, and as the MMA development progressed, there was increasing interest in locating the MMA in Chile. NRAO needed to convince the NSF that Chile was worth the additional cost as well as the added administrative burden involved in spending federal funds in another country. In 1994, Paul Vanden Bout escorted NSF AST Director Hugh Van Horn and MPS Assistant Director William Harris on a visit to potential sites in Chile in the hope that they would be sufficiently impressed to ignore the negatives (Fig. 10.8). Apparently they were, but working in Chile turned out to be more expensive and more difficult than anyone anticipated.

Fig. 10.8 NSF MPS Assistant Director William Harris, NSF AST Director Hugh Van Horn, and NRAO Director Paul Vanden Bout standing on level ground at the 16,500 foot MMA—later ALMA—site, with 20,000 foot mountains rising in the background. Credit: NRAO/AUI/NSF

10.7 The Atacama Large Millimeter/Submillimeter Array (ALMA)

Although strongly endorsed by every review committee and enthusiastically supported by the NSF Astronomy Division, the MMA first needed the additional blessing of the National Science Board before it could be considered by the Administration or by Congress for construction funding. Largely as a result of the Congressional initiative to fund the GBT, the NSF had been able to establish the new Major Research Equipment (MRE) funding line to fund the construction of large new projects without impacting the operation of ongoing programs or grants to Individual Investigators.[70] However, by the time the MMA Development Plan was presented to the National Science Board in 1994, "the Federal funding landscape [had] changed substantially. In particular, Congress [had] made it increasingly clear that the viability of projects as large as the MMA may depend on the extent to which they are based on international partnerships."[71] International projects presented both opportunities and challenges. Vanden Bout declared at the start that NRAO was not interested in establishing an international partnership for the MMA just to save money or for the sake of satisfying the perceived Congressional wishes, but would do so only if a joint international program were to result in a more powerful capability. Conveniently, at the same time that NRAO was planning for the MMA, both European and Japanese scientists were developing their own plans for millimeter and submillimeter wave arrays. Both projects, as well as the MMA, were looking at potential sites in the Atacama Desert in northern Chile.

Japanese radio astronomers were discussing a Large Millimeter and Submillimeter Array (LSMA) to consist of fifty 10 meter antennas operating in six bands up to 500 GHz or 0.6 mm wavelength (Ishiguro et al. 1994). In order to explore a possible joint effort with Japan, Brown and Vanden Bout met with members of the Nobeyama Observatory and they "agreed on a memorandum to explore the possibility of a collaboration."[72] Initially, the two observatories discussed only the separate construction and operation of the MMA and LMSA on the same site, but perhaps with periodic joint operation of the 90 element array to give increased sensitivity, resolution, and image quality.[73]

There was also some earlier discussion of a Dutch participation in the US MMA.[74] But the potential Dutch collaboration became tied to an additional contribution to CARMA and conflicted with the Dutch aspirations for the 1hT (later called the SKA), and so the prospects for a Dutch collaboration evaporated.[75] Nevertheless, with a then estimated cost of $175 million, NRAO set out in a confidential memo the terms and conditions under which partners who contributed to the capital and operating costs could become MMA Associates with appropriate prorated shares of the observing time. Notably, the long standing NRAO Open Skies policy was being threatened by the statement that "aside from [Associates], U.S. observing time will not be available to non--U.S. observers."[76]

Meanwhile in Europe, IRAM, ESO, Sweden, and the Netherlands were developing their own plans for the Large Southern Array (LSA) to have a collecting area of 10,000 m^2, about five times that of the MMA, and to work to wavelengths only as short as 3 mm (Downes 1995). Early strawman concepts were for an array of fifty 16 meter dishes or one hundred 11 meter dishes with an estimated cost of 270 million Ecu ($360 million).[77] The European planning program was initially led by IRAM, and then later by ESO under its charismatic strong-minded Director, Riccardo Giacconi.

