RECOLLECTIONS OF “TUCSON OPERATIONS”

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Recollections of “Tucson Operations”

The Millimeter-Wave Observatory of the National Radio Astronomy Observatory

by

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The 36-ft millimeter-wave telescope operated by the National Radio Astronomy Observatory
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To Jim Warwick, who introduced me to radio astronomy.

Foreword

The millimeter-wave radio telescope of the National Radio Astronomy Observatory (the NRAO) was one of the most successful telescopes ever built in the United States. Planned in 1962 and constructed on Kitt Peak, Arizona, this 36-ft parabolic antenna was not completed until 1967 because of the technical challenges associated with its novel design.

Its early years produced few astronomically significant results. These observations consisted of continuum observations primarily at $\lambda 3\,\mathrm{mm}$ but also at $\lambda 1.2\,\mathrm{mm}$. The problem was the low sensitivity of millimeter-wave radio receivers available at the time. What could be detected was just not interesting.

In contrast, its later years were spectacularly productive. Starting in the 1970s, astronomers began detecting emission lines from interstellar molecules in these same wavelength bands. Unlike the earlier continuum observations, these results were completely new, creating a new way to explore the characteristics of cosmic objects. In time, they revolutionized our understanding of the nature of interstellar gas, chemistry at extremely low temperatures, and how stars form and galaxies evolve. The observations even provided a way to study the structure of the molecules themselves. For several years, the 36-ft telescope was in more demand than any other telescope in the United States, optical or radio.

Apart from astronomy, the demands of millimeter-wave astronomy themselves stimulated developments in electronics and in computer software. These advances increased the sensitivity of the millimeter-wave telescope which, in turn, created new pressures for continued technical improvements and resulted in more astronomical discoveries. This symbiotic or, perhaps, "symtechnic" cycle is a hallmark of cutting-edge telescopes and continues today.

With this success, the imperfections of the innovative 36-ft telescope became increasingly intolerable. Astronomers asked for improvements. Several attempts were made but most fell short of what was needed. To serve their astronomer clientele better, the NRAO proposed as a replacement a 25-m telescope on the 13,792-ft Mauna Kea in Hawaii, but it was never funded. While awaiting a decision on the proposal for Mauna Kea, the NRAO replaced the venerable 36-ft surface of the Kitt Peak telescope with a low-cost but much more accurate 12-m surface as a stop-gap measure.

Good as it was, this improvement fell short of what was needed. In the end, the results from these telescopes and similar ones elsewhere stimulated plans for an enormous synthesis array of 64 12-m paraboloid antennas at millimeter and submillimeter wavelengths, known as the Atacama Large Millimeter[-wave] Array or ALMA. The United States, Canada, Spain, and member countries of the European Southern Observatory (ESO) are funding this telescope jointly in cooperation with the Republic of Chile. Now under construction at a 16,500 ft site in northern Chile, this telescope is the child of the original 36-ft telescope and others and, of course, of the millimeter-wave interferometers of the California Institute of Technology (Caltech), Berkeley–Illinois–Maryland (BIMA), and the Institut de Radio Astronomie Millimètrique (IRAM).

Meanwhile, the 12-m millimeter-wave telescope has been turned over to the University of Arizona. Over the years, more than 240 NRAO employees have worked for Tucson Operations, including summer students. Based upon conversations with the original planners, assorted documents, and my personal involvement, this is the story of this innovative group.

Many astronomers and NRAO employees read sections of the manuscript to verify the accuracy of my recollections. I have also discussed specific recollections with some of them. I do not cite their names individually because of the personal nature of this book but I am grateful to each of them. Editorially, I thank Ellen Bouton, Butler Burton, Colin Miller, and my wife, Julie, for reading the entire manuscript and giving me counsel regarding its content.

