THE DECISION TO CONSTRUCT A LARGE RADIOTELESCOPE, THE VLA

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PREFACE[1]

This case study is an effort to trace the decision-making process that led to the construction of the largest, most expensive, and most sophisticated ground-based astronomical instrument ever built. The VLA (Very Large Array) is the hugh aperture-synthesis radiotelescope now being built in New Mexico by the National Radio Astronomy Observatory. The author was closely associated with the early development and design of the VLA, and with its promotion as a concept within the scientific community.

The need for the VLA was recognized in the late 1950s. The decade of the 1960s was spent in developing the technical concept and the method and in attempting to secure financial and administrative support for the program. The construction of the instrument has occupied most of the 1970s, with full operation expected in 1980. The long construction period is dictated in large part by the incremental funding pattern established for the project, rather than by technical considerations.

A chronological framework has been adopted for this case study. The data have come from personal interviews with government officials and radio astronomers who were involved in the process, from correspondence from the files of the National Radio Astronomy Observatory and of members of scientific advisory committees, and from the author's personal files and recollections. The decision-making history of the project is quite well documented. Only very few conclusions were necessarily arrived at by implication, and these have been identified as such.

Most of the government officials interviewed strongly emphasized the political realities of the decision-making process. The radio astronomers, on the other hand, take a much more idealistic view. The result is taht the scenario that has evolved for radio astronomy instrumental development departs from any of the models postulated by the reports of the various scientific advisory committees. There was considerable conflict in the evolution of the scenario. It is, of course, impossible to know the intentions of all the personalities and agencies involved in the process. What seems very certain, however, is that all of the individuals concerned believed that their actions were in the best interests of the science of radio astronomy and of the American radio astronomical community. Thus every interviewee spoke freely and candidly about his views and recollections, whether or not he was still active in radio astronomy or in a government agency.

Gloria B. Lubkin, senior editor of Physics Today, has written a paper entitled, "The Decision to Build the Very Large Array," in connection with her Nieman Fellowship at Harvard (Lubkin 1975). In researching this paper, she interviewed many of the participants in the decision-making process and examined many of the pertinent documents. The present author interviewed several of the same participants, as well as others, and independently searched out the appropriate documents. Lubkin's report presents essentially the same findings as the present one in the areas of mutual coverage. In a few cases, the author used transcripts of interviews made available by Lubkin, rather than repeating interviews.

The author thanks all the many individuals who have assisted in this case study. Special thanks are due to D.S. Heeschen for his exceptional cooperation.

HISTORICAL SUMMARY OF RADIO ASTRONOMY: THE SEARCH FOR ANGULAR RESOLUTION AND SENSITIVITY

Radio astronomy had its genesis as a science in the experiments of Karl G. Jansky of the Bell Telephone Laboratories, who, in the early 1930s, demonstrated that our galaxy, the Milky Way, is the source of electromagnetic radiation at radio wavelengths. This discovery was exploited by Grote Reber of Wheaton, Illinois, who established the basic instrumental principles of radio astronomy and investigated the radio emission of the galaxy and the sun in the late thirties and early forties.

Shortly after World War II, British and Australian radio astronomers discovered a number of other discrete radio sources and attempted to measure their angular sizes. In many cases, only upper limits could be established, as the observational techniques then in use were incapable of resolving more than a few cosmic radio sources.

To obtain better resolution than was possible with single-reflector antennas or contiguous phased-array systems, the British and Australian laboratories made early experiments with radio-interferometers, long wavelength analogs of the classical Michelson interferometer of optics. Such a device generally consists of two similar antennas, positioned well apart and connected by long transmission lines. Its output response depends strongly on the angular size of the source and the distance between the antennas. Thus, if the distance can be varied, or if several different antennas are available, the source structure can be recovered from a series of measurements made with various antenna spacings, or "baselines." In technical terms, the response of an interferometer with a given baseline is the coefficient of a corresponding term of the Fourier series representing the brightness distribution of the radio source on the celestial sphere. Observation with a sufficient number of different baselines enables one to sum the Fourier series and thus to reconstruct the brightness distribution of the source.

An advantage of the interferometer is that it can be made very large without incurring impractical costs or structural difficulties. Despite the fact that in the early 1950s radio astronomers recognized the possibilities of "aperture synthesis" by interferometers, several practical difficulties prevented the early implementation of the principle in its full generality. These involved the state of the art in electronics and in large-scale digital computation, neither of which was sufficiently advanced at the time.

Instead, compromise designs were used which were less dependent on computational capacity and on the stability and reliability of electronic components. These included the "cross"-type antennas pioneered by Mills and Christiansen in Sydney, Australia and the synthesis interferometers of Ryle and his group at Cambridge. By the late 1950s, these instruments were producing catalogs which included thousands of discrete, cosmic radio sources.

To detect a discrete source one must be able to distinguish it from its neighbors. This is the "confusion" problem. Its solution requires high resolving power, or, equivalently, a narrow "beam." In addition, one must be able to detect the extraordinarily faint radiation from the source; this, in turn, requires that the telescope possess a large collecting area. In a single-reflector telescope, both resolving power and collecting area improve as the antenna diameter is increased. In an interferometer, however, only the resolving power improves as the baseline is lengthened, other parameters remaining fixed.

The early catalogs produced by the Sydney and Cambridge groups contained little information concerning the spatial structure of the sources therein. The measured source positions were generally insufficiently precise to permit unambiguous identification with sources detected by optical telescopes. Thus, although the confusion problem had been solved to the degree necessary to demonstrate the existence of thousands of cosmic radio sources, it was widely recognized by the end of the 1950s that much better angular resolution and sensitivity would be needed to permit further advances in radio astronomy. At that time, the original Mills Cross antenna had a beamwidth of 50 arcminutes. Nobody knew with certainty what resolution would ultimately be required, but radio astronomers rather wistfully regarded the one-second resolutions regularly obtained by optical astronomers as an ultimate, perhaps unrealistic, goal.

AMERICAN RADIO ASTRONOMY

Although the founding discoveries in radio astronomy were made in America, the principal activity during the 1950s occurred in Australia, Britain, and Holland. This period saw the early cataloguing of discrete sources and the detailed continuum mapping of the galaxy. In 1951, the 21-centimeter (cm) spectral line of neutral hydrogen was observed in the galaxy by Ewen and Purcell at Harvard University, confirming an earlier prediction by van de Hulst of Holland and adding important new dimensions to radio astronomy. By 1954, there were radio astronomy research programs using small parabolic antennas or improvised arrays underway at Harvard, the Naval Research Laboratory, the Carnegie Institution of Washington, and Ohio State

University. Leading U.S. astronomers and radio physicists had become concerned at what seemed the slow-paced development of the science. As a result, a substantial program of support for radio astronomy was undertaken by the Office of Naval Research (ONR), the Air Force Office of Scientific Research, and the newly-established National Science Foundation (NSF). This resulted in the construction of general-purpose parabolic telescopes in the 85-foot class at the University of Michigan, the University of California at Berkeley (Hat Creek), the Naval Research Laboratory, and the Harvard facility at Ft. Davis, Texas. Larger, special-purpose instruments, mainly for cataloguing, were also built at the University of Illinois and Ohio State.[2] In 1955, John Bolton, of the Australian group, came to the California Institute of Technology to establish a broad radio astronomy program and to found an American school of interferometry, constructing two 90-foot antennas on a system of railway tracks. This program was financed by ONR, as were many other major programs. Cornell University began construction of a 1000-foot spherical telescope in Arecibo, Puerto Rico, with funds from the Advanced Research Projects Agency of the Department of Defense. This instrument was designed to be used largely for upper-atmosphere research, but assumed great importance in astronomy as well.