Collaboration between NRAO and ESO appeared attractive to both sides, and in June 1997, Giacconi (for ESO) and Vanden Bout (for NRAO) signed a resolution agreeing to an LSA/MMA Feasibility Study. Three Joint Working Groups, Science, Technology, and Management, were established to continue the design and planning. At NRAO, the design work continued using the $26 million that had been authorized for the MMA design. Both sides understood the complexities and delays of their ambitious plans that would be introduced by a joint project, and agreed they would insist on a project that was more powerful than either the MMA or the LSA. Ironically, at the end of his term as ESO director in 1999, Giacconi returned to the US where he accepted a position as President of AUI (Sect. 6.8), during which time he oversaw the AUI/NRAO negotiations with ESO to establish the governing structure of the joint facility in Chile.

In early 1999, Bob Brown ran a competition asking for ideas to name the new facility and received 33 suggestions. Following a ballot sent to about 100 individuals to choose among the 33 names, Brown presented the top eight candidates to a 30 March 1999 meeting of NSF, ESO, and PPARC representatives in Garching. The name ALMA appeared only sixth on the list, but according to Brown, Ian Corbett from PPARC, declared "ALMA is the best. I like acronyms I can pronounce." The entire room mumbled in agreement and the committee went on to the next agenda topic.[78] ALMA also means "soul" or "spirit" in Spanish.

In June 1999, just weeks before Giacconi joined AUI, the NSF signed a Memorandum of Understanding with European institutions for a joint "design and development phase of a large aperture mm/sub-mm array to be known as the Atacama Large Millimeter Array (ALMA)." ALMA joined the MMA (40 eight meter dishes working to 1.3 mm) with the European Large Southern Array (50 sixteen meter dishes working to 3 mm) to build an array containing 64 twelve meter diameter antennas with an angular resolution up to 0.005 arcsec at the shortest operating wavelength of 0.35 mm.[79] On the European side, the MOU was signed by Giacconi for ESO, CNRS, the MPG, the Netherlands Foundation for Research in Astronomy (NFRA), and the British Particle Physics and Astronomy Research Council (PPARC). But not everyone was enthusiastic. IRAM in Europe and CARMA in the US were building powerful millimeter wave arrays of their own that they knew would be threatened by the proposed plan for ALMA.

The first construction funding in the US for the joint ALMA project was approved by Congress in November 2001. Initially an ALMA Executive Committee (AEC), with Bob Brown as chair, was established to coordinate the ESO and NRAO activities. But establishing ALMA as an international project was not straightforward. ESO, NRAO, and later Japan, all came to the table with different goals. The ESO LSA emphasized a large collecting area to enable extragalactic spectroscopy, while the NRAO MMA stressed image quality, and the Japanese LSMA highlighted submillimeter wavelengths. Agreements among the five European partners, on one hand, and among the North American partners, US and Canada, on the other hand, and between the US and Europe were followed by separate agreements between the ALMA partners and the government of Chile and Consejo Nacional de Ciencia y Technologia (CONACyT). As part of the NAPRA (North American Program in Radio Astronomy) agreement, Canada agreed to work with the NSF in funding and supporting ALMA. But NRAO/AUI and the NSF first had to establish their own rules of engagement.

For various reasons, including the ongoing funding of the Japanese 8.2 meter Subaru optical telescope, Japan was unwilling or unable to enter into a firm agreement to participate in a combined telescope on the same time scale as Europe and the US. Japan, Europe, the US, and Canada agreed on a resolution expressing the intent to jointly construct ALMA and starting as early as 1999, a US-European-Japanese ALMA Liaison Group had met regularly to exchange technical progress and to establish the foundations for an "Enhanced ALMA." Bob Brown and Peter Napier represented NRAO at these discussions.[80] Japan did not formally join the ALMA project until funds became available in 2004 when Japan proposed to build a "Compact Array, a new correlator and new receivers, as well as to contribute to the infrastructure and operation."[81] By this time, the NSF/AUI/NRAO and ESO had already agreed on the legal structure and the basic parameters of the Array.

