NATIONAL RADIO ASTRONOMY OBSERVATORY

LONG RANGE PLANS CY 1981 - CY 1985

INTRODUCTION

Since radio astronomy is an observational, not an experimental science, progress in this field tends to be paced by the continual evolution of the instruments and techniques used to make radio astronomical observations. Over the past five years the advances made in radio astronomy at the NRAO have come about as a result of improvements made in the sensitivity and resolution of the telescopes and instrumentation used at traditional radio frequencies as well as by the efforts made to explore new domains by providing opportunities for observations at increasingly higher frequencies. This two-fold thrust--to improve and expand the capabilities of the existing NRAO telescopes and instrumentation and also to vigorously pursue an expansion of radio astronomical research at higher frequencies--will be the challenge, and the opportunity, for the Observatory over the next half-decade.

The plan outlined below describes the principal directions that the National Radio Astronomy Observatory should follow in the years CY 1981-CY 1985 in order that it may continually provide facilities commensurate with the requirements of the astronomical community. To this end, goals have been set for each of the six operating units of the Observatory and for the development of new instrumentation and the construction of new facilities. The funding levels required to support this plan are summarized in Table I.

I. BASIC RESEARCH SUPPORT

This unit is comprised of the scientific staff, visiting scientists holding appointments at the Observatory, and the graduate and undergraduate students involved with the various student programs at the Observatory.

The scientific staff of the Observatory, in addition to conducting their individual research programs, serve a critical role in the development and operation of new instrumentation. As active research scientists they are able to support and augment the advice received from the Users' Committee about new directions for the science and new technical opportunities for instrumentation. Moreover, since the staff is in residence, they are able to provide scientific help with a continuity and regularity that would be difficult to obtain solely with outside groups of scientists. Thus, for example, during the construction of new instrumentation the staff may serve on working groups to ensure that the instrumentation will meet the desired scientific goals. At the end of the construction phase they are called upon to debug and calibrate the instrument, and to advise visiting observers on the optimum use of the instrument. Recent specific examples of such staff activity include the design of the 25-m millimeter wavelength telescope, the design and implementation of map processing techniques for VLA and VLBI data, and the upgrading in the high-frequency performance of the 140-ft telescope.

With the increased data rates which have arisen both because of better electronics and because of more powerful telescope systems (the VLA, the VLBI network), and with the increasingly sophisticated data analysis techniques that are used, the current staff level of 28 is too small to meet the demands which are placed on them. The Long Range Plan allows for a growth in this group throughout the planning period to a level of 40 by the end of 1985.

II. TECHNICAL SUPPORT AND DEVELOPMENT

Included in this unit are the Central Electronics Laboratory, responsible for the development of devices to be used as components in radiometers or in other Observatory-wide applications of special technology (for example, digital correlators, spectrum expanders); the Central Computer Division, responsible for the equipment used in general data processing and analysis, as well as for the operation of the MK II processor; the Engineering Division, which provides the design effort required in the construction of new facilities and provides engineering support for the existing facilities; and the Library and Technical Illustrations staff.

During the planning period additional electronics personnel will be required to support millimeter wavelength instrumentation. The group will be involved both in the development of improved radiometers for the Tucson Operations and in the construction of electronics for the 25-m telescope. The current staff in the computer division will be increased by two or three people; the principal task in this group will be in acquiring and operating an expanded central computer facility, described in greater detail below. The Engineering Division will be heavily committed in the construction of the 25-m telescope. The small group in Library and Illustrations will continue at the current level.

An Expanded Central Computer Facility

The central computer used at the NRAO is an IBM 360/65, and it will be adequate for the needs of the Observatory through the end of 1980. The machine was recently purchased, because the purchase price was less than the cost of a lease for this period.

During the planning period the computing facility will be required to support activities in the areas of single-dish data, VLBI post-observation processing, VLA post-observation processing, and general Observatory programs in telescope design, theory and the like.