In this same period, the National Radio Astronomy Observatory (NRAO) was being established as a laboratory of the National Science Foundation. NRAO is operated under contract by an autonomous nonprofit corporation, Associated Universities, Inc. (AUI) which is sponsored by nine universities, each of which nominates two trustees.[3] The purpose of the NRAO is to provide radio astronomers with large-scale observation facilities regardless of their institutional affiliation. The initial intention was to supplement but not to supplant the radio astronomy programs of the universities and the other private and governmental laboratories.

NRAO's site of Green Bank in the Allegheny Mountains of West Virginia was chosen to avoid, insofar as possible, locally-generated radio interference. The founders clearly did not intend to construct there any extremely high-resolution radio telescopes, as the site does not lend itself to such purpose. The first instrument constructed for the NRAO was an 85-foot equatorial paraboloid essentially similar to one built simultaneously at the University of Michigan. Subsequently, two additional single-reflector telescopes were built, a 300-foot meridian-transit paraboloid and a 140-foot equatorial paraboloid, the latter completed in 1965.

From the outset, the NRAO has been closely involved with the American radio astronomy community, not only by providing observing time to visiting scientists, but also through frequent and almost continual consultation on policy and technical questions. A Visiting Committee of several astronomers who had directed several optical observatories. He served from 1959 to 1961, at which time he retired. To succeed him the AUI trustees recruited Joseph L. Pawsey, the highly respected leader of the radio astronomy group of the Commonwealth Scientific and Industrial Research Organization in Australia. Pawsey expected to move to Green Bank in the fall of 1962, and spent some time in the preceding several months planning programs for NRAO, particularly in the area of high-resolution instrumental development.[4] During a visit to the United States in early 1962, he fell victim to an illness to which he succumbed before actually assuming the directorship. David S. Heeschen, an astronomer on the NRAO staff, was appointed interim director for about a year, and then was confirmed director. He still retains that post.

THE PERCEIVED NEED FOR HIGH-RESOLUTION INSTRUMENTS

The realtionship between instrumental size and angular resolution has been discussed briefly, as have the problems of confusion and sensitivity. The situation at the close of the 1950s was that several groups throughout the world were compiling source catalogs with telescopes with resolutions in the order of tens of minutes of arc, at various wavelengths, between several meters and several decimeters. At the shorter wavelengths, confusion effects and the electronic art permitted reliable detection of sources with flux densities of about 10^{-26} Watt Meter^{-2} Hertz^{-1}; at the longer wavelengths somewhat less sensitivity was the rule.

Several important discoveries had been made which suggested that considerably improved resolution would yield an important new understanding of the structure of the galaxies and of the structure and history of the universe. The identification of several very strong radio sources with very distant optical objects suggested that numerical counts of radio sources could be used to test cosmological hypotheses. The mapping of hitherto-obscured regions of our galaxy was made possible by 21 cm hydrogen spectroscopy. Together with the tentative mapping of radio structure in the relatively nearby Andromeda galaxy, this suggested that greatly improved knowledge of galactic structure and dynamics could be achieved.

It was in this context that the National Science Foundation in 1960 convened a panel on large radio telescopes under the chairmanship of John R. Pierce, a renowned electronics and communications expert of the Bell Telephone Laboratories. The Panel made several recommendations (Keller 1961), among which was the need for a telescope with a beamwidth of one arcminute, sufficient, for example, to map accurately the structure of the Andromeda nebula. The panel's report included a tentative design for a four-element interferometer array by Bolton in response to the above requirement. Although the report was available to the NSF and other agencies in 1960, it was not published until 1961, and it is not clear to what degree it influenced the thinking of government agencies interested in radio astronomy.

During mid-1962, after accepting the appointment as the director-elect of NRAO, Pawsey studied appropriate directions for instrumental development for the organization. His correspondence and notes indicate that he contemplated an array of some sort, capable of angular resolution of a fraction of an arcminute in the decimeter range of wavelengths.[5] He wished to attract to Green Bank several individuals experienced in the design of interferometers and arrays and in the interpretation of their results.[6] Several 1-arcminute instruments were in the planning or construction stages at foreign observatories: a cross-type array in the Netherlands; another near Canberra, Australia; and a very large circular array, also in Australia. The two-element interferometer at Caltech's Owens Valley Radio Observatory (OVRO) had successfully mapped a few dozen sources with a resolution of a few arcminutes. Pawsey visualized a new NRAO array bearing the same relation to these instruments that the Palomar 200-inch telescope bears to the 48-inch Schmidt telescope: the latter surveys and maps the sky while the former makes detailed examinations of interesting objects revealed by the surveys. Pawsey's notes, so far as the record shows, represent the genesis of the high-resolution astronomy program at NRAO. With his untimely death this program was temporarily interrupted.

As has been mentioned, under the sponsorship of the Office of Naval Research Bolton and his OVRO group at Caltech were operating successfully a two-element interferometer comprising two 90-foot paraboloids on a system of railway tracks. Some synthesis work had been done at decimeter wavelengths by 1962, and it was clear that the technique had great potential. Much of the attention of the group, however, was devoted to necessary preliminaries such as surveys and precise position measurements of compact sources at decimeter wavelengths. Their close association with a preeiminent group of optical astronomers encouraged them in these latter activities, so that optical identifications of radio sources could be made. Thus the techniques of aperture synthesis were not pressed as vigorously at Caltech as might have been expected. Even so, there is no doubt that this group constituted the principal American expertise in interferometry and aperture synthesis at the time. They were anxious to move ahead along the lines suggested by the report of the Pierce Committee.

In 1964, OVRO proposed to NSF that a four-element array be built, each element to be a 40-meter paraboloid. Funds were granted in 1965 to build a prototype antenna element, and this was done.

THE VLA PROJECT AT NRAO, TO 1968

By mid-1962, Heeschen had been acting director of NRAO for a few months, and presumably had discussed with Pawsey the subject of large arrays. In June, Heeschen assigned responsibilities[7] for various studies relating to the VLA and to a prospective two-element interferometer to five members of the scientific staff. In October, Marc Vinokur, a French scientist working at Green Bank, visited Caltech, the University of Illinois, and Stanford University to discuss antenna-array techniques, and at the end of the year a series of memos on technical design problems was written.[8]

In October 1962, Heeschen was appointed director of NRAO. In the same month, A.E. Whitford of the University of California's Lick Observatory issued an invitation[9] to representatives of all U.S. institutions with substantial radio astronomy programs to attend a meeting in November to discuss future instrumental needs of radio astronomy. This meeting resulted in a statement[10] of the principal needs for new instrumentation, including a "high-resolution array" for 3 cm wavelength. Also mentioned was the possible expansion of the OVRO interferometer to five or even one arcsecond resolution. Upon receiving the report, Heeschen responded[11] immediately to Whitford, urging that it be revised specifically to designate NRAO as the agency to build and operate the high-resolution array.