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The Early Years

"Radio astronomy" involves detecting and analyzing radio waves generated naturally by cosmic bodies. Like the optical waves our eyes detect (commonly called "light"), radio waves are part of the electromagnetic spectrum emitted by any warm material. Unlike light, radio waves require a different technology for detection. Tuned between broadcast stations, ordinary radio receivers detect this cosmic radio emission as a background signal called "static noise." To astronomers, these radio waves carry astrophysical information that can help unravel the secrets of the universe in which we live, supplementing and complementing information carried by infra-red, optical, ultraviolet, Xray, and other parts of the cosmic electromagnetic spectrum.

In practice, the term "radio" is imprecise. Officially, it refers to frequencies from 30 Hz ($\lambda 10^4$ km)to 300 GHz ($\lambda 1$ mm). Nowadays, radio astronomers include much higher frequencies, defined generally by the radio techniques used to detect them. Accordingly, the exact distinction between radio and far infra-red is somewhat blurred.

1.1 The National Radio Astronomy Observatory

World War II stimulated great improvements in the apparatus and techniques for detecting radio waves. Later, astronomers of many countries were quick to employ these new tools to pursue their studies of the cosmos. The results were exciting, producing discoveries impossible to make with traditional optical astronomy.

In the early 1950s, the idea of a federally funded, national observatory for US radio astronomy attracted widening support [1, 2, 3, 4]. The initial idea was to create a large, centrally managed, general purpose radio telescope that could be shared by astronomers from different institutions. According to Heeschen [3], to this end the National Science Foundation (NSF) established a committee of prominent astronomers and physicists (Bart Bok, Jesse Greenstein, John Hagen, John Kraus, Donald Menzel, Rudolf Minkowski, Ed Purcell, and Merle Tuve, chair) for advice on how best to promote the emerging science of radio astronomy.

A similar process was underway for establishing a national optical astronomy observatory in the Southwest. In addition to the same "sharing" objective, dependably good weather was probably an additional consideration for the optical astronomers. Many of them belonged to institutions plagued by unpredictable, dismal weather. "In contrast to the optical astronomer's smooth and businesslike progress toward their goal, however, the course of the radio group was rough and stormy" according to the NSF historian Merton England [2].

The problem lay in widely differing views on how a national radio observatory should operate. Donald Menzel wrote to Associated Universities, Inc., (AUI) on behalf of a Harvard-MIT group consisting of Bart Bok, Cecilia Payne-Gaposhkin, Julius Stratton, Fred Whipple, and Jerry Wiesner to see if AUI would develop a plan for such a facility [3]. AUI consisted of nine northeastern universities organized in 1948 to manage Brookhaven National Laboratory (BNL)—a high-energy physics laboratory on Long Island, NY—for qualified university physicists from anywhere in the US. Not only was this kind of operation what the Harvard-MIT group envisioned for radio astronomy, both Harvard and MIT were also members of AUI and so, in a sense, the new radio astronomy observatory would be an addition to the family. The president of AUI at that time, Lloyd Berkner, believed this would be a worthwhile venture for the consortium and promoted it aggressively.

Merle Tuve promoted a contrary view. He felt that research flourished best in small settings like university departments or in ad hoc departments of large laboratories like the Naval Research Laboratory, where astronomers built and used their own telescopes. To him, a big-science, centralized observatory would not be in the best interest of a newly emerging branch of astronomy. Consequently, Tuve tried to block the formation of the big new observatory proposed by "a very small group of men" and managed by "self-approving groups of 'experts' " [2]. Furthermore, Berkner and Tuve not only held greatly different ideas of how research should be conducted but also did not like each other personally, which further widened the gulf between these two concepts for a national observatory. [3]

In May, 1954, AUI hosted a conference at its New York City offices to consider the new observatory for radio astronomy. The participants recommended that AUI ask for funds from the NSF for a planning and feasibility study for a large radio astronomy facility, which they did.