With the advent of sophisticated on-line computer systems, coupled with the much greater data rates provided by the improved instruments, the nature of the support requested of the central computer is changing. The amount of computing related to daily support of telescope operations is reduced, and the amount of post-observation analysis is increasing. Most of the latter work deals with two-dimensional problems not only for VLA and VLBI data, as was expected, but also for single-dish spectral-line mapping.

Concurrent with the changing scientific needs are the changing technical considerations to be evaluated in meeting these needs. Minicomputers now provide flexibility and economy for many of the required tasks. The Observatory's computer center will make effective use of a mixture of dedicated minicomputers and a large central processor.

In the benchmark system now being designed the central computer provides batch capability for the map processing tasks which do not require interactive processing. It will of course also satisfy the general computing needs, including access to the mass storage device and programming and text-editing capability. The associated minicomputers will be almost entirely devoted to map processing, and will by design be interactive. Much of the workload in terms of computer cycles is handled by the peripheral processors. The mass store provides a capability to store the large amounts of data produced, for example, by the VLA when it operates in the spectral-line mode. It is designed to support several observers, each of whom is selecting data from an assigned data base.

The annual rental for the central machine having the needed computing power is estimated to be approximately $900k.

III. GREEN BANK OPERATIONS

The five divisions of this unit are devoted to the support of observations with the 300-ft and 140-ft telescopes.

At the outset of the planning period, the next generation of radiometers based on maser amplifiers and upconverters will be installed on the two telescopes. At this point it will be difficult to improve on the radiometers, as we anticipate they will provide complete coverage throughout the range of frequencies 300 MHz - 26 GHz, with an exceptionally low noise figure of about 30 K. The limitations to increased sensitivity on the Green Bank telescopes will then not be the radiometers but the telescopes themselves. We foresee therefore that a major effort will be required to upgrade the telescopes' performance: Improved feed legs to minimize aperture blockage, a controllable subreflector, and a reconfiguration or resetting of the telescopes' surfaces are representative areas that need detailed investigation.

It is expected that the demand for observing time on each of the telescopes will continue to be high. The 300-ft telescope, as a transit telescope, is well suited to studies of classes of objects--for example, the hydrogen content in selected groups of galaxies; the nature of the radio emission from clusters of galaxies--and, with receiver sensitivities that enable confusion to be reached in one transit, studies can be taken to lower flux levels than were previously possible. The 140-ft will undertake little continuum work, apart from the VLBI, although it may be required to support VLA studies in complex fields. However, the spectral-line studies, especially in areas of galactic structure, dark clouds, and interstellar chemistry, will continue to have a major part of the observing time. The 140-ft will of course continue as a principal element in the VLBI network. With the advent of new recording equipment, coupled with the availability of an increasing number of well-equipped network stations, the study of compact sources may lead to fundamental scientific discoveries.

This Long Range Plan envisions a reduction in the Green Bank staff levels of about eight percent during the planning period. The Plan contains no provision for operating the interferometer. If operations of that instrument on behalf of the USNO are continued, funds beyond those shown in Table I will be required.

IV. MILLIMETER-WAVELENGTH OPERATIONS

The current staff level of 24 people in Tucson appears to be adequate for support of operations with the 36-ft telescope. In anticipation of the 25-m telescope, no major improvements are planned for the 36-ft, although some modifications (for example, the telescope drive system) will be made. In addition, some major refurbishing, such as recovering the existing astrodome, will be necessary.

The principal activity in this area, apart from the construction of the 25-m telescope, will be the development of improved radiometers, initially for the 36-ft but ultimately for the 25-m as well. This activity is provided for in the Other Observing Equipment budget, especially during 1981-1983, and in the personnel levels of the Central Laboratory. Improvements will also be sought in the area of millimeter feeds.

With the completion of the 25-m, a new telescope group will have to be formed in Hawaii. This group, totalling 27 people, should be organized beginning in 1983, to assist in the completion and calibration of the telescope.

The current plan makes no provision for the incremental cost associated with the operation by the NRAO of the Caltech 10-m submillimeter telescope. The plan will be modified to include this feature if the proposed collaboration comes to pass.