Whitford had been asked by the Committee on Science and Public Policy of the National Academy of Sciences (NAS) to act as chairman of a committee that would study the equipment needs of ground-based astronomy for the next 10 years, and the November meeting was concerned with the radio astronomical aspect of this study. Further correspondence[12] between Heeschen and Whitford ensured during December 1963 and January 1964. When the "Whitford Report" (NRC 1964) was published by the Academy in August 1964, it assumed great importance as an authoritative statement on the direction in which astronomical instrumentation should move. Perhaps inevitably, it resulted in a certain amount of jockeying for position among institutions desiring to undertake projects bearing this imprimatur. However, the report clearly states with respect to the "major high resolution instrument," "...the whole undertaking [is] a very complex one. The project thus appears to be beyond the capabilities of a single university and, in fact, falls naturally into the category of instruments that should be constructed by the National Radio Astronomy Observatory.[13]

By fiscal year 1963 (June 1963) the National Science Foundation was already specifically funding studies of the VLA at Green Bank.

NRAO had obtained funding for a second 85-foot equatorial paraboloid to be used in conjunction with the first one (the Howard Tatel Telescope) as an interferometer. This program was to serve the dual purpose of working research instrument and engineering test facility for VLA techniques. It was constructed in 1964 and both dishes were outfitted with receivers of 11 cm wavelength and the other electronic appurtenances of a single baseline interferometer. This facility became operational in the winter of 1964-65.

In the fall of 1964, this author joined the Green Bank staff (on leave from the University of Illinois) specifically to work on VLA studies. An informal group of the scientific staff was formed to experiment with the new interferometer and to formulate a tentative design philosophy for the VLA. The interferometer's maximum baseline at Green Bank was sufficient to give 8-arcsecond fringe spacing, and it soon became apparent that even the relatively unstable atmosphere of this locality would sustain aperture synthesis observations at this angular resolution.

Studies of array configurations and operational modes were undertaken, and in December 1965, "VLA Report #1" was issued. This report illustrated several possible array schemes and concluded that a fully correlated, earth-rotation synthesis array was the most appropriate. This scheme involved a number of antennas, each possible pair of which is connected as an interferometer. The number of interferometers is N (N-1)/2, where N is the number of antennas. Each interferometer provides one term in the Fourier series representing the brightness distribution of the source. As the earth rotates, all antennas track the source, and each baseline projection on the celestial sphere is rotated and foreshortened. Thus each interferometer pair produces a whole sequence of different Fourier components as the day progresses. The aggregate of all these components represents the Fourier transform of the source brightness pattern and can be converted into a map of the source by inverse Fourier transformation. The configuration recommended by the NRAO group was an equilateral, equiangular Y with arms 21 kilometers (km) long, each arm having 12 antennas 25 meters in diameter. This gives excellent synthesized beams throughout the sky, even on the celestial equator where more modest instruments perform poorly.

This report was submitted to NSF, who immediately responded that more substantial documentation was required. Studies continued at Green Bank, and later in Charlottesville, Virginia when many of the observatory staff moved there in 1966. A portable, 42-foot antenna was built and operated as an interferometer element at various sites up to 35 km from the 85-foot antennas, using a phase-compensating radio link in place of the usual coaxial cables to interconnect the antennas. This experiment gave reason to expect that 1-arcsecond resolution could be achieved by the VLA.

In April 1966, Heeschen formalized the VLA project organization by appointing a VLA Design Group consisting of 10 persons with Swenson as chairman. Four of the members were from outside institutions and served as consultants to the working group. Detailed studies of antenna structures and costs were subcontracted to industrial firms, site explorations and surveys were carried out, and array configurations were further investigated. In January 1967, a two-volume VLA Proposal was submitted to NSF (1967) and published in the public domain. In February 1967, Heeschen and Swenson informed NSF by letter[14] of the selection of the Plains of San Augustin near Socorro, New Mexico, as the preferred VLA site. The site selection was determined by topographic and meteorological considerations after a vigorous study of several possible locations. The site recommendation was not formally accepted by NSF until several years later; presumably, it was considered more appropriate that the site decision await governmental approval of the entire program.

The Green Bank interferometer had achieved some popularity as a research instrument, and a third 85-foot antenna was added on the original northeast-southwest baseline. All the electronics systems were upgraded and sophisticated computer hardware and software installed, giving it the best resolution and the best instrumental stability of any existing interferometer system. The hour-angle limitations of the telescopes and the skewed geographical orientation of the baseline limit its performance as a synthesis instrument, but in the absence of a better facility it has been extensively used for this purpose. Thus the NRAO staff acquired excellent experience in interferometry, and this experience was intimately involved in the design of the VLA.

The VLA proposal at the end of 1965 represented a perfectly workable program (estimated to cost

$52 million) to give excellent synthesized beam patterns on two frequencies. Sufficient work had been performed to be confident that reasonable solutions existed to all technical problems involved in the program. From this time on it can be said that NRAO was prepared to build the VLA at any time the project was authorized and funded. The NRAO VLA group, during the period 1964-1968, held many "public-relations" meetings[15] for members of the scientific community, papers (Heeschen 1967) on the VLA concept were presented at scientific meetings in the United States and abroad, and press releases[16] were prepared for the media.

COMPETING PROPOSALS FOR LARGE RADIO TELESCOPES

The NAS "Whitford Report" recommended construction of several instruments in addition to the very high-resolution array. These included expansion of the OVRO interferometer, two fully steerable 300-foot paraboloids, and approximately 15 special-purpose instruments averaging $2 million each. Studies of the "largest feasible steerable paraboloid" were to be conducted, looking toward the day when such a project could be realistically contemplated.

Three years later none of these projects had been initiated, except for the single 40-meter telescope built at OVRO. NSF needed guidance regarding priorities, as it was apparently unlikely that funds could be obtained for all the proposed instruments as well as for the programs desired by scientists of other disciplines. An "Ad Hoc Panel on Large Radio Astronomy Facilities" was established by NSF under the chairmanship of Robert Dicke of Princeton University to consider the available proposals and to indicate an order of priority. An NSF official involved in the establishment of the Dicke Panel commented on its composition, as follows:

> Constructing a panel to review major projects is not easy--particularly if the

embedding "scientific community" is small. Panel members should be sufficiently remote from the matter at hand so their own research careers are not dependent upon their recommendations. However, they must be sufficiently close to the matter at hand so their recommendations are perceptive and credible. I believe the Dicke Panel was an effort by the National Science Foundation to do that.

The radio astronomy groups in Cambridge, Massachusetts, including representatives from Harvard, the Massachusetts Institute of Technology, the Smithsonian Astrophysical Observatory, and the M.I.T. Lincoln Laboratory had organized the Cambridge Radio Observatory Committee (CAMROC) in 1963. In 1965, they issued a two-volume report of design objectives and preliminary studies and asked NSF for $1.1 million for detailed design studies of a 400-foot, fully steerable paraboloid. These funds were granted in November 1966. The following year CAMROC incorporated, expanded its representation to include 13 New England and New York universities, and renamed itself North East Radio Observatory Corporation (NEROC). In July 1967, NEROC submitted to NSF and the Dicke Panel a proposal for a 440-foot steerable antenna, enclosed in a radome and precise enough for operation at 5 cm wavelength. Its cost was estimated at $28 million. This proposal was revised in 1970 to provide for operation at 1.2 cm. This proposal was very thoroughly engineered and, along with the VLA, represented the most completely studied programs before the Dicke Panel.