ESO and the NSF had different legal status with the government of Chile for the operation of ESO and CTIO respectively, and these agreements had to be respected with the joint ALMA project. In 1998, NRAO/AUI hired Eduardo Hardy, a native of Argentina, as the AUI representative in Chile, and in 2006, Hardy became the NRAO Assistant Director for Chilean Affairs. The 2006 Management Agreement for the construction and early operation of ALMA was a bilateral agreement between ESO and AUI acting as the NSF Executive. The management of the ALMA project was first overseen by an ALMA Coordinating Committee (ACC), and since 2017 by the ALMA Board, which includes representatives from the NSF, NRAO/AUI, the Canadian NRC, ESO, NOAJ, Chile, and ASIAA (Taiwan) as well as at-large members from Europe and Japan. A Joint ALMA Office (JAO) was established in Chile and managed by the ALMA Director to oversee the construction, commissioning, and operation of ALMA. Within Europe, the partners had their own European Coordinating Committee.

Due to the high 5,000 meter altitude of the ALMA site, it was clear that, to the extent possible, supporting activities should take place a lower altitude. An Operations Support Facility (OSF) was established not far from the town of San Pedro de Atacama at 9,500 feet elevation. Ground-breaking for the OSF took place in November 2003 (Fig. 10.9), and ground-breaking at the 16,500 feet Array Operations Site occurred in October 2005.

Paul Vanden Bout became the first ALMA Director and stepped down from his role as NRAO Director to concentrate on building ALMA. He served as ALMA Director between June 2002 and March 2003, during which time he led the negotiations between ALMA and the Chilean partners (Chilean Government and CONICYT). Massimo Tarenghi from ESO was the ALMA Project Scientist, and he succeeded Vanden Bout as ALMA Director in 2003. Tarenghi was followed by Thijs de Graauw from the Netherlands, Pierre Cox from France, and Sean Dougherty from Canada. In 2004, Anthony (Tony) Beasley returned to NRAO as the ALMA Project Manager. Beasley had previously been an Assistant Director at NRAO, after which he went to California to be Project Manager for CARMA. As the ALMA Project Manager, he inher-

Fig. 10.9 Groundbreaking for the ALMA Operations Support Facility. NSF's Bob Dickman is pouring Chilean wine in a tribute to the earth goddess Pachamama. Standing from left to right are Eduardo Hardy (AUI), Fred Lo (NRAO Director), Massimo Tarenghi (ESO), Catherine Cesarsky (ESO Director General) and Daniel Hofstadt (ESO). Credit: I. Dickman/NRAO/AUI/NSF

ited a project that was headed for a major cost overrun due to the unforeseen large cost of the antenna elements, the unanticipated complexity and cost of the international partnership, the unappreciated cost of building on the remote and challenging site, and unfavorable changes in the value of the Chilean peso. Following an agreement to "re-baseline," in December 2004, ALMA was downsized to 50 antennas, 25 each to be provided by NRAO/AUI and by ESO, and the number of frequency bands was reduced. Some of these were later restored when Japan joined the project.

Building a state of the art scientific instrument at this altitude was a challenge. At 16,500 feet elevation, the air density is only about half of that at sea level. Aside from the well-known impact to human performance, many electronic components do not function properly at this elevation. The ALMA correlator is among the faster supercomputers in the world, operating at about 2×10^{13} operations per seconds. Like all large computing systems, it needs to be cooled, but at 16,500 feet it takes twice as much cooling as it would at sea level. Ordinary computer disk drives do not work at the ALMA site, so solid state disks are used on all computers. Many other electronic components, such as electrolytic capacitors, are not rated for these altitudes. Another continuing problem is so called, "Single Event Upsets" (SEUs) which are the random flipping of a bit (zero to one, or one to zero) when a chip is hit by a cosmic ray particle. These SEUs are more common at ALMA than at sea level.

