# 3

# The Millimeter Array

"Big things have small beginnings."

T. E. Lawrence

## First Concept of a US National Array

To understand the origins of the Millimeter Array (MMA), NRAO's precursor project to ALMA, we need to go back to the early development of interferometers working at millimeter wavelengths in the decade preceding the Barrett Report. As was mentioned in the previous chapter, this occurred first at the Hat Creek Radio Observatory (HCRO) of the University of California, Berkeley, simultaneous with the Observatoire de Bordeaux, and a little later at the Owens Valley Radio Observatory (OVRO) of Caltech. The first astronomical observations of this kind were obtained at HCRO. A description of that interferometer, operating at 13.5 mm wavelength, was reported in the Proceedings of the IEEE.[1] At that time, it consisted of two antennas, one of diameter 3 m and another of 6.1 m, spaced 265 m apart. The interferometer was operated using a PDP-8/S minicomputer with data storage of only 4 kbytes of 12-bit memory, which was respectable for the early 1970s. Plans were reported in the article for a larger interferometer capable of operating at considerably shorter wavelengths. That instrument was built with three 6.1 m diameter antennas that could be moved on two perpendicular tracks, providing an angular resolution of 1–2 arcseconds for radiation received at 2 mm wavelength. With this instrument, observations were made of interstellar water vapor sources and planets. High-resolution measurements of the positions of water vapor emission regions constitute the first reported astronomical results from a millimeter-wavelength interferometer,[2] although, strictly speaking, the wavelength of the observations was 1.35 cm.



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**Figure 3.1** Photograph of the two-element interferometer built at the Observatoire de Bordeaux to observe the Sun. Courtesy of Alain Baudry, © Collection Observatoire Aquitain des Sciences de l'Univers, Laboratoire d'Astrophysique de Bordeaux, reproduced by permission.

Pioneering work on millimeter interferometry was also carried out abroad. An article, published back-to-back with the paper describing the HCRO interferometer in the Proceedings of the IEEE, reported the first operation of a small millimeter interferometer at the Observatoire de Bordeaux,[3] in France. As shown in Figure 3.1, it consisted of two 2.5 m diameter antennas spaced 64.4 m apart and operating at 8 mm wavelength. It was operated using a Honeywell H316 computer having a small memory (8 kbytes) similar to the HCRO instrument. The interferometer was built to make observations of the Sun, and the interferometer's resolution of roughly 20 arcseconds was designed to enable more detailed measurements of active regions in the Solar photosphere, which are typically of 1–2 arcminutes in diameter. Solar observations were first achieved on 29 January 1973. The Bordeaux and Berkeley groups closely cooperated with one another. Jack Welch received an honorary degree from Bordeaux University in 1979.

The international radio astronomy community that coalesced after the Second World War was relatively small, very competitive, but strongly collegial. Consequently, the scientific and engineering staff at the NRAO were aware of these developments well before the publication of the papers in the IEEE Proceedings. Indeed, in the mid-1970s, in a scientific staff meeting called by then director Dave Heeschen, the issue of whether NRAO should build a millimeter wavelength interferometer as a development project was discussed. Heeschen decided it was best for the NRAO to leave this effort to the universities that were already aggressively pursuing millimeter instrumentation. Heeschen was keenly aware that the NRAO had been founded to build and operate radio telescopes that were *beyond* the capability of a single university to fund, build, and operate. He was overheard to say,[4] when declining to compete with individual universities, that "*NRAO should stick to its knitting.*"

Nearly a decade later, when Mort Roberts was the observatory director, the discussion in a routine scientific staff meeting was on which major new NRAO telescope could follow the recently completed Very Large Array (VLA). Frazer Owen made the off-the-cuff suggestion of a millimeter wavelength array, by which he meant something more like the VLA, composed of more than just a few antennas, something bigger than the millimeter interferometers being developed at HCRO, OVRO, and Bordeaux. It is the authors' opinion that this suggestion is the very first of all the early concepts that would lead to ALMA. As he thought further about his suggestion, Owen developed the initial concept and wrote it up in a memorandum to the NRAO staff. It eventually became the first in an NRAO series of MMA Memos, where "MMA" stood for "MilliMeter Array," the working name NRAO chose for this new telescope project.[5]

Owen's memorandum presented the outline of an array that might be built in five to ten years. It was not a formal proposal but was intended to stimulate discussion that could lead to a real proposal. By 1982, the HCRO and OVRO millimeter arrays were in the early stages of operation, and at IRAM planning for an array on the Plateau de Bure near Grenoble, France, was well underway. Owen felt that it was time for a US national array operating at millimeter wavelengths. In his original concept, fifteen 10 m antennas with another fifteen 3 m antennas, were distributed in a Y-shaped configuration like the VLA. Antenna separations up to 1 km in length would be supported and the array would operate at frequencies around 115 GHz and, during good weather, up to 230 GHz. Owen proposed construction on the VLA site in order to take advantage of the substantial infrastructure and expertise already available there. His very rough cost estimate was $33 million in 1980 dollars, that is, a project in the price range of the recently abandoned 25 Meter project, not on the $100 million scale of the VLA.

The two frequency bands suggested by Owen were not arbitrary. In the 12 years since its discovery in 1970, interstellar carbon monoxide (CO) had come to be recognized as the most easily observed signpost of interstellar molecular clouds and the localized regions of star formation contained within them. Because interstellar molecular hydrogen ($H_2$) cannot be observed in cold gas, the demonstration[6] by one of the authors (Dickman) that CO emission is a reliable quantitative proxy for molecular hydrogen ($H_2$) made radio observations of carbon monoxide the observational leading edge of molecular cloud exploratory studies in the late 1970s and early 1980s. The two lowest energy spectral lines of CO are at 115 and 230 GHz.

On 11–12 October 1982, a workshop was held at NRAO's Green Bank site to discuss future instrumentation for the Observatory. Members of both the scientific and the engineering staffs attended. A number of millimeter wavelength projects were presented, but the discussion centered on millimeter arrays. Siting a single millimeter wave dish in the southern hemisphere was proposed but gained little support. The report of the workshop meeting was subsequently summarized by Director Roberts, in an article in the NRAO Observatory Newsletter.[7] The article reaffirmed the Observatory's goals of completing the upgrade of the 12 Meter Telescope and realizing the VLBA.