In April 1966, Caltech submitted a proposal to NSF for the addition of seven 40-meter antennas to the one already existing at OVRO, to complete an east-west aperture-synthesis array. The cost was estimated at $15 million. It was to operate at a minimum wavelength of 3 cm with a synthesized beamwidth of 1.3 x 1.3 arcseconds over a 1.7 arcminute field.

Cornell University, which had built and operated the 1,000-foot Arecibo spherical reflector as a meter-wavelength facility for ionospheric scatter-sounding, planetary radar studies, and radio astronomy, wished to upgrade its surface and feed systems to permit operation at 10 cm wavelength. They proposed to do this for about $3 million.

A proposal was made by a consortium of Stanford, Caltech, the University of California, and the University of Michigan, called Associates in Radio Astronomy (ARA). ARA proposed a 100-meter antenna to be built at OVRO.

The Aeronomy Research Group of the University of Illinois submitted a proposal for a 100-meter dish, primarily for aeronomy, but with applications to radio astronomy as well. This proposal was submitted under the aegis of the Committee for Institutional Cooperation (CIC), an organization of midwestern universities for cooperation in all scholarly disciplines. The presentation was esentially a pro forma one, for information.

The Dicke Panel met in Washington, D.C., in July 1967. At that time, it heard presentations by all the groups submitting proposals, met several times in executive session, and questioned technical representatives of the VLA and OVRO groups. Their report was issued on August 14, 1967; its recommendations are unequivocal and are reproduced here verbatim:

> 1. The Panel urges that the proposal by the California Institute of Technology for an array of eight dishes be accepted in its entirety and funded as soon as possible, with an adequate operating budget, and with the proviso that at least 50% of the observing time be made nationally available;
>
> 2. The Panel urges that the proposal by Cornell University for upgrading the 1,000-foot spherical dish in Arecibo, Puerto Rico, to permit observations at

10 cm wavelength or shorter, be accepted in its entirety and funded as soon as possible, with anadequate operating budget, and with the proviso that at least 50% of the observing time for astronomy be made nationally available;

3. It is imperative that there be definitive studies directed towards assessing the potential of large, fixed, spherical dishes with multiple feeds (the Arecibo type) since this approach may lead to instruments of the largest collecting area;

4. The Panel recognizes the present need for a large array and ultimately for a very large array. Acceptance of the Caltech proposal (recommendation 1) will take care of the immediate needs for a large array. While it is too soon to make a decision as to the exact form a very large array should take, the ultimate need for such an array is evident;

The proposal by the National Radio Astronomy Observatory for a one-second-of-arc-resolution Very Large Array consisting of 36 dishes is a promising approach to an array of very high resolution, and the Panel urges continued funding of this design study. In this connection it is recommended that the NRAO concentrate in the next few years extensively on phase-coherent radio astronomical research at a resolution of one second of arc or better in order to show conclusively the expected tremendous stride forward that should result from a very large array with this resolution;

5. The Panel recognizes the success of the North East Radio Observatory Corporation in studies of a new type of vertical-truss, light-weight, fully steerable dish in a radome. However, it is the judgment of the Panel that the NEROC proposal should be deferred until more is known of the capabilities of an Arecibo-type spherical dish as a large precision

instrument, operating at short wavelengths. (See recommendation 3);

6. The proposal by the California Institute of Technology for the Associates in Radio Astronomy concerning the design of a conventional 330-foot dish should be declined because of the more revolutionary possibilities inherent in the Arecibo and NEROC concepts;

7. Very large radio telescopes, such as those under consideration by this Panel, present such unusual research opportunities and are so expensive that at least 50% of the time available for astronomy on such facilities shoudl be made nationally available to qualified visitors.

As can be seen, the panel gave the VLA a low priority. While recognizing that an instrument of its capability would ultimately be required, they preferred that an interim measure, the Owens Valley Array (OVA), be undertaken immediately while further study was given to the VLA.

The panel gave high priority to the upgrading of the Arecibo dish, and recommended deferring the NEROC project more or less indefinitely. The ARA proposal was rejected.

The report was promptly disseminated. NSF requested the Bureau of the Budget (BOB) to include the Arecibo upgrading and a first step in the OVA in the budget for fiscal year 1969; however, this was not done. Instead, Arecibo was included in the fiscal year 1970 budget, but this time it was eliminated in the NSF authorization legislation by the House of Representatives Committee on Science and Astronautics.[17]

Morale in the VLA group was considerably shaken by the Dicke Panel report. The management of NRAO formulated plans to continue engineering work on the project, and reorganized the VLA project staff. Swenson was relieved of overall management responsibility, which was assigned to Hein Hvatum, and was assigned to Hein Hvatum, and was assigned responsibility for the scientific studies aspect of the program. Swenson left NRAO in the spring of 1968.

Two years passed without any further significant decisions regarding major new radio telescopes. No funds were made available for new construction, but, in line with the Dicke Panel recommendations, NSF continued to supply funds for further engineering studies on teh VLA, for the NEROC 440-foot dish, and for the Arecibo upgrading. The Arecibo Observatory had been transferred to the cognizance of NSF and was to be regarded as a national facility, still operated by Cornell University. The Haystack antenna of the M.I.T. Lincoln Laboratory, a 120-foot precision radar antenna in a radome, became available for radio astronomy use under NEROC control.

THE SECOND DICKE PANEL

On June 9, 1969, NSF reconvenend the Dicke Panel in Washington to reconsider the proposals they had dealt with at their first meeting. Their report was issued on August 15, 1969, and contained the following (verbatim) recommendations:

> Two years have passed without the implementation of any of the 1967 recommendations of this Panel for the construction of major new radio astronomical telescopes. A need that was then urgent has now become critical. While our country has stood still, Great Britain, the Netherlands, Germany and India have started new, large radio telescopes and several are essentially complete and ready for operation.
>
> The ordering of the following recommendations is <u>not</u> on the basis of priority.
>
> The Panel reaffirms its previous recommendation that the Arecibo telescope be improved and that the Owens Valley Array be constructed. It recommends, with equal urgency, the construction of the large radome-enclosed fully steerable dish and the Very Large Array. Certain technical obstacles to the construction of the latter

two facilities have now been overcome. All of these facilities should be nationally available.