It was clear that the biggest challenge, and certainly the biggest technical risk facing ALMA, was in meeting the exacting specifications for the construction of the high precision antenna elements. In order to obtain a competitive design and cost, AUI/NRAO and ESO agreed to procure two separate prototypes for evaluation. ESO contracted with the French Alcatel-EIE consortium for their prototype, while AUI/NRAO chose the California based Vertex Antenna Systems, LLC for the design and construction of their prototype. Alcatel-EIE was the result of a complex series of mergers including the US Lucent Technologies, the successor of AT&T Bell Laboratories. Later Alcatel-Lucent became part of the Finnish Nokia Networks, and more recently was sold to a Chinese consortium. Vertex Antenna Systems was formed from mergers including TIW (Toronto Iron Works) and RSI, which had been involved in earlier NRAO antenna projects. The design and much of the fabrication of the AUI/NRAO prototype antenna actually came from the German based Vertex Antennentechnik subsidiary of Vertex Antenna Systems which had its origins in the Krupp group that was involved in building the Effelsberg, Pico Veleta, and HHT telescopes.

The two prototype 12 meter diameter antennas were erected at the VLA site where their performance was evaluated by a joint NRAO/ESO Antenna Evaluation Group (AEG), led by Jeff Mangum from NRAO. Although, at the time, Japan had not yet formally joined the ALMA project, a third prototype was built by the Japanese Mitsubishi Electric Company and was also erected at the VLA site, but was independently evaluated by a Japanese team. Owing to the late delivery of both the Alcatel and Vertex antennas to the VLA site, the evaluation (Mangum et al. 2006), especially for the Alcatel antenna, was not fully complete by the time the two partners had agreed to try to select a single contractor for the production antennas.[82]

Nevertheless, NRAO/AUI and ESO each issued a separate Request for Proposals, anticipating that the evaluation of the two prototypes would be completed in time to make a coordinated decision on the contractor. Both requests had common performance specifications but different business terms and considerations which were necessitated by their respective procurement policies. NRAO/AUI received bids from both Vertex RSI, which was later acquired by General Dynamics during the procurement process, and from Alcatel, which now included the German MAN, the former partner of Krupp in building the Effelesberg antenna. ESO received bids from Alcatel, the German based Vertex Antennentechnik as well as from the Italian contractor, Alenia Aerospace. Based on cost and performance, NRAO/AUI chose General Dynamics. In order to meet the July 2005 deadline before both of the General Dynamics pricings expired, NRAO/AUI signed a contract for $169 million for the construction of 25 antennas, fully anticipating that ESO would contract with Vertex for the other 25 antennas.[83] Previously, ESO had selected Vertex Antennentechnik, even before the NRAO/AUI/NSF decision to choose Vertex RSI (General Dynamics), but a last minute revised bid from the newly reorganized European-led Alcatel was lower than the Vertex bid, and ESO signed a separate contract with Alcatel for the other 25 ALMA antennas. Although the engineering design of the NRAO/AUI production antennas was led by Vertex Antennentechnik in Germany, fabrication actually took place in many countries. The project was managed by General Dynamics C4 Systems in Texas, where each antenna was first assembled and tested, then broken into sub-assemblies for shipment by boat from Houston to Chile.

Neither ESO nor NRAO/AUI management, scientists, and engineers were pleased with the separate contracts which involved different designs including different drive systems and a different sub-reflector support structure. Each side blamed the other for ending up with two different antennas. ESO considered that NRAO/AUI had acted prematurely in signing a contract with General Dynamics before the prototype evaluation was fully complete, while NRAO/AUI suspected that Alcatel had lowered their price below the Vertex price to make their bid more attractive to ESO. One can only speculate whether or not the Vertex bid was leaked to Alcatel, allowing them to undercut the Vertex price.