The Barrett Committee (as discussed in Chapter 2) was well aware of all these developments at the time of its deliberations. A joint meeting of the Committee with community participants, held at Bell Labs Crawford Hill on 10–11 February 1983, was attended by Owen. He and six others had submitted possible science cases for an MMA to the Committee.[8] Each wrote to his own particular interest: Owen on continuum studies; Charles Lada and John Bally, on the formation of stars and planets; Jack Welch on the molecular component of the Galaxy; an extensive list of projects by Jill Knapp; chemistry studies by Bill Langer; and complex galactic molecules by Lew Snyder. These authors were clearly already thinking of an instrument on a national scale: Lada and Bally assumed an array of thirty 6 m diameter antennas, and Knapp assumed sixteen antennas of the same size. These two straw instruments had only 66 percent and 35 percent, respectively, of the collecting area of Owen's concept, but both comprised significantly more antennas than the millimeter arrays then under development.

## A Revised Concept

On 3 March 1983, Roberts sent a memorandum[9] to Owen, who was by then an NRAO scientific staff member, urging him to form a committee, preferably of NRAO scientists, to establish the parameters of an MMA required by

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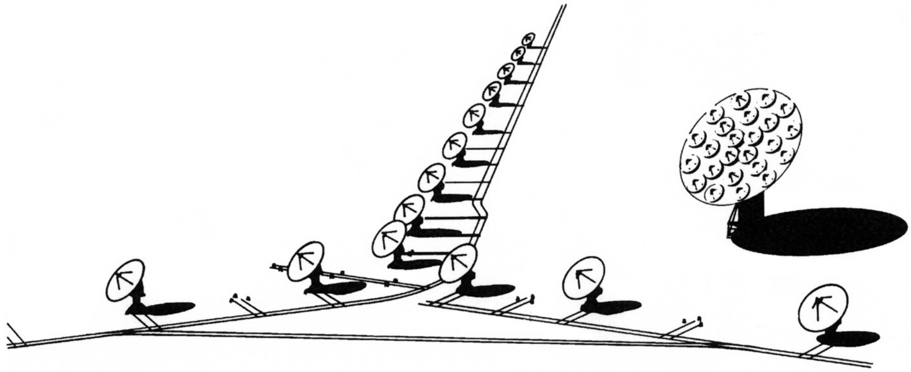

**Figure 3.2** First revision of the original MMA concept with the 6 m diameter antennas in a Y-configuration on tracks and the 3 m diameter antennas mounted on a steerable platform. Credit: NRAO/AUI/NSF, CC BY 3.0.

the science to be done. The technical and engineering staff would then translate these requirements into specifications and a price for the array. Owen responded with a memorandum[10] on 16 March 1983 stating that he had already appointed such a committee and urging Roberts to provide significant help from the technical staff. The closing statement of the memorandum was, "*I hope the VLBA does not totally blind the Observatory to the future*." The tasks Owen had in mind were to define the configuration of the array, that is, the arrangement of antennas on the ground, the signal correlator that compares signals from the antennas, and the site. By "significant help" he was hoping for one or two full-time engineers.

Owen's committee struggled with a conundrum: how to compromise between the number and size of the antennas. Those choices affect the area of the sky seen by the individual antennas, and the sensitivity of the array to widely distributed, comparatively weak sources, such as CO emission from the outer regions of interstellar molecular clouds. To address these issues, Owen's original concept was changed to that shown in Figure 3.2. The 6 m diameter antennas were left in a Y-shaped configuration, but the 3 m diameter antennas were mounted close together on a large steerable platform. Having them close together provided sensitivity to widely distributed sources. It also precluded the antennas from blocking one another's view when observing near the horizon. This revised concept[11] was the largest of the proposals discussed at another NRAO future instrumentation workshop, also held at the Green Bank site, on 20 September 1983.

In spite of all this discussion, the construction of a national MMA – the highest priority project suggested by the Barrett Committee to NSF – was nowhere

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to be seen in the Observatory's 1983 Long Range Plan. It would be unfairly harsh, however, to assume that the Observatory was indifferent to the Barrett Committee's report. The Report had, after all, been public for only six months. The Observatory was losing no time moving forward with the VLBA – the most mature NRAO project endorsed by the NSF Astronomy Advisory Committee – and what was to become the MMA seems to have been viewed as a more long-range project by most NRAO science and engineering staff. Even so, the Observatory recognized the need for further technical development of the concept, and preliminary design studies of some critical components, like the signal correlator, had begun. A study[12] of the atmospheric stability at 13 mm wavelength had indicated that the VLA site could be used for observations at 3 mm wavelength on antenna separations up to 1 km for 50 percent of the time. The possibility of using the VLA site for the MMA was to remain on the table for another 10 or 15 years, even as the interest in using the array at higher frequencies became more and more incompatible with the atmospheric conditions at the VLA site.

## Steps to the MMA Proposal

Over the years, the development of the MMA involved a number of external advisory committees whose reports helped define the concept and laid the basis for an eventual proposal to the NSF for the MMA. News of meetings and results were reported in the NRAO Newsletter and also in the MMA Newsletter, which went into more details on subjects of interest. In addition to the formal reports from the advisory committees and working groups, the MMA Memo Series[13] published memoranda on largely technical subjects by anyone who wished to contribute. The leader of this effort was Owen, who was the driving force in the development of the MMA until Bob Brown assumed leadership of the project in 1985.

*Technical Advisory Committee* – An external Technical Advisory Committee (TAC) was appointed by NRAO in 1983, chaired by Bob Wilson, with eight more members[14] from various universities as well as Bell Labs. The first meeting of the committee occurred on 1–2 March 1984.[15] The agenda, along with Owen's notes made in preparation for the meeting are contained in MMA Memo #14.[16] The committee's report was published in MMA Memo #16.[17] Among the most significant of the recommendations to emerge from this meeting was advice intended to define better the scientific program of the array. Without knowing how the array would be used, it was difficult for the committee to judge whether the present concept would be well matched to detailed scientific requirements. In fact, it would be another year before the Observatory appointed the external science advisory committee (SAC) that would be needed to develop the detailed case for the MMA's science mission. Nevertheless, some important points were already recognized by the TAC, perhaps first among them being the need to begin working on the design implications of an MMA capable of making large-scale maps of the sky using a technique called "mosaicking." The first generation of millimeter wave radio telescopes had already shown that many galactic sources were so extended that high-resolution interferometric images would have to be stitched together from multiple smaller images. This process is considerably more complicated with interferometric data than making a composite image with an optical telescope, and it was already clear that multiple options for observing protocols and data processing algorithms would need to be researched.