V. VLA OPERATIONS

The operations staff will continue to grow until 1981. When the array becomes fully operational, it reaches a level of 111 people. The plan provides for an additional nine people by 1985.

Because of the speed, versatility, and complexity of the VLA, the operating staff must face a number of challenges during the early years. First, the maintenance strategy and schedule now being developed will undoubtedly have to be refined as experience is gained in operation. Second, it is anticipated that large numbers of observers whose primary experience is at other wavelengths (optical, infrared, x-ray) will use the VLA either in coordination with or to complement observations made on other telescopes. These observers will require a higher degree of support from the NRAO staff than has been necessary with the other telescopes. Third, there will be increasing interest in map processing techniques, including the detailed comparison and analysis of maps made with greatly differing telescopes. These techniques will be explored and developed at a number of observatories, but there is no question that, because of the VLA, the NRAO will have to have a heavy involvement. Finally, the VLA staff will carry the burden of the development and installation of the new instrumentation which will be required over the years to keep the VLA at the state-of-the-art.

VI. GENERAL AND ADMINISTRATION

This unit includes the personnel in the Director's Office, the Fiscal Office, and in Business Management. It also has the budget for the AUI Management Fee and for the rent and upkeep of the Charlottesville buildings. Growth in this unit will be kept to a minimum.

VII. NON-EXPENDABLE EQUIPMENT

The principal item in these funds is Other Observing Equipment (OOE), which includes new radiometers, advanced electronics, and updated computing facilities necessary to keep the NRAO telescopes at the state-of-the-art. It is impossible to overemphasize the importance of this activity to both the quality and the kind of the research that can be undertaken with the Observatory's instruments.

Because of the rapidly changing technology, it is difficult to discuss in detail the particular devices that will be of interest five to seven years hence. However, it is clear that the NRAO will need to develop and produce instrumentation in the following areas:

1. <u>The VLA</u> - Beginning in 1981, additional instrumentation for the VLA will require approximately $1M per year. The VLA can readily

accommodate advances in technology, particularly in the general area of receiver front-ends. Among the projects that could increase the power of the VLA, using OOE funds, are the addition of low-noise preamplifiers at 2 and 1.3 cm, thereby increasing the sensitivity by a factor of 3 at these wavelengths, and the addition of a decimeter wavelength system (probably about 50 cm) to enable the VLA to study faint sources with steep spectral indices. Another activity of possible interest would be the development of a radiometer to measure the total water vapor in the ray path over each array element; data from such devices could in principle be used to correct for atmospheric-induced phase fluctuations.

2. Millimeter wavelengths - Development of radiometers for these wavelengths continues to be high priority for the NRAO, especially as the 25-m telescope comes to fruition towards the end of the planning period. Current emphasis is on the production of an improved 3-mm radiometer, and on a system for 1.3 mm. The development of systems for use at 800 μm will have to be started. Presently available instruments are still far short of the theoretical sensitivity limits, so there is considerable room for improvement. Unfortunately, the development of these devices is still somewhat of an art, and the rate of progress will therefore be unpredictable.

3. VLBI support - The current plan does not make provision for the construction of a new processing unit. However, there are a number of important activities which will require OOE funds. The NRAO will continue to support VLBI observing with both MKII and MKIII terminals, and will build additional terminals as needed. Spectral-line VLBI will continue to be run with MKII for many years, and some modifications and improvements to the MKII processor are planned Finally, as the use of seven to ten elements in the network becomes more common, the users of the network will face many of the same map-handling problems that the VLA users will, and the NRAO plans to develop a system which will enable VLBI data, processed on either the MKII or MKIII processor, to be analyzed with the VLA system now under development.

4. Centimeter and decimeter wavelengths - As was described earlier, the maser-based systems now being developed will serve as the principal radiometers at centimeter wavelengths throughout the planning period. The principal development effort will concentrate on better feeds, on the reduction of the numerous small contributions to the overall system temperature (for example, losses in waveguide and in switches), and on general radiometer systems. There is some interest in multibeam techniques, although the application of such techniques is perhaps more attractive at millimeter wavelengths.