In response, the NSF committee "imposed a condition that the site be located within 300 miles of Washington, D.C. ... [probably] because all major optical telescopes were in the west and it was felt desirable to counterbalance that by putting the new radio observatory in the east." [3] Of about 20 sites considered, Green Bank, West Virginia, was an easy choice because of its isolation from radio interference. The committee recommended funding, and in February, 1955, the NSF allocated $85k for a study.

AUI submitted the study to the NSF in August, 1956, but Tuve continued to oppose its proposed scope. While Berkner envisioned the new observatory providing extensive equipment and services to facilitate observations by visiting astronomers, Tuve "wanted the observatory to consist of just a telescope, with minimal staff, facilities and services. Visitors would bring their own receiving equipment and staff, and even camp out in tents." [3]

The debates continued for months, with various scientists and government administrators expressing their individual, often conflicting views for how the new observatory should be operated. Nonetheless, the NSF negotiated an agreement with AUI for the new observatory and awarded a contract for $4M for construction in November, 1956. [2] (See Figure 1.1.) The Army Corps of Engineers acquired 2,700 acres (1,093 hectares) in Green Bank for the new observatory site over the next several years, while AUI began to construct the buildings and telescopes. The contract specified the construction of buildings and facilities and a 140-ft diameter radio telescope but did not mention other telescopes. The telescope would be designed primarily for centimeter wavelengths, that is, to operate at frequencies up to 30 GHz. "In fact, Alan Waterman, director of the NSF, specifically stated during a congressional hearing on the NSF budget that the new observatory would never need any other telescopes!" [3] Whatever the details of the process, the National Radio Astronomy Observatory (NRAO) had been finally created.

Figure 1.2 shows the principals associated with the new observatory at the dedication of the NRAO on October 17, 1957. John Findlay and Dave Heeschen remained with the observatory for about four decades more.

Figure 1.1: The signing of the contract on November 17, 1956, between AUI and the NSF to construct and operate the National Radio Astronomy Observatory. *Seated:* Lloyd Berkner (AUI President) and Alan Waterman (NSF Director), *Standing:* left to right, Lee Anna Embrey (Assistant to the Director), Wilson F. Harwood (NSF Assistant Director for Administration), James M. Mitchell (Assistant to the Director), Franklin J. Callendar (Grants Administrator), C. E. Sunderlin (NSF Deputy Director), Charles B. Ruttenbery (Attorney), William J. Hoff (NSF General Counsel). [2]

1.2 A Millimeter-Wave Telescope

While the NRAO was being established on its radio-quiet site of Green Bank, West Virginia, some of its staff members [5] believed the new observatory should offer the astronomical community full coverage of the radio spectrum, that is, not only access to the short meter and long centimeter ranges where most of the "action" then existed in radio astronomy but also to the short millimeter wavelengths that lay near the infra-red band. If the new NRAO was to be an effective national radio astronomy observatory, it should cover all the "radio" wavelengths.

At that time, other radio astronomical observatories were beginning to explore the millimeter-wave part of the astronomical spectrum and had con-

Figure 1.2: Dedication of the National Radio Astronomy Observatory on October 17, 1957. From left: R. M. Emberson, L. V. Berkner, G. A. Nay, J. W. Findlay (seated), N. L. Ashton, D. S. Heeschen, and H. Hockenberry. A model of the 140-ft telescope is on the table in the background. NRAO photo.

structed radio telescopes appropriate to this purpose. For example, in 1953 the world-famous P. N. Lebedev Physics Institute in Moscow had built a 22-m dish whose surface had been manually adjusted by turning 40,000 bolts! It operated to wavelengths as short as $\lambda 8$ mm. By 1959, an improved version of this telescope was being built in the Crimea to take advantage of better atmospheric transmission afforded by drier air.

The NRAO did not have instrumentation to observe at millimeter wavelengths. A relatively new frontier, millimeter-wave astronomy used specialized equipment unknown to most practicing radio astronomers. At Texas Instruments, Frank Low had developed germanium bolometers cooled by liquid helium, which NRAO astronomer Frank Drake knew about. Flying to Dallas, Drake persuaded Low to leave his well-paid, comfortable position to move to Green Bank in 1961, where he could use his bolometer to detect cosmic radio emission [6].