The TAC also advised investigating sites other than the VLA, if only for due diligence. In doing so, the Committee further urged that detailed studies be made of the transparency and stability of the atmosphere above the VLA site, thus providing a quantitative baseline for evaluating other sites. Because it was already developed and linked to existing NRAO infrastructure, the Committee also noted that if the VLA site was found to be acceptable it should be considered as the MMA default location barring changes in the array's scientific mission. With respect to antennas, the committee expressed uneasy feelings based on NRAO's experience with the difficult resurfacing project[18] of the Observatory's 12 Meter Telescope. Carbon fiber technology was thought to be a risky but promising approach to making the high-precision radio antennas that would be required for a millimeter wave array. Superconductor-insulator-superconductor (SIS) receivers were thought to be the most promising technology. Unsurprisingly, given the makeup of the TAC, the report ended with a call for more university involvement in the development of MMA's technology. Sometime after the report was forwarded to the NRAO Director, it was decided to focus on three areas: antenna configurations, the design of the support structure of the central element carrying the small antennas, and atmospheric studies of the VLA site. Interestingly, the suggestion of a site in South America for the MMA was dismissed by the committee as "*not an attractive idea.*"

In late 1984, NRAO staff scientist Mark Gordon wrote a prescient memorandum[19] entitled "Are We Thinking Boldly Enough?" He thought it was absolutely necessary for NRAO to build an MMA that would be unique compared to anything existing or planned elsewhere. The obvious solution to him was to build the array in Chile, which hosted three major optical observatories. Again, this idea was not taken seriously, as those involved at NRAO thought Chile was as too

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far away from US expertise in interferometry and was likely to add additional construction and operations costs to the project. More than a decade later, the MMA would be an international project requiring operation at frequencies much higher than 230 GHz, and the case for a Chilean location would be considered much more compelling.

*Science Advisory Committee* – The appointment of the TAC soon made clear the value of involving the US astronomical community in defining the science mission of the MMA. It was also obvious that, along with the TAC, an SAC was needed as a complementary standing body. The SAC's task would be both detailed and broadly contextual since NRAO would eventually need to write a formal proposal to the NSF for funding the MMA. The proposal would have to establish the general scientific discovery space that the instrument would occupy and describe where it would fit into the suite of leading-edge US astronomical instruments, such as the Hubble Space Telescope (HST) and the Keck 10 m (optical) telescopes, already under construction or being planned for the next decade.

The appointment of an external SAC[20] was announced on 1 March 1985. The committee chair was Jack Welch of U.C. Berkeley, one of the leaders in the development of millimeter-wave interferometry. It would have two meetings during the next year that would be open to the astronomical community. The first was to be held in Tucson, Arizona, at the University of Arizona, 9–10 May 1985, following the NRAO Users Committee meeting. The second was scheduled for Charlottesville, Virginia, at the NRAO Headquarters, just before the meeting of the American Astronomical Society at the University of Virginia. The agenda for the latter meeting was published in the NRAO Newsletter #23.[21] At that time, NRAO scientist Al Wootten started the MMA Science Memo Series.

The SAC held a workshop on 30 September–2 October 1985, at the NRAO Green Bank site for the purpose of defining the science goals of the MMA. About 60 attendees were organized into seven working groups chaired by the SAC members. The working groups and chairs were: Solar System (Imke de Pater), Sun and Stars (George Dulk), Evolved Stars and Circumstellar Shells (Phil Schwartz), Star Formation and Molecular Clouds (Neal Evans), Astrochemistry (Lew Snyder), Low-z Extragalactic Studies (Leo Blitz), and High-z Extragalactic Studies (Bruce Partridge). The letter of invitation stated that the reports of the working groups would form “the backbone of the science section of a conceptual proposal to be prepared in 1986.” A brief report was published in the November 1985 NRAO Newsletter (#25).[22] The reports of the working groups were announced in the NRAO April 1986 Newsletter (#27)[23] and the reports of each of the working groups were published as the MMA Science Memo Series.[24]

A much more extensive report was given later in *Science with a Millimeter Array – MMA Design Study Volume I,* issued in January 1988.[25] Chapter I presented the MMA concept at that time. There were to be 21 moveable antennas of about 10 m diameter and 21 antennas of about 4 m diameter mounted on a structure about 29 m in diameter. Several configurations were illustrated. Chapters II–VIII gave the reports of the working groups, who generally found their science goals to be satisfied by the concept of Chapter I. These science goals became the basis for the science case of the MMA proposal.

*Management Changes Affecting the MMA* – On 1 January 1985, one of the authors (Vanden Bout) was appointed the NRAO Director. On 1 May 1985, he announced the appointment of Bob Brown as NRAO Associate Director for Operations, a position that effectively made Brown his deputy. The eventual division of responsibilities had the Tucson and Green Bank sites reporting through Brown to Vanden Bout, along with the Central Development Laboratory in Charlottesville, where NRAO's electronics were developed. The Socorro site and the VLBA Project reported directly to Vanden Bout. This left Brown sufficient time to supervise the MMA development while Vanden Bout worked to secure funding for the VLBA and, eventually the MMA. Later in 1985, it was learned that the State of New Mexico would provide funds to construct an operations center for the VLBA on the campus of the New Mexico Institute of Technology in Socorro. Now called the Pete V. Domenici Science Operations Center, this facility also became the site for VLA operations, which moved from the Plains of San Augustín 60 miles west of Socorro. This development strengthened the vision shared by some NRAO staff members of Socorro becoming the center for all NRAO arrays, including the MMA.

*Final Steps toward a Formal MMA Proposal* **–** The first formal report[26] of specifications for the MMA based on identified scientific goals was *Millimeter Array Design Concept – MMA Design Study Volume II,* issued in January 1988 along with Volume I. It refined the concept presented in Volume I in a series of steps. Chapter I restated the recommendations of the Barrett Report. Chapter II went into more detailed requirements from each of the science areas. In Chapter III, the heterogeneous array of 10 m and 3 m diameter antennas had disappeared to be replaced by a homogeneous array. Wide-field images were to be produced by "mosaicking," a technique that stitches together multiple images.[27] Chapter IV discussed practical details, including the selection of a site. Mount Baldy near the VLA site was discussed in particular. It concluded with the parameters of the new design concept: forty 7.5 m diameter antennas of surface accuracy such that deviations from a perfect parabola are less than 0.043 mm on average; moveable into configurations of 90, 300, 1,000,

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and 3,000 m largest extent; operating in bands of 36–48, 70–115, 200–270, and 270–350 GHz. This concept would provide images with 0.1 arcsecond angular resolution at 230 GHz, equivalent to discerning a basketball hoop at 600 miles distance. In Chapter V, the technique and application of mosaicking were discussed in more detail. It requires the ability to move the antennas quickly, which is a challenge for the antenna design. The principal player here was Tim Cornwell, a scientist at the VLA. He wrote a series of articles on image processing relevant to the MMA, the one on mosaicking appeared as MMA Memo #24. The construction budget was estimated to be $66 million in 1988 dollars including $11 million for contingency. Major construction was to begin in 1992.