(a) The Panel is especially disappointed that the new surface of the 1,000-foot spherical dish in Arecibo, Puerto Rico, has not yet been constructed, and feels that the need for it is even more pressing now than it was earlier. It wishes to emphasize that the facility should be improved in its entirety and be made nationally available;

(b) The Panel sees no need to change its earlier recommendation regarding the Owens Valley Array. It again urges that the proposal by the California Institute of Technology for an array of eight dishes be accepted in its entirety and funded as soon as possible, with an adequate operating budget, and that it be made nationally available;

(c) The Panel recommends with equal urgency that the final design and construction of a nationally available fully steerable 440-foot dish enclosed by a radome be started now. It further recommends that this final design upgrade as large a portion of the dish as is feasible for use at 1.2 cm wavelength, and that improved transparency of the radome at this wavelength should be sought. An attempt should also be made to improve the pointing accuracy to be compatible with the resolution implied above;

(d) The Panel recognizes the need for the Very Large Array, as proposed by the National Radio Astronomy Observatory. Because of the long time required to construct this array, it strongly urges that an immediate start be made on its construction, and that this construction proceed in stages over a period of several years. At the completion of each stage, that portion of the Array should be operational and available for observations. The Panel considers the prompt implementation of this recommendation important to the continued vitality of the National Radio Astronomy Observatory;

(e) The Panel is impressed with the progress made in the study of methods for building very large steerable dishes, particularly in the application of the principle of homologous structure deformation. The Panel recommends that such studies be continued, but oriented towards the engineering design of a very large antenna useable down to wavelengths of 3 to 6 millimeters;

(f) The Panel submits that the roots of the success of U.S. radio astronomy lie in the universities. It would therefore be a mistake not to support, at a high level, the universities from which have come the astronomers who make radio astronomy such an outstanding science. The Panel therefore strongly urges that parallel to the support of the major facilities, the support of radio astronomy research and facilities be the universities be substnatially improved;

(g) It is important for the best progress of radio astronomy that unique facilities, such as those recommended in this report, be available to the maximum number of competent scientists and be responsive to the needs of the scientific community as a whole. For this reason, the Panel recommends that grants or contracts for Federal support of these facilities include not only a requirement that at least 50% of the observing time should be available to visitors, with priorities based on the relative merits of the proposals, but also require appropriate management arrangements to insure that policy is formed and operations are carried out with truly national representation and with the needs of visitors in mind. Ample electronic equipment and technical help should be provided so that the visitor, unfamiliar with the organization and perhaps less skilled in electronic matters, can effectively carry out his research. Sufficient operating funds to meet this need should be provided.

These recommendations were given equal weight in the report. This meant, given the chronic shortage of money for astronomical instruments, that NSF perforce had to assign priorities, a difficult task without current, inhouse experience in radio astronomical research. The Arecibo upgrading project was requested again for the fiscal year 1971 budget, this time successfully.[18]

NSF also requested the Bureau of the Budget to include in the fiscal year 1971 budget $2 million for initiating construction of the VLA. It was late in the budget cycle, so it was not included.[19] Various NSF officials, past and present, have commented unofficially on the selection of the VLA from among the several other projects recommended equally strongly by the Second Dicke Panel. Their opinions are somewhat diversified but seem to add up to the following:

-- The Advisory Panels supplied no clear-cut scientific rationale for the choice of priorities. This being the case, the best engineered and documented program was the one to choose. Furthermore, with the provision for Arecibo upgrading, a high-resolution instrument was called for as the next major innovation.
-- NRAO is an NSF-owned, contractor-operated laboratory. Its staff and the NSF staff had a close working relationship. NSF officials had

been closely associated with the VLA project since its conception in 1962. Millions of dollars had been spent on VLA planning. While NSF tried sincerely to be even handed, these factors certainly were important.

-- The VLA would be easy to defend in the Executive Branch and the Congress because of its excellent documentation (NEROC's proposal was also thoroughly documented, at NSF expense) and because it could, as a fall-back maneuver, be constructed in stages with each stage being scientifically useful (as could OVA).
-- An university research group owes its primary allegiance to its own institution and its own program, while a National Center (NRAO) is specifically established to serve the entire national community of its discipline. The sharing of facilities could be expected be accomplished more smoothly at NRAO than at the observatories making the competing proposals.

In any case, all agree that the decision to give the VLA top priority was made by NSF immediately after the Dicke Panel rendered its second report. An NSF official who was central to the decision-making process stated during the preparation of this case study:[20]

> In the process of decision making for science it is counter productive to buck the initial decision over into the Office of Management and Budget (OMB) or to Congress. The Foundation had made its decision following the Second Dicke Panel Report so, of course, the level of outside awareness was greater for VLA than for NEROC and Owens Valley Radio Observatory (OVRO). But that is necessary. A large project often takes several years to get underway. Therefore, it is incumbent upon the agency (NSF) to make a sound choice initially. By the same token an agency should be prepared to drop its selection, if the passage of time makes the project undesirable. However, an agency can hardly hope to make

progress if it runs back and forth to OMB with a different top priority every other month. Careful selection and continuity of effort are both important.

Although Congress was not asked for funds for VLA construction, money was available for continued engineering studies, including comparative studies of various possible sites. Through 1970 and 1971, effort was directed toward studies and documentation which would be needed to defend choice of site, configuration, and scale before the Office of Management and Budget (OMB, formerly BOB) of the Executive Branch and before the Congress. A smaller "mini-VLA" with only 12 antennas was designed as a contingency plan in the event that the full VLA be considered too expensive. (Apparently, OVA was not seriously considered for this role.) By 1971, OMB, the President's Office of Science and Technology (OST), the President's Science Advisory Committee (PSAC), and the science-cognizant committees of Congress were all very much aware of the VLA.

THE GREENSTEIN COMMITTEE

In early 1967, many influential U.S. scientists and science administrators felt that it was time to update the "Whitford Report," to reassess the needs of astronomy. Discussions among members of PSAC and the NAS Committee on Science and Public Policy, the NAS Division of Physical Sciences, and the Bureau of the Budget (BOB, later known as OMB) all focussed on such a study. BOB formally suggested such a study in 1968, in response to requests from NSF and the National Aeronautics and Space Administration (NASA) for several large astronomical programs. In January 1969, NSF asked the NAS Committee on Science and Public Policy to submit a proposal to NSF for funds for such a study. NAS submitted the proposal in May 1969. An ad hoc committee of scientists was first set up to nominate the membership and draft the program of the study group, with the advice of NASA and NSF.

Jesse Greenstein of Caltech served as chairman of this committee which included 23 well-known astronomers, three of whom were radio astronomers. A subcommittee on radio astronomy was formed with nine members, five of whom were also on the main panel. David Heeschen, director of NRAO and for many years the chief protagonist of the VLA, chaired the subcommittee, which also included representatives of NEROC, OVRO, and Cornell (Arecibo).[21]

The radio astronomy subcommittee met for the first time on November 10, 1969, with the intention of discussing the major facility requirements of radio astronomy. A representative of NSF attended that meeting.[22] He advised the subcommittee that NSF had already asked OMB to include the VLA in the fiscal year 1971 budget (this later proved to be unsuccessful), and suggested that it would be helpful if the subcommittee's report assigned first priority to the VLA. In about the same time frame, another NSF official spoke to the full Greenstein committee in the same vein.

The NSF "position" should be considered in the context of a budget for that particular year. NSF had asked for funds for the VLA in the fiscal year 1971 budget. If the scientific community were to find a serious flaw in that "position," it was unlikely that funds for some other option could be obtained until some year later than fiscal year 1971. The time scale for budget making was such that NSF would have had to make a final decision in 1969 to introduce a major item into the fiscal year 1971 budget.

This set the pattern for the radio astronomy discussions in teh Greenstein Committee and the radio astronomy subcommittee. There was vigorous debate within both bodies. The first "quick study" report[23] of the subcommittee to Greenstein endoresed the second Dicke Panel report without assigning priorities, and urged its earliest possible implementation.

By October 1970, a draft of another subcommittee report,[24] while still endorsing all the Dicke Panel recommendations, assigned equal first priorities to the VLA and to a 65-meter telescope for millimeter wavelengths, both NRAO proposals.