As it has turned out, many of the concerns about the operation and performance of two different antenna structures were unfounded, although the Vertex and Alcatel antennas do require different maintenance procedures. To complicate the situation, when Japan formally entered the project, they contracted with the Japanese Mitsubishi Electric Company to build four more 12 meter diameter antennas, as well as the twelve 7 meter antennas for the so-called "Compact Array" to provide critical short baselines. The Mitsubishi 12 meter dishes are yet a different design from either the ESO or NRAO/AUI 12 meter antennas. Although all of the Japanese antennas are primarily intended for use in the separate "Compact Array," in principle they can be used together with the AUI and ESO antennas as part of a single 54 or even 64 element array.

ALMA scientific observations officially started on 30 September 2011, and on 13 March 2013 ALMA was formally inaugurated after nearly three decades of planning, engineering, and construction at NRAO (Fig. 10.10), as well as in Europe and Japan. ALMA operates at wavelengths from 0.32 mm to 1 cm in configurations ranging from 150 meters to 16 km. By agreement, scientists from North America (US, Canada, and Taiwan) and the 14 ESO member states each get 33.75 percent of the observing time; East Asia (Japan, Korea and Taiwan) 22.5 percent; and Chile 10 percent. Taiwan participates in ALMA, not only through the Japanese East Asia group, but is also part of the North American group along with the US and Canada.

Interestingly, ALMA, which was the most expensive ground based telescope facility ever built, was itself never proposed to the NSF or reviewed in competition with other facilities by a US Decade Review Committee. Rather, it was only the more modest MMA that was recommended by the Bahcall (1991) committee at a projected construction cost of $115 million. The final cost of constructing ALMA was about $1.4 billion, with ESO and the NSF each paying 37.5 percent and Japan the other 25 percent.[84] The official cost to the NSF was $499 million.

Fig. 10.10 The completed Atacama Large Millimeter-Submillimeter Array (ALMA) shown in a compact configuration. Credit: NRAO/AUI/NSF

The operation of ALMA is perhaps unique among astronomical observatories. Instead of proposing for a specific amount of observing time, ALMA users propose to achieve a certain sensitivity, resolution, image quality, etc., and the ALMA staff determines the appropriate amount of observing time and the antenna configuration needed to meet the observer's requirements. In this way, observers (if one can still use that name) are not adversely impacted by bad weather or instrumental failures traditional to conventional telescope scheduling. Another innovative aspect of ALMA is that instead of raw data, the observers are given essentially science ready data products. ALMA Regional Centers (ARCs) were established to handle proposal review, scheduling, data reduction, and analysis, as well as archive support. The North American ALMA Science Center (NAASC), located at the NRAO in Charlottesville, is the North American ALMA Regional Center (ARC). In Europe, ALMA is supported by a central node at ESO in Garching, Germany, as well as eight ALMA regional nodes and centers of expertise. Other ARCs are located in Chile, Japan, and Taiwan.

NOTES

1. Millimeter waves are absorbed by oxygen and especially water vapor in the lower atmosphere. The amount of absorption is determined by what is called the precipitable water vapor (PWV) content, which decreases with altitude and with decreasing temperature.
2. FDD, Report of Visit to Texas Instruments, Inc., 2 February 1962, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 2.
3. FDD to F. Low, 27 March 1962, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 2; KIK interview with FDD, 14 September 2010, NAA-KIK, Oral Interviews. https://science.nrao.edu/about/publications/open-skies#section-10
4. J. Pawsey, Notes of Future Program at Green Bank, 17 July 1962, NAA-NRAO, Founding and Organization, Antenna Planning. https://science.nrao.edu/about/publications/open-skies#section-10
5. FDD to file, 7 February 1963, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 2.
6. AUI-BOTXC, 15 May 1964.
7. KIK interview with FDD, op. cit.; AUI-BOTXC, 22 February 1962.
8. F. Callender (NRAO Business Manager) to F. Lowe [*sic*], 16 November 1963, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 1.
9. As a general guideline the antenna surface accuracy should be at least as good as $\lambda/16$. At this level the antenna gain is reduced by ½ over a perfect surface.
10. AUI-BOTXC, 20 March 1964.
11. The unusually large *f/D* or focal length/diameter meant that the feed support legs would need to be twice as long as normal to reach the focal point. AUI-BOTXC, 15 October 1964.
12. P. Mezger, Principal Considerations of Radioastronomical Observations at Very High Frequencies, March 1964, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 3. https://science.nrao.edu/about/publications/open-skies#section-10