### MMA Proposal

On 6 October 1986, Frazer Owen distributed draft chapters for an MMA proposal to the NRAO staff for comment. The TAC met later that month to hear updates on site testing and imaging studies and to review the draft proposal. (The alert reader will notice that this is more than a year prior to the publications of the Millimeter Array design volumes which were the basis for the proposal. The contents of those reports were available in draft long before their final publication, which was essentially a formality by 1988.) Refining this material and settling, to the extent possible, as many of the remaining questions took another year. A meeting at NRAO Tucson discussed technical issues on 1 November 1988. A second science workshop was held on 19–23 October 1989 in Socorro, NM. In January 1990, AUI formally submitted the proposal[28] to the NSF. The proposal began with an introduction recalling the requirements stated in the Barrett Report and noting that although millimeter astronomy had been pioneered in the United States, in contrast to other countries, "*no major national millimeter-wave instrument has ever been funded.*"

The proposal called for an array of forty identical 8 m diameter antennas that would provide a total collecting area of 2,010 $m^2$. Figure 3.3 shows the relative collecting area of the MMA compared with the arrays discussed in Chapter 2 and the area that was later achieved with ALMA. The surface accuracy of the antennas would be sufficient to allow observations at wavelengths as short as 1 mm. That is, the array would be able to observe all three of the lowest frequency transitions of CO: 115, 230, and 345 GHz; these being the anticipated workhorse observational frequencies. The proposed array had four configurations for the antennas. Figure 3.4 illustrates the proposed configurations. One was a compact array whereby all the antennas were placed as close together

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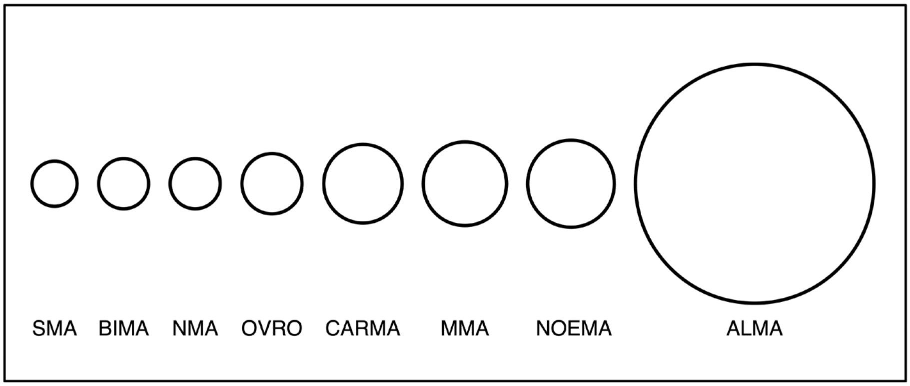


**Figure 3.3** The circles indicate the relative geometric collecting areas of the millimeter/submillimeter arrays that have been discussed, for comparison with the proposed MMA, as well as that of ALMA. The actual power of an array depends on additional factors: efficiency of the antenna optics, performance of the electronics, and quality of the atmosphere at the array site. Courtesy of Thomas van den Bout, reproduced by permission.

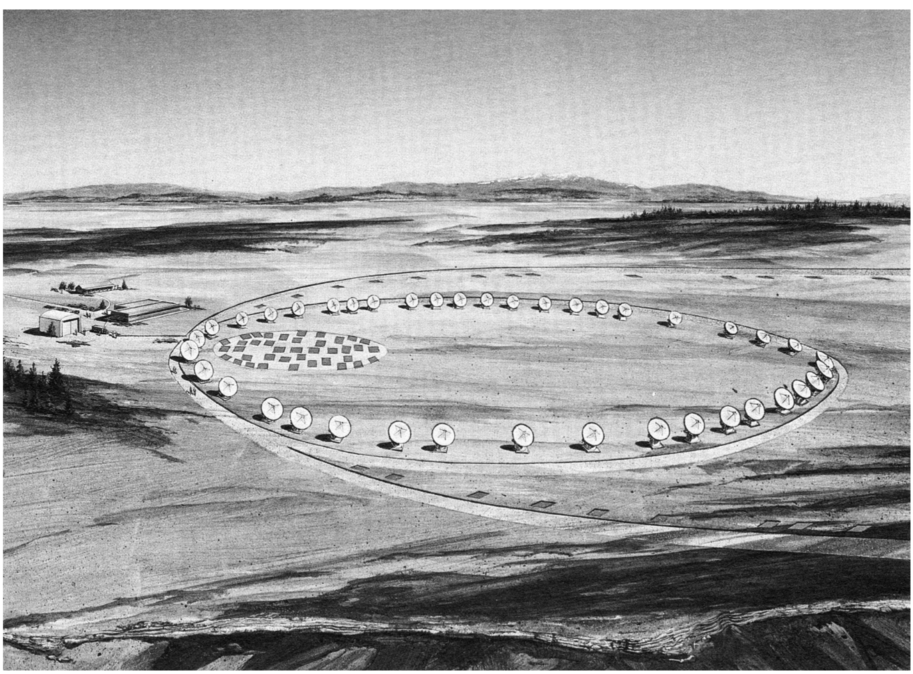

**Figure 3.4** Illustration on the cover of the MMA proposal showing an artist's conception of the array on a high, arid, flat site. Credit: NRAO/AUI/NSF, CC BY 3.0.

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as practical. There were three more extended configurations of 250, 900, and 3,000 m in diameter. The angular resolution of the largest configuration was 0.07 times the observing wavelength in arcseconds. At 115 GHz, this is about 0.2 arcseconds, 10 times better than the Barrett Report recommendation. There were to be four observing bands: 30–50, 68–115, 130–183, and 195–366 GHz with the ability to observe in more than one band at a time. In short, the MMA was to be a flexible array, a millimeter version of the VLA.