5. Computing systems - The capability of the central computing system at the NRAO will have to be expanded during the planning period, as was described in Section II. In addition to the main computer, it is anticipated that OOE funds will be required for additional tape drives, disks, and minicomputers used either at the telescopes or for analysis and display of the data.

VIII. CONSTRUCTION AND INSTALLATION

(a) The Very Large Array

The construction and installation of the Very Large Array will be completed by the end of 1980. The project staff will be disbanded, with a number of employees transferring to the operating staff.

(b) The 25-m Millimeter Wavelength Telescope

As part of its long-range planning, the NRAO periodically reviews the capabilities of its various telescopes in the light of the continually changing research requirements which are placed on them. Guided by the millimeter astronomy community, we have concluded that advances in millimeter astronomy require a telescope having higher surface precision and larger collecting area than any now available. A proposal for such a telescope--the 25-m millimeter wavelength telescope--is before the National Science Foundation. The Long Range Plan provides for the construction and subsequent operation of this telescope.

Many exciting developments have occurred in millimeter-wave astronomy in the past six years, as the spectral range down to wavelengths 0.8 mm has opened. Millimeter-wave spectroscopy has shown the existence of a bewildering array of complex molecules in interstellar clouds and opened up whole new fields of investigation of great importance to molecular chemistry, the physics and chemistry of the interstellar medium, and star formation. Continuum observations of various galaxies and external galactic objects have indicated that the millimeter-wave region will be most important in understanding problems of energy mechanisms and time variations.

Spectroscopically, interstellar molecules have provided the first astrophysical probe of the dense regions of the interstellar medium out of which stars form. Their millimeter wavelength emission lines enable astronomers to see inside the interstellar dust clouds. We have glimpsed an intricate relationship between molecular masers, powerful infrared sources, dense molecular clouds containing species not previously known terrestrially, and compact HII regions. Only with larger telescopes will the characteristics of these star-forming regions become clearer. Higher resolution will also permit an attack on the interesting problems related to molecular clouds that surround highly evolved stars. Among these are whether evolved carbon stars are progenitors of planetary nebulae, and whether circumstellar molecular shells release significant quantities of molecules into interstellar space. Nucleosynthesis of elements in these stars will be better studied through detailed observations of different isotopic molecular species. A larger telescope is also necessary to follow up the recent detection of molecules in external galaxies, by relating in detail the physical state of the gas to morphological type. At short millimeter-wavelengths, presently inaccessible, one can bring a whole new class of molecules into radio astronomy, those with only one heavy atom. These will permit for the first time a study of interstellar regions of intermediate density.

Increased resolution, sensitivity, and wavelength capability will also open up many important areas of research in the continuum. The conspicuous gap between radio and infrared observations will be narrowed. Theoretical mechanisms for the energetics and time variations in quasars and active galaxies will be most critically tested in this region. In our own galaxy, the interaction of newly formed stars with surrounding dust clouds, of solar winds with the ambient interstellar medium, of ionized and neutral gas, and of dust grains and molecules, will all be capable of study for the first time. X-ray sources, binary star systems, and novae all pose current problems that should yield to a more powerful instrument.

The 25-m telescope provides a major improvement in sensitivity, resolution, and operating wavelength range over existing instruments. The design goals are a diameter of 25 meters, a surface error of 75 μm rms, and a pointing error of 1.2 arcsec rms. The design is based on the concept of homologous deformation, in which the reflector support structure remains parabolic in shape (but may change its focal length) as its aspect changes relative to gravity. The telescope is an altitude-azimuth, wheel-and-track instrument weighing 168 tons. The reflecting surface consists of 528 adjustable plates, supported by 44 intermediate structures of four types, themselves each designed to deform homologously under gravity. The intermediate structures are supported by 60 "homologous points" of the main homologous backup structure.

The performance of the telescope has been analyzed in detail for a varity of non-ideal ambient conditions. The pointing accuracy is adequate for wind speeds under about 20 mph and under most expected temperature conditions. The surface accuracy deteriorates significantly under temperature gradients larger than about 1° C over the structure. Thus, short millimeter-wave performance is not possible under sunlit or highly windy conditions. For these reasons the telescope must be housed in some form of enclosure.