13. DSH to F. Low, 9 March 1965, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 2.
14. DSH to F. Low, 1 April 1965, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 2.
15. P. Mezger, op.cit.
16. F. Low to eight prospective suppliers, 19 March 1964, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 1.
17. NRAO Memorandum summarizing 23 January 1963 meeting between NRAO and Rohr. NAA-NRAO, Green Bank Operations, LSFT, Box 5. Bob Hall was then an antenna design engineer at Rohr. Earlier, while at Blaw Knox he had contributed to the design of the Green Bank 85 Foot antenna and then the 300 Foot transit dish. Later he joined NRAO as project manager for the construction of the GBT.
18. AUI-BOTXC, 15 October 1964.
19. AUI-BOTXC, 20 March 1964.
20. R. Hall to DSH, 26 October 1965, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 2.
21. E. Conklin to DSH, HH, and WEH, 31 January 1971, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 3.
22. FORTH: an Application-Oriented Language Programmer's Guide, NRAO Computer Division Internal Report No. 11, 1973. http://library.nrao.edu/public/memos/comp/CDIR_11.pdf
23. AUI-BOT, 19–20 October 1967.
24. AUI-BOTXC, 16 November 1967; DSH to T. Glennan, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 5.
25. Bolometers are used to make an incoherent measurement of the energy falling on a cooled detector. Carefully designed filters define the bandwidth which is otherwise limited by the atmospheric window. The challenge is to design filters that are low loss within the desired frequency band, but have sufficiently high attenuation outside the window to eliminate responses due to fluctuations in tropospheric water vapor content.
26. M. Simon to WEH, 1 March 1971, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 3.
27. K. Jefferts to WEH, 16 November 1972, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 4.
28. DSH to M. Kundu, 26 February 1969, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 4.
29. J. Payne to DEH, 7 April 1975; J. Payne to HH, 20 October 1979, NAA-NRAO, Tucson Operations, Site and Administration, Box 2.
30. A. Penzias to WEH, 27 February 1969, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 4.
31. L. Snyder to DSH, 17 January 1978, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 3.
32. KIK to DSH, 12 May 1978, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 3.
33. E. Wetmore to E. Conklin, 21 July 1972, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 3.
34. B. Turner, The NRAO 25-Meter Telescope: 2nd Status report, NAA-NRAO, Tucson Operations, 25 Meter Telescope, Box 2.