Harvey Brooks, chairman of the NAS Committee on Science and Public Policy, to whom the Greenstein panel reported, urged the establishment of priorities (Lubkin 1975). In November 1970, NSF Director William MacElroy wrote to the National Science Board, "In spite of the present fiscal stringencies, I am convinced that the U.S. must start on the VLA and initiate engineering studies for the High Precision Antenna if it is to maintain a strong position in astronomy."

NSF finally convinced the radio astronomy panelists that one instrument must be given first priority, and that it should be the VLA. It also convinced them that any other decision would be delayed well beyond fiscal year 1971. In early 1971, Greenstein was notified[25] by Heeschen that the radio astronomy panel had agreed on the VLA. NSF now had the approval of the radio astronomy panel of the Greenstein Committee.

On March 30, 1971, the radio astronomy subcommittee met with Carl York,[26] an assistant to Edward E. David, Jr., Science Advisor to the President. York arranged a meeting with David. Heeschen had informed the subcommittee that York had strongly urged that the radio astronomers present a united front, otherwise everything would be ruined. David informed the group, in effect, that the Executive Branch had decided to recommend the VLA to Congress.

Meanwhile the Greenstein Committee continued the preparation of its study report, "Astronomy and Astrophysics for the 1970's," (NRC 1972) in which was issued in two volumes by the National Academy of Sciences in April 1972. It recommendations are given here verbatim:

In spite of the diversity of interests and specialities of its membership, the Committee succeeded in defining with remarkable unanimity four programs of highest priority. In order of importance, these are:

1. A very large radio array, designed to attain resolution equivalent to that of a single radio telescope 26 miles in diameter; this should be accompanied by increased support of smaller radio programs and facilities at the universities or other smaller research laboratories;

2. An optical program that will vastly increase the efficiency of existing telescopes by use of modern electronic auxiliaries and at the same time create the new large telescopes necessary for research at the limits of the known universe;

3. A significant increase in support and development of the new field of infrared astronomy, including construction of a large ground-based infrared telescope, high-altitude balloon surveys, and design studies for a very large stratospheric telescope;

4. A program for x-ray and gamma-ray astronomy from a series of large orbiting High Energy Astronomical Observatories, supported by construction of ground-base optical and infrared telescopes.

The following items were also identified as being of high scientific importance, but the Committee agreed that their funding, although urgent, should not create a delay in funding the above items;

5. The construction of a very large millimeter-wavelength antenna to identify new complex molecules, to study their distribution in interstellar space, and to study quasars in their early, most explosive phases;

6. A doubling of support for astrophysical observations from aircraft, balloons, and rockets, at wavelengths ranging from the far infrared to gamma rays;

7. A continuation of the Orbiting Solar Observatories through OSO-L. -M. and -N. together with an updating of existing ground-based solar facilities;

8. A sizable increase of support for theoretical investigations, including an expansion of capability for numerical computation;

9. An expanded program of optical space astronomy, including high-resolution imagery and ultraviolet spectroscopy, leading to the launch of a large space telescope at the beginning of the next decade;

10. A large, steerable radio telescope designed to operate efficiently at wavelengths of 1 cm and longer to obtain observations with high angular resolution and record emission from more distant objects than is now possible;

11. Construction of several modern astrometric instruments at geographic locations chosen to permit systematic measurement of accurate positions, distances, and motions in both northern and southern hemisphere.

THE DECISION-MAKING PROCESS

The crucial decisions influencing the VLA up to this point could be listed as follows:

1. Endorsement of the VLA by the radio astronomy community through actions of the Pierce Committee, the Whitford Committee, the Dicke Panels, and the Greenstein Committee.
2. Decision by NSF to give first priority to the VLA rather than to one of the competing instruments.
3. Decision by OMB, with advice from OST, to provide a major facility for ground-base astronomy.

Stage 1, of course, occupied a whole decade. The scientists involved took the whole procedure very seriously, produced excellent documentation for their recommendations, and clearly influenced the thinking of the scientific community. However, in retrospect it is not clear whether it was crucial to the final outcome.

The rank and file members of the Radio Astronomy Subcommittee of the Greenstein Committee, having ascertained that they were, in effect, not in a position to establish their own priorities, decided to present a united front for the VLA. An anecdote[27] serves to illustrate the prevailing attitude at that time. The NEROC group had been seeking alternative means of funding for their proposed 440-foot paraboloid. The Smithsonian Astrophysical Observatory (SAO), colocated and jointly administered with the Harvard College Observatory, is a department of the Smithsonian Institution. The latter had agreed to sponsor the 440-foot telescope, and with the concurrence of NSF, had succeeded in having appropriate legislation introduced into Congress. At a meeting of the Greenstein Committee in the summer of 1971, Bernard F. Burke of M.I.T. became concerned that the Smithsonian bill would cause difficulties for the VLA. He telephoned some of his colleagues in NEROC for their concurrence, then approached Fred Whipple, Director of SAO, with the result that the bill was withdrawn.

Stage 2 also took several years. Several of the cognizant science administrators of NSF had been quite aware of NRAO activity in array investigation since at least 1962, and had gradually become committed to the idea of the VLA. The process of educating BOB/OMB and the Congress began very early.[28] For several years, NRAO had been provided with VLA study funds on the order of $500,000. These sums could have been buried in other budget items but, in order to make the bugetmakers and the Congress aware of the VLA and the design studies visible to all interested parties, the budget requests were explicitly stated and were discussed during hearings.

From beginning to end, Heeschen exerted constant pressure on NSF to promote the VLA. As director of a major national observatory, he had personal access to a higher level of NSF administrator than does a university scientist who is expected to submit proposals through a formal, anonymous reviewing process.

While the NSF administration was interested in the views of the advisory panels with respect to scientific priorities, those view could not automatically be translated into governmental decisions on priorities since the latter necessarily take other factors into consideration.[29] Of course, if a panel had stated that a given proposal were scientifically or technically unsound, it would have been discarded forthwith. That situation did not occur.

The preceding remarks were distilled from several interviews with NSF research-administration officials, past and present. While not all agreed exactly regarding motives and attitudes, these statements represent a consensus. To summarize, certain members of the NSF scientific staff arrived at a commitment to the VLA very early in the time span considered here, but the agency did not move until it was apparent that there was a reasonable amount of support from the scientific community and that the political and fiscal climate was advantageous. The collective decision of the Agency was made immediately following the Second Dicke Panel report. While it seems clear that the NSF bureaucracy was committed to the VLA as the first priority program, it is also clear that many individuals therein deeply regretted that insufficient funds existed to provide all the facilities requested by the Second Dicke Panel, for example.

A former director of NSF, Leland J. Haworth,[30] has stated in substance:

> Having established a National Center for a research discipline, the NSF cannot "let the center down," but must continue to support it with state-of-the-art facilities. At the same time, in astronomy, the NSF is the major source of support for

non-federal programs, and must attempt to support healthy programs at a number of universities and other institutions. These requirements are sometimes in conflict, especially in view of limited budgets, and require delicate management.