The proposal's science goals had broadened beyond the observation of interstellar carbon monoxide. These were summarized in the introduction as follows:

1. Image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as $z = 10$.
2. Reveal the kinematics of optically obscured galactic nuclei and QSOs on spatial scales smaller than 100 pc.
3. Assess the influence that chemical and isotopic gradients in galactic disks have on star formation and spiral structure.
4. Image heavily obscured regions containing protostars, and protostellar and preplanetary disks in nearby molecular clouds, with a spatial resolution of 10 AU and kinematic resolution <1 km/sec.
5. Detect the photospheric emission from hundreds of nearby stars in every part of the Hertzsprung–Russell (H–R) diagram.
6. Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of stellar nuclear processing and envelope convection.
7. Resolve the dust-formation region and probe the structure of the magnetic field in stellar winds.
8. Establish the relative distributions of the large number of complex molecular species in regions of star formation, relating them to shock fronts, grain disruption, and energetic outflows – information that is essential to the understanding of astrochemistry.
9. Obtain unobscured sub-arcsecond images of cometary nuclei, hundreds of asteroids, planetary atmospheres and surfaces, and solar regions of active particle acceleration.

Chapter II of the proposal gave an expanded discussion of the array, particularly of its sensitivity. The fact that the array should detect the continuum radiation from a 0.1 mJy source in one hour of observing time was noteworthy. A graph showed that this placed the MMA in the same class for detection of extragalactic sources as the VLA, the Spitzer InfraRed Telescope Facility (SIRTF) in the infrared, the HST in the optical, and the Advanced X-ray Astronomy Facility (AXAF) in X-rays. A more detailed discussion of the science proposed for the MMA was given in Chapter III: observations of the distant Universe, the Universe nearby, the Sun and stars, molecular clouds and star formation, astrochemistry, evolved stars and circumstellar shells, and planetary science. Chapter IV discussed the techniques for transforming array observations into images. Simulations of these techniques were presented. The proposal did not include a large single dish, thought heretofore to be necessary for accurate imaging. Instead, the chapter concluded with a pledge to continue research into the viability of the mosaicking technique.

Chapter V discussed computing needs, both to operate the array and to produce images from recorded data. The so-called real-time system needed to operate the array was modest in scope and cost, estimated at $200k per year. The systems needed for later image processing were much larger and more expensive. Its components were:

1. A machine with a total computing power of 8 billion operations per second, costing $5 million;
2. a minimum of 300 Gbytes of off-line storage, costing $1 million;
3. about 10 high-performance graphics workstations for a total of $500,000;
4. 40–50 personal workstations for a total of $500,000–1 million;
5. a system of mass storage, costing $1 million;
6. local area networks, costing $500,000; and
7. printers etc., costing $200,000–300,000.

The site selection process and status at the time of the proposal were presented in Chapter VI. The requirement to observe at 1 millimeter wavelength implied a site with less than 2 mm precipitable water vapor overhead for at least some of the time. This meant a high site, at least 2,700 m in elevation, and one large enough to accommodate the 3 km configuration. The search identified 50 sites in the continental United States south of 36 degrees north latitude with this elevation. The latitude requirement was imposed to allow observations of the center of the Milky Way, our own galaxy. Eliminating sites that were too small, that were in national wilderness areas, or had access problems, left only three that were worthy of serious study: two in the Apache National Forest near the towns of Springerville and Alpine, both in Arizona, and one on Mt. Baldy in the Magdalena Mountains near the VLA site.

The proposal illustrated the placement of the 3 km configurations on these sites and presented atmospheric opacity data obtained with a tipping radiometer operating at 225 GHz on the Magdalena Mountain site. The measurements showed that the site had an atmospheric transparency of 85 percent for about half the time. That is, the MMA could operate there although operation at 345

GHz would be limited. NRAO built four of these “tippers.” One had operated on Maunakea at the CSO site for several months at the time of the proposal and the data indicated that Maunakea was, indeed, a very dry site, suggesting expanding the site search to Hawaii. The proposal also mentioned studying sites in northern Chile. Sites in both Hawaii and Chile would come at a premium in cost, so the focus at the time was on the US continental sites. The proposal fairly presented the question of where to locate the MMA as an ongoing investigation.

Chapter VII discussed the antennas for the MMA, a subject still under investigation. Making the backup structure that supported the reflecting panels of carbon-fiber-reinforced plastic (CFRP) material was attractive. A structure made of CFRP would be both lighter and stiffer than one of steel. But the technology was relatively new at the time and so the proposal called for a hybrid like that being used at IRAM – a combination of CFRP and steel structural members. Whether the panels would use CFRP technology was left open. The conceptual design of the antenna was a very compact structure, as shown in Figure 3.5.

Despite the uncertainties surrounding the antenna design, a cost estimate was made that came to $1.25 million per antenna. The issue of how the antennas were to be moved from one configuration to another was left for future investigation.

The MMA electronics plan was presented in Chapter VIII. It was clearly stated that the receivers would require development work to meet the specifications. There was a lengthy discussion on the choice of style for the signal correlator – one like the VLBA or one like the VLA. The VLA type was chosen as being less expensive, of order $6.2 million. Chapter IX estimated operations costs on the assumption that the MMA would be located at one of the continental US sites, that is, not too far from the VLA. With a staff of 90, the annual cost to operate the MMA was estimated to be $6.6 million. Chapter X presented a summary of all the estimated component costs that totaled $104.3 million. A contingency of $15.7 million (15 percent) was added to make a grand total of $120 million. It must be noted that at the time NRAO was not running construction projects with the management tools that are now standard for large projects. This total cost estimate was not built bottom-up with a budgeted contingency based on the sum of contingencies for each component. In fact, there was an overriding consideration that went into the cost estimate – that the total request does not exceed the inflated cost of other NRAO projects like the VLA and VLBA. It all added up to a number that was judged to be one the NSF could swallow. The schedule presented called for three years of development, starting in 1991 at $1 million and continuing in 1992 at $2 million and in 1993 at $5 million.