35. Phil Solomon via Marshall Cohen to KIK, 24 March 1981, NAA-KIK, VLBA History and Development.
36. W. Horne to HH, 11 February 1980, NAA-NRAO, Tucson Operations, 25 Meter Telescope, Box 3a.
37. Telegram from MAG to J. Jefferies, 15 November 1979, NAA-NRAO, Tucson Operations, 25 Meter Telescope, Box 3a.
38. P. Strittmatter to G. Huguenin, 7 September 1978, NAA-NRAO, Tucson Operations, 25 Meter, Box 3a. Huguenin was a member of the Astronomy Advisory Committee (as was one of the authors, KIK).
39. Draft report of the Subcommittee on Millimeter Wave Facilities of the Advisory Committee for Astronomical Sciences, NAA-NRAO, Tucson Operations, 25 Meter Telescope, Box 1.
40. L. Snyder to F. Johnson, 3 May 1982, NAA-NRAO, Tucson Operations, 25 Meter Telescope, Box 4.
41. MAG to MSR, 17 April 1980; MAG to M. Balister and JWF, 26 November 1980, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 3.
42. JWF, Notes on Improving the 36-Foot Telescope, 24 October 1973, NAA-NRAO, Tucson Operations, 36 Foot Telescope, Box 3.
43. J. Marymor to WEH, 5 January 1980, NAA-NRAO, Directors' Office, NSF Correspondence.
44. NAA-NRAO, Tucson Operations, 36 Foot/12 Meter Telescope.
45. William (Bill) Irvine has written an undated personal account of the history of the FCRAO, NAA-KIK, Open Skies, Exploring the Millimeter Sky.
46. See "The LMT Book" written by W. Irvine for further details. http://www.lmtgtm.org/the-lmt-book/
47. Proposition Commune pour Ondes Observatoire sur Ondes Millimetriques, NAA-NRAO, Millimeter Array, Planning, Box 1. The early history of French radio astronomy leading to IRAM is given by Encrenaz et al. (2011).
48. E. Blum to DSH, 4 April 1975, Tucson Operations, 25 Meter Telescope, Box 2.
49. DSH to file, 21 May 1975, NAA-NRAO, Tucson Operations, 25 Meter Telescope, Box 2.
50. R. Wilson to PVB and others, 29 Oct 1982, NAA-NRAO, MMA, Planning, Box 1.
51. R. Wilson (Bell Labs), P. Solomon (Stony Brook), L. Snyder (Illinois), N. Scoville (Massachusetts), P. Vanden Bout (Texas), W. Welch (Berkeley), B. Ulich (MMT Observatory), F. Lovas (National Bureau of Standards), M. Kutner (Rensselaer), P. Palmer (Chicago), P. Goldsmith (Massachusetts), G. Knapp (Princeton), E. Churchwell (Wisconsin), A. Barrett (MIT), P. Thaddeus (Goddard Inst. for Space Studies), T. Phillips (Caltech), A. Stark (Bell Labs), and J. Bally (Bell Labs) to L.P. Bautz and F. S. Johnson, 29 October 1982, NAA-NRAO, Millimeter Array, Planning, Box 1.
52. Ibid.
53. L.P. Bautz to R. Wilson and Co-Signatories, 23 November 1982, NAA-NRAO, Millimeter Array, Planning, Box 1. Members of the Subcommittee were Alan Barrett, Chair (MIT), D. Downes, C. Lada, P. Palmer, L. Snyder, and W. Welch, with V. Pankonin as NSF Staff Liaison.
54. B. Turner to MSR, 17 February 1983, NAA-NRAO, Millimeter Array, Planning, Box 1.