Stage 3 occurred over a shorter time span. OMB was well aware of NSF's longstanding interest in the VLA, but had not encouraged a start on construction because it was an expensive project, easily deferred. By 1969, there was a feeling in OST of underinvestment in ground-based astronomy because of the glamour of the space age and the powerful pro-NASA sentiment in Congress. A substantial investment in ground-based astronomy was desirable. Some peripheral issues bore on the question:[31] in the space-astronomy area the High-Energy Astronomical Observatory satellite (HEAO) had high priority; more sohpisticated electronics were enhancing the performance of many optical telescopes and two large, new optical telescopes were being built; the Department of Defense was phasing out radio astronomy support. Clearly radio astronomy needed help more urgently than other branches of the discipline.

Cuts in the space program and in support for accelerators had given the Nixon Administration a bad image among scientists, and the Administration was anxious to rectify this situation. Radio astronomy was originally an American discovery--many of the most important subsequent discoveries have been American. However, there has been no improvement in instrumentation in this country for many years, whereas the British, Dutch, and Germans have made outstanding advances. It was decided in OST/OMB to build a large radio telescope. The available proposal with the greatest visibility was the VLA; its planning, engineering, and documentation were comprehensive and meticulous. NSF assured that the radio astronomy community supported the VLA. Conflicts with the space astronomy program made it important to keep costs to a minimum, and the ability to fund the VLA on an incremental basis was a significant advantage.

Carl M. York, a physicist on the staff of OST, was assigned responsibility for the VLA. His job was to see that all agencies of the Executive Branch were properly informed, that the unequivocal support of the astronomical community was obtained, that all necessary documentation and approvals were in order, and that proper procedures were followed so that any challenges during Congressional hearings could be answered with confidence. York worked with Hugh Loweth of OMB on a "crosscut" review, in which government-supported astronomy programs of all agencies were discussed. Russell Drew of OST had the responsibility for space science, and he and York decided to arrive at a compromise between the requirements of space and ground-based astronomy. Loweth presented the various alternatives to Caspar Weinberger, director of OMB, and Donald Rice, assistant director for science, and it was decided to fund the full VLA in yearly stages and to fund a less expensive version of HEAO.

Edward E. David, Jr.,[32] at that time the President's Science Advisor and head of OST, endorsed the VLA and discussed it with Weinberger. David recently stated that he was unaware of competitive telescope proposals, and that he does not recall seeing either Dicke Report. When asked whether or not the approval of the VLA had any bearing on the 1972 presidential election, he replied that it did not. David stated that he supported the VLA with something less than complete enthusiasm for the reason that huge instruments themselves tend to become the rationale for scientific activity rather than the search for new scientific knowledge. He distrusts very large research instruments because they rob scientists of their flexibility and limit their research options. Of course, astronomy and high-energy physics must have large instruments, but he cautioned that one should proceed with restraint and seek less elaborate, less expensive alternatives where possible.

Thus the Executive Branch decided to propose the VLA to Congress. NSF presented its plan at an authorization hearing before the House of Representatives Committee on Science and Astronautics, Subcommittee on Science, Research, and Development, in March 1972.

CONGRESSIONAL ACTION

The staff of the House Committee on Science and Astronautics had been generally kept apprised[33] of the VLA program through several years of requests for planning and engineering funds. Both the congressional staff and the NSF staff have observed that executive agencies tend to introduce Congress to these large projects gradually. The first extensive exposure to the VLA began in October 1971. NSF assured the committee that the astronomical community was solidly behind the VLA, and it had the Greenstein Report to back up this statement.

Apparently the VLA budget passed the scrutiny of the Congress with little difficulty.[34] The first year's appropriation was only $3 million, and it was intended that it be followed by seven consecutive years of level funding at $10 million per year plus a final year, fiscal year 1981, at $3 million.

Congress had become wary of inadequately planned programs which escalated in cost in an unacceptable way after the initial appropriations were made. Thus the staff of the Committee on Science and Astronautics (later Science and Technology) made a special investigation of the VLA in 1974 and 1975, including trips to Charlottesville for thorough briefings by the NRAO. John D. Holmfeld[35] of the Committee staff prepared an extensive exhibit on the VLA which was printed in the record[36] of the Hearings on H.R. 12816 (superseded by H.R. 13999) before the Subcommittee on Science, Research, and Development of the Committee on Science and Astronautics, March 12-19, 1974. Holmfeld stated that the VLA project appeared to have been exceptionally thoroughly engineered and cost-estimated.

On August 14, 1972, President Nixon signed into law the appropriation bill, H.R. 15093, containing the initial funding for the VLA.

Its authorization and the appropriation of its first year's construction budget did not eliminate all hazards to the VLA, as the following anecdote[37] illustrates. NSF appropriations are included in the same bill as those of housing, war veterans' services, selective service, space, and securities regulation. In October 1973, when the first of the $10 million VLA construction budget increments was being discussed in the House of Representatives, one Congressman grumbled that "the stars will still be shining in 20 or 30 years," and that the money was needed for more urgent projects. In the subsequent voting, the $10 million was first authorized in the authorization bill and then deleted in the appropriations bill, many members having voted both for and against the VLA. (This is not an unusual situation. The authorization bill establishes the outer limits of a program, while the appropriations bill picks out fundable subareas within those limits.) The second action had the effect of killing the VLA; the only remedy was to have the funds restored by the Senate. By chance, Senator Joseph M. Montoya, Congressman Harold Runnels, and Governor Bruce King, all of New Mexico where the VLA site is situated, were travelling to Washington together, and discussed possible action. NSF Director H.Guyford Stever made a strong plea to the Senate. Senator Montoya's membership on the Senate Appropriations Committee gave him a strategic advantage. He interceded with Senator William Proxmire, chairman of the subcommittee that deals with science, and sent letters to the subcommittee's other members. The Senate bill had the $10 million restored.

Now is was necessary to compromise with the VLA-less House bill. At a conference of the House and Senate Appropriations Committees, the simplest compromise was reached: half the money was restored. The hope in NSF and NRAO was that the missing $5 million would be restored in subsequent years, and this, in fact, has occurred.

EPILOGUE

As of November 1977, <u>eleven</u> of the VLA antennas have been completed on the Plains of San Augustin and the balance are under contract. Prior to fiscal year 1977, $37 million has been appropriated by Congress. The buildings and utilities at the site have been completed and 15 kilometers of the eventual 61 kilometers of railway track are scheduled for completion by September 1976. The computers are in operation. Astronomical observations are underway with several antennas.

The project is essentially on schedule and nearly within the budget proposed at the time the initial authorization was granted. Provided the remaining funds are appropriated as originally scheduled, the full VLA, consisting of 27 antennas and 61 km of railway track, is expected to be in operation in 1980, a total of $78 million having been spent.

The instrument will be operable on four wavelength bands from 1.3 cm to 21 cm, and will be able to synthesize two maps simulatneously, on different wavelengths or with polarization data, in a 12-hour observing period. At 1.3 cm, the best angular resolution will be 0.14 arcsecond (assuming no atmospheric degradation); at 21 cm, the resolution will be two arcseconds. Spectrographic capability is also being provided; in effect, the instrument will provide simultaneous maps of a cosmic object on 256 different but close-spaced wavelengths. The instrument thus has extremely impressive technical characteristics.

By its very nature, the VLA is capable of useful research in a partially completed state. Thus it is anticipated that scientifically useful data can be obtained at each stage of construction. The number of antennas and the extent of the railway tracks will continue to grow, and each increment of the system will be incorporated into the working system, until, eventually, the entire VLA is "on line."