Two types of enclosure are possible, in principle. One, the radome, consists of a space frame of quasi-randomly oriented members covered with a membrane of high radio transparency. The other, the astrodome, consists of a rotatable steel dome having a slit which can be closed in poor weather. The slit cover is itself a radome section, which will transmit radio waves through it. Although the available membranes have excellent transmission at frequencies below approximately 150 GHz, their transmissivity degrades rapidly at extremely high frequencies. So as not to restrict the performance of the 25-m telescope at these frequencies, the NRAO has chosen an astrodome for the telescope enclosure, despite its higher cost.

In choosing a site for such a telescope, the prime consideration is the significant absorption by atmospheric water vapor--particularly at extremely high frequencies. Low latitude is also important, because most millimeter-wave astronomy is involved with the inner regions of our galaxy. Of the several sites on U.S. soil which were considered, the one which best meets both of these requirements is Mauna Kea, an extinct volcano on the Island of Hawaii. An additional advantage of this site is its particularly favorable seasonal weather pattern and its easy access compared to other high altitude sites.

The Long Range Plan shows funding on a three-year plan, enabling the telescope to be completed by the middle of 1984, at a total cost of approximately 25 million dollars. The cost estimates are derived from the second volume of the proposal. Other funding schedules are feasible, but would result both in further delay in this badly needed telescope and in an increased cost of the project.

TABLE 1

(dollars in millions)

	CY 1978 (Actual)*	CY 1979 (Estimate)*	CY 1980	CY 1981	CY 1982	CY 1983	CY 1984	CY 1985
I. SCIENTIFIC RESEARCH								
A. Operations								
Research Support[1]	0.92	1.15	1.28	1.39	1.54	1.67	1.84	2.00
Technical Support & Development[2]	1.74	1.86	1.98	2.88	3.17	3.50	3.55	3.83
Green Bank Operations	2.80	3.01	2.98	3.11	3.29	3.49	3.70	3.88
Tucson Operations	0.79	0.93	1.06	1.07	1.14	1.22	1.30	1.40
25-m Telescope Operations	-	-	-	-	-	0.50	1.50	3.05
VLA Operations	1.20	2.32	3.31	4.40	4.76	5.19	5.71	6.28
General & Administration	1.14	1.36	1.39	1.53	1.66	1.78	1.91	2.04
Subtotal - Operations	8.59	10.63	12.00	14.38	15.56	17.35	19.51	22.48
B. Equipment								
Research Equipment[3]	0.86	1.10	0.64	2.10	2.37	2.49	2.26	2.41
Operating Equipment	0.37	0.06	0.05	0.06	0.07	0.07	0.07	0.08
Subtotal - Equipment	1.23	1.16	0.69	2.16	2.44	2.56	2.33	2.49
TOTAL - SCIENTIFIC RESEARCH	9.82	11.79	12.69	16.54	18.00	19.91	21.84	24.97
II. CONSTRUCTION								
Very Large Array	12.87	11.50	4.70	-	-	-	-	-
25-m Millimeter-Wave Telescope	-	-	-	4.40	13.67	7.32	-	-
TOTAL - CONSTRUCTION	12.87	11.50	4.70	4.40	13.67	7.32	-	-
TOTAL	22.69	23.29	17.39	20.94	31.67	27.23	21.84	24.97

* Figures shown for Scientific Research in CY 1978 and CY 1979 are the expenditures and commitments made each year, reduced by the commitments carried forward from the previous year. Figures shown for VLA Construction are the sums allocated for the calendar year.

4/25/79

Notes to the Table

1. Provides for an increase in the scientific staff from 30 persons at the end of 1979 to 40 persons at the end of 1985.

2. Provides additional support for millimeter wavelength instrumentation, beginning in 1981. Provides for increased computer capability, beginning in 1981, at an annual cost of $900k.

3. Provides for Other Observing Equipment for the VLA, at a level of approximately $1M in 1981, rising to $1.3M in 1985.