55. Report of the Subcommittee on Millimeter- and Submillimeter-Wavelength Astronomy, NSF Astronomy Advisory Committee, April 1983, NAA-NRAO, Millimeter Array, Planning, Box 1. http://library.nrao.edu/public/memos/alma/memo009.pdf
56. F. Owen's memo, dated 10 September 1982, later became Millimeter Array Memo No. 1. NAA-NRAO, Millimeter Array, Planning, Box 1. http://library.nrao.edu/public/memos/alma/main/memo001.pdf
57. MSR to F. Owen, 3 March 1983, NAA-NRAO, Millimeter Array, Planning, Box 1.
58. F. Owen to MSR, 16 March 1983, NAA-NRAO, Millimeter Array, Planning, Box 1.
59. NAA-NRAO, Millimeter Array, Planning, Box 1.
60. Wootten and Schwab eds. 1988, *Science with a Millimeter Array*. http://library.nrao.edu/public/collection/02000000000303.pdf; Brown and Schwab eds. 1988, *MMA Design Study*. http://library.nrao.edu/public/collection/02000000000256.pdf
61. Report of the MMA Technical Advisory Committee, 13 April 1984, NAA-NRAO, Millimeter Array, Planning, Box 1.
62. M. Gordon, Millimeter-Wave Array Memo Series No. 25, 1 October 1984, NAA-NRAO, Millimeter Array, Planning, Box 1. http://library.nrao.edu/public/memos/alma/main/memo025.pdf
63. V. Pankonin to PVB, 4 November 1991, NAA-NRAO, Millimeter Array, Planning, Box 2.
64. R. Dickman to RLB and PVB, 30 March 1994, NAA-NRAO, Millimeter Array, Planning, Box 2.
65. M. Rieke (ACAST Chair), 6 January 1992, Resolution on the Millimeter-wave Array, NAA-NRAO, Millimeter Array, Planning, Box 2.
66. As with previous Decade Reviews, NRAO was well represented. K. Kellermann chaired the Radio Panel, which included NRAO staff members R. Fisher, M. Goss, J. Uson, as well as D. Heeschen as Vice Chair. Heeschen and R. Wilson (Bell Labs) were the two radio astronomers on the parent Survey Committee.
67. As Chair of the Radio Panel, KIK participated in most of the Parent Survey Committee meetings. There was little or no support among the Survey Committee members for the Southern Hemisphere 8 meter telescope. Both the Northern and Southern Hemisphere 8 meter telescopes were built as part of the US-UK Gemini project at a cost of approximately $184 million, half of which was born by the NSF. Construction was completed in 1999 and 2000 respectively, more or less simultaneously with construction funding for the GBT (Sect. 9.7).
68. MMA Design and Development Plan, September 1992, NAA-NRAO, Millimeter Array, Planning, Box 2.
69. Carbon fiber reinforced plastic (CFRP) has a very low thermal coefficient of expansion.
70. The NSF MRE budget was restricted to construction funding only.
71. Material presented to the NSB, September 1994, NAA-NRAO, Millimeter Array, Planning, Box 3.
72. MOU between NAOJ and NRAO for Cooperative Studies for the LSMA and the MMA, 12 June 1995; renewed March 1998 and 11 December 1998.

Following the formation of ALMA, the MOU was again renewed on 10 June 1999, and was signed by ESO, AUI, and NOAJ. NAA-RLB, ALMA.

73. R.L. Brown, The Atacama Array: A Possible LMSA-MMA Collaboration in Chile, MMA Management Document No. 3, December 1995. https://library.nrao.edu/public/memos/mma/MMA_MD_03.pdf
74. Proposal for Dutch Participation in a Large Millimeter Array, (undated), NAA-NRAO, Millimeter Array, Planning, Box 2.
75. N. Scoville, P. Vanden Bout, and W. Welch, Confidential memo on CARMA, the MMA, and potential Dutch participation, 31 January 1995. Also H. Butcher to R. Dickman, PVB, and RLB, 17 April 1996, NAA-NRAO, Millimeter Array, Planning, Box 2.
76. Confidential draft Prospectus for Foreign Participation in the Millimeter Array, 9 February 1995, NAA-NRAO, Millimeter Array, Planning, Box 2.
77. The European currency unit (Ecu) was the predecessor of the Euro and was worth about $1.35 at the time.
78. RLB to C. Madsen, 28 February 2012, NAA-RLB, ALMA.
79. MOU between the NSF, ESO, CNRS, MPG, NFRA, and PPARC, June 1999, NAA-NRAO, ALMA, Multi-Institutional Agreements.
80. Papers relating to the various MOUs, Coordinating and Liaison Committees may be found at NAA-NRAO, ALMA, Multi-Institutional Agreements.
81. Japanese participation in ALMA: A Proposal from NOAJ, 16 August 2002, NAA-NRAO, ALMA, Multi-National Agreements.
82. In 2014, the University of Arizona obtained the ESO ALMA prototype antenna and erected it on Kitt Peak to replace the old NRAO 12 Meter Telescope. The North American prototype was sent to Greenland to be used as part of the Event Horizon Telescope. (https://eventhorizontelescope.org/).
83. NRAO and ESO had previously agreed that all of the antennas would be of the same design and would be purchased from a single contractor, with consideration to secure “juste retour” vendors in the ESO Vertex bid. However, no formal agreement was ever established to achieve this goal.
84. The full story leading to the construction and operation of ALMA is a complex one beyond the scope of this book but is conveyed in a forthcoming book by Robert Dickman and Paul Vanden Bout.

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