The VLA apparently will not solve the problem of the enigmatic quasars, as was hoped when it was conceived. The quasars' critical angular dimensions are so small as to require the use of "VLBI" (very-long-baseline interferometry), with baselines of continental or intercontinental extent. The VLBI technique will eventually be used in the full aperture-synthesis mode to make maps of quasars and radio galaxies at the limits of the observable universe. In order to do this, it will be necessary to use the VLA to map the field surrounding the object in order to resolve ambiguities (aliasing). Thus the VLA can, in a sense, be extended to global dimensions, and must be in order to solve some of the most pressing problems of current astronomy. Other current radio astronomical problems exist of great scientific import to which the VLA will contribute little. These include millimeter-wavelength studies, that is, those astrochemical problems involving very small or very large molecules, and problems of galactic and extragalactic astronomy involving diffuse sources of very low brightness.

When complete, the VLA will produce stupendous amounts of data, particularly in the spectrographic mode. Even in the continuum mode, it could make, say, 600 maps of cosmic objects per year, and each of these would have such intricate detail as to merit analysis by an astronomer for days, perhaps weeks or months. There is some concern in the astronomical community that there may not be enough support for astronomical research to assure that this magnificent instrument is appropriately utilized. Concurrently, there is concern that the capacity of the VLA to produce enormous quantities of data about those cosmic sources within its purview may result in decreased support for the study of the other aspects of radio astronomy.

These questions notwithstanding, the astronomical community looks with enthusiastic anticipation toward the substantial expansion of astronomical knowledge which must result from the use of such a powerful research tool.[38]

NOTES

1 All source materials collected for this paper have been deposited with the University of Illinois Archives, Urbana, IL 61801. Reference: G.W. Swenson Papers, Record Series 11/6/21.

2 A number of radio astronomy programs of the sun and Jupiter are omitted from this discussion as having little bearing on the VLA case history.

3 AUI also has some "at-large" trustees elected by its board without regard for institutional affiliation. Also see the case study on the establishment of the Brookhaven National Laboratory by Charles Dunbar, Leland Haworth, and J.B.H. Kuper.

4 See a letter from Pawsey to W.C. Erickson, University of Maryland, June 27, 1962, regarding a large array; a letter from Pawsey to P. Scheuer, Cambridge University, July 4, 1962; and a memo by Pawsey on future programs at Green Bank, July 17, 1962.

5 Memo by Pawsey on future programs at Green Bank, July 17, 1962.

6 Letter from Pawsey to W.C. Erickson, University of Maryland, June 27, 1962; and letter from

Pawsey to P. Scheuer, Cambridge University, July 4, 1962.

7 Memo from Heeschen to J.W. Findlay, NRAO, et al., September 7, 1962, assigning responsibility for studies relating to the VLA.

8 Memos by Vinokur and N. Keen, December 10 and 11, 1962, on VLA technical topics; memo by Vinokur, December 31, 1962, on "Very Large Antenna"; letter from Heeschen to Geoffrey Keller, NSF, November 19, 1962 regarding a high-resolution antenna system and draft "request for proposal" by J.W. Findlay, NRAO, November 5, 1962 concerning VLA design studies.

9 Letters from Whitford to Heeschen, October 16 and 25, 1963.

10 Minutes of November 1 and 2, 1963, meeting of radio astronomers, by Whitford, November 11, 1963.

11 Letters from Heeschen to Whitford, October 14, 1963, and November 26, 1963. Further correspondence in December 1963 and January 1964.

12 Letters from Heeschen to Whitford, October 14, 1963, and November 26, 1963. Further correspondence in December 1963 and January 1964. Letters from Whitford to Heeschen, October 16 and 25, 1963.

13 It should be noted that a number of complex and very large scientific facilities in other branches of science have been successfully constructed and operated by single universities.

14 Letter from Swenson and Heeschen to Randall M. Robertson, NSF, February 16, 1967.

15 Letter from Swenson to A. Sandage, et al., Mt. Wilson and Palomas Observatories, October 26, 1964, invitation to a VLA meeting at Green Bank.

16 "A Proposed Very Large Radio Telescope Array," Sky and Telescope XXXIII, No. 4, April 1967.

17 Interview with W.E. Wright, NSF, June 17, 1975; and interview with Leland Haworth, former director of NSF, July 26, 1976, and following.

18 Interview with T.B. Owen, former NSF official, June 17, 1975; interview with W.E. Wright, NSF, June 17, 1975; and interview with Leland Haworth, NSF, July 26, 1976, and following.

19 Interview with W.E. Wright, NSF, June 17, 1975; and interview with Leland Haworth, NSF, July 26, 1976, and following.

20 Letter from W.E. Wright, NSF, to David Beckler, National Academy of Sciences, June 17, 1976.

21 Minutes, correspondence, and working papers of the Astronomy Survey Committee (Greenstein Committee).

22 Minutes, correspondence, and working papers of the Astronomy Survey Committee (Greenstein Committee); interview with Robert Fleischer, NSF, June 17, 1975; and interview with M.H. Cohen, California Institute of Technology, January 15, 1976.

23 Minutes, correspondence, and working papers of the Astronomy Survey Committee (Greenstein Committee).

24 Minutes, correspondence, and working papers of the Astronomy Survey Committee (Greenstein Committee).

25 Minutes, correspondence, and working papers of the Astronomy Survey Committee (Greenstein Commitee).

26 Minutes, correspondence, and working papers of the Astronomy Survey Committee (Greenstein Committee); and interview with York, OST, July 24, 1975.

27 Minutes, correspondence, and working papers of the Astronomy Survey Committee (Greenstein Committee); interview with Robert Fleischer, NSF, June 17, 1975; and interview with Gloria B. Lubkin, June 1975.

28 Letter from W.E. Wright, NSF, to David Beckler, National Academy of Sciences, June 17, 1976, and interview with Randall M. Robertson, NSF, June 19, 1975.

29 Interview with W.E. Wright, NSF, June 17, 1975; letter from Wright to David Beckler, National Academy of Sciences, June 17, 1976, and interview with Randall M. Robertson, NSF, June 19, 1975.

30 Interview with Haworth, NSF, July 26, and following.

31 Interview with Russell Drew, NSF, June 18, 1975; and interview with York, OST, July 24, 1975.

32 Interview with E.E. David, Jr., OST, February 2, 1976.

33 Interview with T.B. Owen, former NSF official, June 17, 1975; interview with John D. Holmfeld, congressional staff, June 18, 1975; interview with Randall M. Robertson, NSF, June 19, 1975; and interview with York, OST, July 24, 1975.

34 Interview with John D. Holmfeld, congressional staff, June 18, 1975; and interview with York, OST, July 24, 1975.

35 Interview with Holmfeld, congressional staff, June 18, 1975.

36 Hearings on H.R. 12816 (superseded by H.R. 13999) before the Subcommittee on Science, Research, and Development of the Committee on Science and Astronautics, U.S. House of Representatives, 93rd Congress, 2nd Session.

37 Interview of Bernard F. Burke by Gloria Lubkin, May 12, 1975.

38 Interviews with Daniel Hunt and Claude Kellett, NSF (June 18, 1975) and with Jesse L. Greenstein (January 15, 1976) were also used in preparing this paper.