With Low's arrival in Green Bank, work on a millimeter-wave receiver

Figure 1.3: Frank D. Drake, the “father” of NRAO’s venture into millimeter-wave astronomy, in Green Bank in 1962. The 300-ft radio telescope lies in the background. NRAO photograph.

proceeded rapidly. Together, Drake and Low acquired a 5-ft diameter spun-cast paraboloid and began to experiment with it at millimeter wavelengths. Drake recalls being amazed by the tiny microscopic feeds[1] required for those wavelengths. In the winter of 1961-62, the new receiver was tested. While they did detect Jupiter, the atmospheric absorption was simply too great for useful work [7] even on clear, cold winter days when most of the atmospheric water vapor had frozen into crystals. The collecting area of the dish was too small and the amount of residual water vapor, too large, to conduct useful millimeter-wave astronomy from Green Bank.

An effective millimeter-wave telescope would require a better site. "Better" meant fewer atmospheric absorbers along the line of sight, that is, much lower precipitable water vapor and, also, fewer oxygen molecules as is characteristic of a dry, high altitude site. Figure 1.4 illustrates the situation quantitatively. Observing prospects from the low level Green Bank site were not good except in winter—and not very good then either.

Daily activity in the new high-tech observatory could be quite different than the agricultural life of the nearby villages. Here is an anecdote told to me by Dewey Ross. In 1960, Dewey was a single, 23-year old electronics technician at the NRAO. Later, in September, 1969 [8], after earning a degree in electrical engineering, he became one of the first NRAO engineers permanently assigned to Tucson.

The new NRAO electronics laboratory in Green Bank used liquid helium (boiling temperature of 4 K) and liquid nitrogen (of 77 K) to cool sections of its ultra-sensitive radio receivers. To control the boil-off rate of these cryogenic liquids and to reduce the formation of ice plugs from atmospheric moisture, it was standard practice to install a perforated condom on the exit tubes of the dewar vessels—in effect, huge stainless-steel Thermos bottles—holding the liquids.

Because of the extremely low temperatures, the latex condoms had a short lifetime and required frequent replacements. One of Dewey's jobs was to buy condoms from the Marlinton, West Virginia, Rexall drug store every month—by the gross. The NRAO fiscal office was reluctant to order the condoms because they did not want these listed as entries in their federally audited books. Consequently, they asked Dewey to pay for them with his own money and to present the receipts for reimbursement as "miscellaneous supplies."

[1] "Feed" is the common name for the small, specially designed device at the focus of a parabolic reflector through which radio waves enter the radio receiver. This device is a small horn antenna.