On 26 July 1990, Bob Hughes, President of Associated Universities, Inc. (AUI), the research management corporation that operates NRAO for the NSF,

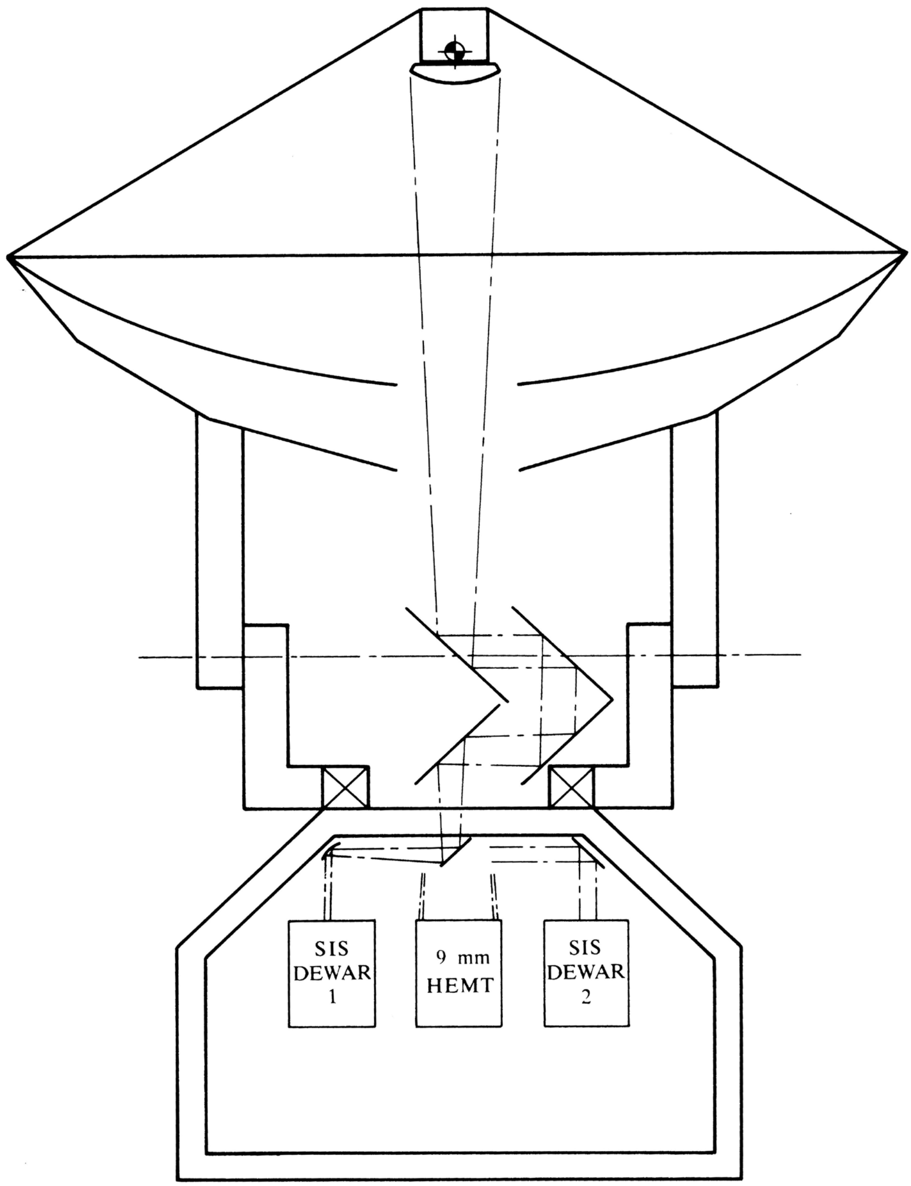


**Figure 3.5** Conceptual MMA antenna design. Plane mirrors guide the beam to one of three cryogenic dewars, two with SIS mixer receivers and one with a high electron mobility transistor (HEMT) amplifier receiver. Credit: NRAO/AUI/NSF, CC BY 3.0.

formally submitted the proposal to the NSF, where it was assigned the proposal number AST-9024403. The request caught the attention of the science press. An article[29] by Robert Crease in the 28 September 1990 issue of *Science* began with the following paragraph. "*In an era of Gramm-Rudman budget cuts, shrinking* *research grants, and post-Hubble sensitivities, it takes more than a little chutzpah to propose yet another big science project, especially one in a relatively new field. But that is what a stalwart band of astronomers, led by Robert Brown of the NRAO, has just done.*" The article went on to trace the history of US millimeter astronomy, note the foreign competition, and end on a somewhat positive note: "*The 25th anniversary of the discovery of the 2.6 mm carbon monoxide line in space will be in 1995. By then astronomers hope to be on the verge of seeing the first glimmers of mm light through the Millimeter Array.*"

### Proposal Review

In her letter[30] acknowledging receipt of the proposal, Pat Bautz, AST Director, informed Hughes that Vernon Pankonin would be in charge of its review. On 2 August 1990, in response to a request from the NRAO Program Officer, Ludwig Oster, Brown sent 37 names of suggested referees, of which 16 were highlighted as being "particularly knowledgeable." The 25 anonymous referees who eventually submitted reviews must have included some of those on Brown's list.

While the referees were considering the proposal, Pankonin convened a 10-member committee to discuss the proposal, with a so-called "site visit," held at NRAO in Socorro, NM, on 9–10 April 1991. The committee was chaired by Charles Townes of the University of California (Berkeley). A number of NSF officials attended the proceedings. The meeting agenda consisted of short presentations on the array concept, project organization, imaging, site options, antenna design, and electronics. Most committee discussions focused on the number of antennas and sensitivity required to accomplish the science goals. Another concern of the committee was the fraction of the time at the sites being considered for which the phase stability of the atmosphere was adequate for observations with the proposed configurations. Owen asserted that for Mt. Baldy the phase stability at 225 GHz was 15 degrees or better for 30 percent of the time, one radian or better 60 percent of the time.[31] If the committee wrote a report, NRAO never received it. Instead, a letter[32] to NRAO from Pankonin on 4 November 1991 summarized the concerns of the referees.

Pankonin's letter gave the selection of a site as the most common concern of the referees. They noted that the sites under consideration were all within a half-day drive of the VLA and wondered if this was merely coincidence. They recommended more studies of the three sites with particular attention to phase stability. The referees were split on whether a 15–20 m diameter single dish was required for good imaging. The majority favored the proposed uniform array of forty 8 m diameter dishes. There was concern over the lack of any management structure. The Joint Development Group (JDG), whereby MMA development work could be funded at university groups, was considered an important step. There was concern that the costs were uncertain, particularly, those for computing and operations. These concerns aside, there was general enthusiasm expressed by the referees for the MMA, and Pankonin urged attention to the issues they raised. He asked for an initial NRAO response before he concluded his own analysis. The response[33] was sent on 13 November 1991.