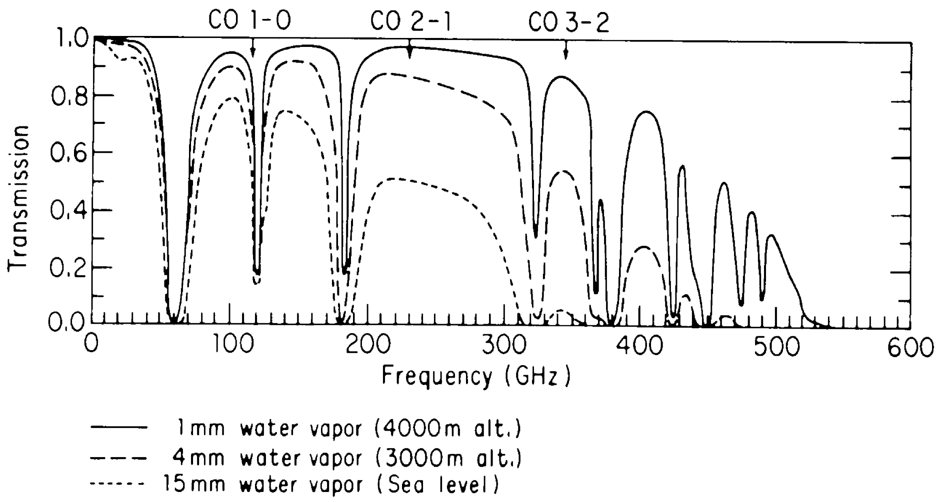

Figure 1.4: The transmission of the Earth's atmosphere as a function of frequency for three amounts of precipitable water vapor. The regions of high transmission are called "windows" because they allow cosmic radiation to reach the Earth's surface. The legend indicates the approximate altitudes associated with these vapor levels for middle latitudes. Marked above the top ordinate are three rotational levels of carbon monoxide that might be observed from astronomical objects at millimeter and sub-millimeter wavelengths.

But Marlinton was a small village of about 500 people. Word regarding unusual activity quickly got around. By 1961, Dewey had become engaged to a Marlington girl—later, his wife—and was especially concerned that the villagers remain unaware of these massive purchases. According to his wife, Kay, [9], one day the local constable walked up to Dewey and said to him, "I know what you've been buying. I'm watching you carefully and you'd better behave yourself." Dewey was horrified. Immediately, he pleaded with the NRAO fiscal office to place and receive these orders themselves.

Evidently, Fiscal finessed this problem by finding a supplier of small balloons especially designed for use with cryogenic dewars. By the time Frank Low had arrived in Green Bank in late 1961, the NRAO lab no longer used condoms.

1.3 The 36-ft Telescope

In 1962, the NRAO staff presented a proposal to the board of AUI to build a large millimeter-wave telescope on an acceptable site. It would cover a wavelength range of $\lambda 1$ to $\lambda 7$ mm. AUI approved the project and authorized the NRAO to proceed. Frank Drake recalls writing a part of the annual NRAO proposal to the NSF for $1.5M for construction, a justification that he remembered as consisting of a single paragraph [5]. He arrived at the estimate by scaling the cost of the 85-ft Tatel telescope at Green Bank by the factor $(\text{diameter})^3/(\text{wavelength})^{1/2}$—a calculation that shows the cost of a radio telescope to be about the price of hamburger per pound [6]. AUI submitted the proposal to the NSF in 1962, which funded the project. There were no peer reviews.

Conceptually, the technical design of the mm-wave telescope had begun to gel. Frank Low heard that a naval shipyard in Newport News, Virginia, was machining ribs for the pressure hulls of nuclear submarines. Reportedly, the shipyard could machine pieces as large as 36 ft in diameter to accuracies of a few thousandths of an inch. The high accuracy of these circular ribs was needed to maximize the crush depths of the submarines. Frank remembered driving to the shipyard from Green Bank through a snow storm to inspect that facility. Indeed he found the shipyard to have that capability and that's why the diameter of new mm-wave telescope was eventually chosen to be 36 feet [7].

Drake remembered the origin of the 36-ft diameter somewhat differently [6]. Wanting to build the largest possible millimeter-wave telescope, he thought $1.5M would be a good estimate for the cost of a first-class facility. Using the "hamburger" formula described above, he calculated the corresponding diameter to be about 36 ft. On the other hand, Drake noted that memories can be unreliable after more than 40 years!

A little later, the NRAO awarded a contract to Rohr Corporation for a feasibility study. Rohr's report stated that it should be possible to build a telescope of that size with an RMS surface accuracy of 0.002 in (50 μm), good enough to support useful observing at $\lambda 1$ mm (300 GHz).

In 1964, armed with the Rohr feasibility study, the NRAO filed a request for proposals for construction of the millimeter-wave telescope. There were several bidders, including Newport News Shipbuilding, North American, Philco-Ford, RCA, and Rohr. After reviewing all proposals, the NRAO awarded a contract to Rohr for $600k to build a 36-ft telescope on Kitt Peak.

The telescope geometry itself was unusual. NRAO astronomer Peter