On 10 March 1992, Julie Lutz, who succeeded Bautz as AST Director, sent a letter to AUI President Hughes stating that the review process had been concluded, and giving the NSF's status for the project. She noted that the MMA had been endorsed by the National Academy of Sciences Survey of Astronomy for the 1990s, the Bahcall Report, as one of two top priorities for ground-based astronomy.[34] Her own advisory committee, the ACAST, had endorsed it as well. She said that the NSF considered the proposal to be a detailed but preliminary description of the project and requested that NRAO submit a detailed plan for research and development. She hoped to begin a research and development phase in the fiscal year (FY) 1994. A decision on actual construction would occur midway in the research and development phase, for which NRAO would need to submit a detailed construction plan. The letter enclosed the 25 (anonymous) referee reports[35] and the ACAST resolution.

## Design and Development Plan

NRAO's MMA Design and Development Plan[36] was submitted to NSF on 31 August 1992. The plan presented a four-year program, 1993–1996, to complete the tasks that would lead to the start of construction in 1997. The approach was to evaluate technical alternatives, construct and test prototypes, build a single-baseline set of electronics, design and build a prototype antenna, and prototype software for evaluation by future users. This work was to be conducted in concert with the university groups in the JDG, represented at the time by Jack Welch (U.C. Berkeley), John Carlstrom (Caltech), Lew Snyder (U. Illinois), Leo Blitz (U. Maryland), and Paul Goldsmith (U. Mass.).

Lest anyone think the MMA concept had gone stale in the two years since the submission of the proposal, the tone of the document's introduction was that of a sales pitch. It ends by noting that all new generation telescopes, such as the Keck Telescopes and the Green Bank Telescope, required advances in technology, an allusion to the need for design and development funding if the MMA was to succeed. The cover of the plan, shown in Figure 3.6, was impressively high-tech for the time. It illustrated progress in electronics that had already been made: a multi-beam receiver that had recently been put in use on NRAO's 12 Meter Telescope.

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**Figure 3.6** The illustration on the cover of the first MMA Design and Development Plan was of a multi-beam receiver for the NRAO 12 Meter Telescope. The six receiver cartridges were cooled by a common refrigerator and held in a common cryogenic container, a scheme later used for ALMA. Credit: NRAO/AUI/NSF, CC BY 3.0.

In addition to the ongoing program of atmospheric monitoring being conducted on the three continental US sites, the plan mentioned monitoring at the CSO site on Maunakea. But the latter was not proposed as a possible site for the MMA. Site tasks included biological assessments; the impacts on operations from staffing, power, and communications, roads and snow removal, difficulty in moving antennas; comparisons of imaging with array configurations possible at the three sites; and community considerations. Environmental studies would be done before giving a priority ranking to the three possible sites.

Reasonably detailed descriptions of the development tasks for the antenna and electronics were presented. The staffing requirements for the entire Design and Development phase rose from 10.5 work years in 1993 to 41.4 in 1994, 51.8 in 1995, and 50.3 in 1996. The total cost of the plan was $22.3 million,

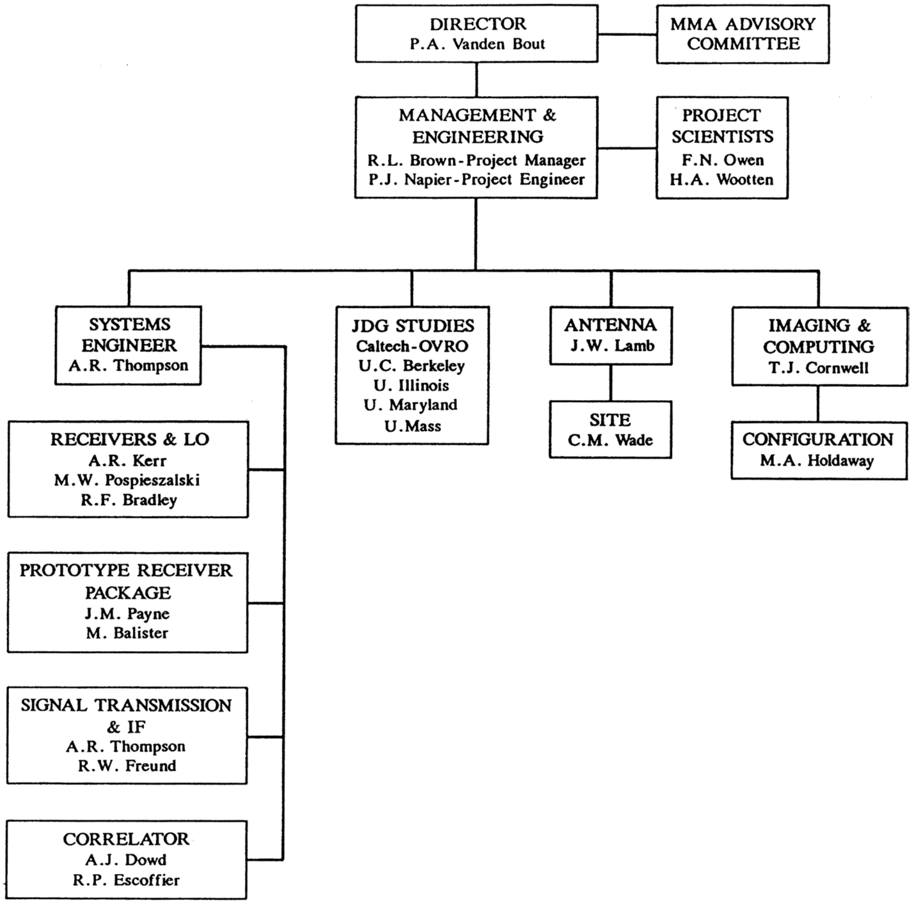


**Figure 3.7** The MMA project organization chart. Credit: NRAO/AUI/NSF, CC BY 3.0.

including $2 million in new test equipment, and a simple work breakdown structure showed how the budget should be spread over four years. Criticism that the project lacked a management structure was addressed with an organization chart shown in Figure 3.7. The management structure for the program was that submitted earlier to NSF. At the end of the plan, progress already achieved was documented in Appendices, 15 in total, that were reprints from the MMA Memo Series.

It would be two years before the National Science Board (NSB) approved the MMA Design and Development Plan. In the intervening years, Hugh van Horn became AST Director and Bob Dickman was appointed Head of the Radio Astronomy Unit. Two years later, Dickman presented the Plan to the NSB and gained its approval in November of 1994. Funding of the Plan had to wait until May of 1998 when it could be accommodated by the Major Research Equipment

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(MRE) account. NRAO spent the six years from submission of the Plan until its funding refining the science goals and engineering requirements and, most significantly, in the selection of a site. Of course, the proposed start of construction in 1997 had already passed by this time.

## Notes

1 Hills et al. (1973) give a technical description of the HCRO two-element interferometer.

2 Hills et al. (1972) report the positions of galactic water emission sources.

3 Delannoy, Lacroix, and Blum (1973) give a description of the U. Bordeaux solar interferometer.

4 T. Riffe and D. Hogg to Vanden Bout, private communication. Both Riffe and Hogg recall Heeschen using this phrase whenever he rejected initiatives that he thought conflicted with or distracted from NRAO's mission.

5 Owen, F. 1982, *The Concept of a Millimeter Array*, MMA Memo #1, http://library.nrao.edu/public/memos/alma/main/memo001.pdf.

6 Dickman (1978) established the correlation between the CO emission from a molecular cloud and the optical opacity caused by interstellar dust, and thence, to the mass of molecular hydrogen in the cloud.

7 Roberts, M. 1982, Future Instrumentation in Radio Astronomy, NRAO Newsletter #9, http://library.nrao.edu/public/pubs/news/NRAO_NEWS_9.pdf.

8 Owen, F. 1983a, *Science with a Millimeter Array*, MMA Memo #2, http://library.nrao.edu/public/memos/alma/main/memo002.pdf.

9 Roberts to Owen, 3 March 1983, NAA-NRAO, MMA, MMA Planning, Box 1.

10 Owen to Roberts, 16 March 1983, NAA-NRAO, MMA, MMA Planning, Box 1.

11 Owen, F. 1983b, *Concept of a Compound Millimeter Array*, MMA Memo #10, http://library.nrao.edu/public/memos/alma/main/memo010.pdf.

12 Sramek, R. 1983, *VLA Phase Stability at 22 GHz on Baselines of 100 m to 3 km*, VLA Test Memo #143, http://library.nrao.edu/public/memos/alma/main/memo008.pdf.

13 All the memoranda for the MMA and ALMA are available on the NRAO Library website. https://library.nrao.edu/allalma.shtml.

14 The membership of the TAC included Paul Goldsmith (U. Massachusetts), Al Moffet (Caltech), Pat Palmer (U. Chicago), Tom Phillips (Caltech), Larry Rudnick (U. Minnesota), Tony Stark (Bell Telephone Labs.), Bobby Ulich (U. Arizona), Jack Welch (U.C. Berkeley), and Bob Wilson (Bell Labs.) chair.

15 Owen, F. 1983c, Millimeter Array Status, NRAO Newsletter #16, http://library.nrao.edu/public/pubs/news/NRAO_NEWS_16.pdf.

16 Owen, F. 1984, *Notes on Presentations at the Meeting*, MMA Memo #14, http://library.nrao.edu/public/memos/alma/main/memo014.pdf.

17 Wilson, R. 1984, Report of the Millimeter Array Technical Advisory Committee on their conclusions as a result of the meeting on 1 and 2 March 1984, MMA Memo #16, http://library.nrao.edu/public/memos/alma/main/memo016.pdf.

18 See Gordon (2005) and Kellermann, Bouton, and Brandt (2020), p. 550, for discussions of the re-surfacing of the 12 Meter Telescope.

19 Gordon, M. 1984, *Are We Thinking Boldly Enough*? MMA Memo #25, http://library.nrao.edu/public/memos/alma/main/memo025.pdf.

20 The announcement of the appointment of the SAC was made by Frazer Owen, Upcoming Open Discussions of the Millimeter Array Project, NRAO Newsletter #22, http://library.nrao.edu/public/pubs/news/NRAO_NEWS_22.pdf. The membership of the SAC included Leo Blitz (U. Maryland), Neal Evans (U. Texas, Austin), George Dulk (U. Colorado,) Fred Lo (Caltech), Bruce Partridge (Haveford College), Imke de Pater (U.C. Berkeley), Lew Snyder (U. Illinois, Urbana), Jack Welch (U.C. Berkeley), chair; NAA-NRAO, MMA, MMA Planning, MMA Advisory Committees.

21 Owen, F. 1985b, Millimeter Array Discussion, NRAO Newsletter #23, http://library.nrao.edu/public/pubs/news/NRAO_NEWS_23.pdf.

22 Wootten, A., 1985, Millimeter Array Science Workshop, NRAO Newsletter #25, https://library.nrao.edu/public/pubs/news/NRAO_NEWS_25.pdf.

23 Wooten, A., 1986, Millimeter Array Science Workshop, NRAO Newsletter #27, https://library.nrao.edu/public/pubs/news/NRAO_NEWS_27.pdf.

24 The science working group reports can be found at: https://library.nrao.edu/mmas.shtml.

25 Wootten and Schwab, eds. (1988). NAA-NRAO, MMA, MMA Planning, Box 2.

26 Brown and Schwab, eds. (1988). NAA-NRAO, MMA, MMA Planning, Box 2.

27 Cornwell gives an early description of mosaicking in MMA Memo #32: https://library.nrao.edu/public/memos/alma/main/memo032.pdf.

28 Brown, R. (1990). NAA-NRAO, MMA, MMA Planning, Box 2.

29 Crease (1990).

30 Bautz to Hughes (undated, ca. July/August 1990), NAA-NRAO, Director's Office, Director's Office Correspondence, NSF Correspondence.

31 The time between reception of a signal by one antenna and that of another is the phase difference. Interferometer images require precise information of these phase differences for image construction. The atmosphere also delays signals. The same delay over all antennas is of no consequence to image formation, but differing atmospheric delays impair it. Phase is measured in degrees and/or radians. The numbers Owen quoted are indicative of a marginally acceptable site.

32 Pankonin to Vanden Bout, 4 November 1991, NAA-NRAO, MMA, MMA Planning, Box 3. https://science.nrao.edu/about/publications/alma.

33 Vanden Bout to Pankonin, 13 November 1991, NAA-NRAO, MMA, MMA Planning, Box 3. https://science.nrao.edu/about/publications/alma.

34 By happenstance, no other large radio astronomy projects had been proposed to the Survey. The Radio Astronomy Panel of the Survey, chaired by K. Kellermann of NRAO, was easily able to identify the MMA as their top choice for a large radio project.

35 Anonymous Reviews of the Millimeter Array Proposal [1991], NAA-NRAO, MMA, MMA Planning, Box 3. https://science.nrao.edu/about/publications/alma.

36 Millimeter Array Design and Development Plan, September 1992, NAA-NRAO, MMA, MMA Planning, Box 3. https://science.nrao.edu/about/publications/alma.