NATIONAL RADIO ASTRONOMY OBSERVATORY

LONG RANGE PLANS CY 1983-CY 1988

INTRODUCTION

Past advances in radio astronomy have been critically dependent on innovative applications of evolving new technologies to the instruments and techniques used to make radio astronomical observations. Improvements in the sensitivity and resolution of the telescopes and instrumentation used at traditional radio frequencies have stimulated many new discoveries over the years. Improvements in technology have been the driving force behind the slow but steady expansion of radio astronomical research into the higher frequency domain. During the planning period and beyond, the NRAO will continually strive to apply technological improvements to its existing telescopes and instrumentation and to vigorously pursue an expansion of radio astronomical techniques to higher frequencies.

The challenge to the NRAO in the coming half-decade will also be strongly influenced by technological developments in other complementary wavelength domains of astronomical research. In the present era of multiwavelength, interdisciplinary approaches to astrophysical problems, enormous strides in technology have had significant impact throughout the electromagnetic spectrum. Space-based gamma ray and X-ray observations demand longer wavelength ground-based follow-up observations, and the NRAO anticipates a continued acceleration of its service to an ever widening user clientele.

The plan outlined below describes the principal directions that the NRAO should follow in the years CY 1983 to CY 1988 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.

I. BASIC RESEARCH STAFF

Included in this operational unit are the scientific staff and visiting scientists holding appointments at the Observatory. Although these are mainly located at the Charlottesville headquarters, a significant fraction are based at the observing sites. This unit is also comprised of graduate and undergraduate students involved with the various student programs at the Observatory. A small group of library and technical illustrations personnel providing Observatory-wide scientific services are in this unit.

The scientific staff of the Observatory provide direct and continuous oversight to ongoing instrumental development programs in a manner unattainable solely from outside groups of scientists. In the normal course of their own individual research programs and during their frequent interactions with visiting observers, the staff are constantly monitoring and evaluating the performance of new and current instrumentation and the procedures for observing and analysis. Their continual presence, availability, and initiative are vital in ensuring the most effective response by the Observatory's technical staff to the needs of the radio astronomical community. In addition, 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. During the construction and implementation of new instrumentation, for example, staff participation runs the gamut from the definition of scientific goals to the calibration of the instrument. They necessarily are heavily involved in debugging the instrument and assessing its scientific performance while at the same time advising visitors on the optimum use of the instrument and insuring that full documentation is generated and distributed. Recent staff involvement of this nature has included design work on the 12-meter upgrade, the 25-meter millimeter-wave telescope, and the VLBA project. The implementation of new VLA and VLBI processing techniques has also demanded much staff interaction.

The scientific staff level of recent years has remained quite stable. Several positions have gone unfilled due to budgetary constraints in spite of a gradual geographic and discipline oriented dilution of expertise and the tremendous increase of scientific initiative associated with initializing the VLA. Current staff levels, however, will become progressively overtaxed and overwhelmed by the demands placed upon it in future years. The present plan seeks to address these shortcomings by gradually increasing the scientific staff by one to two positions per year.

II. TECHNICAL SUPPORT AND DEVELOPMENT

This operation unit is the backbone of existing and future technical capabilities at the Observatory and is composed of three principal subunits. The Central Development Laboratory carries out forefront research and development on state-of-the-art electronic devices to be used as radiometer components or in other Observatory-wide applications of spectral technology (e.g., digital correlators, spectrum expanders). They have also developed into a community-wide resource in providing plans, advice and hardware to non-NRAO observatories worldwide. The Central Computer Division is responsible for evaluating and operating the hardware and developing the software used in general data processing and analysis as well as for the operation of the MkII VLBI processor. The Engineering Division provides the design and structural analysis required in the construction of new facilities and provides in-house engineering support for the existing facilities.

During the planning period, additional electronics personnel will be required in order to ensure innovative development of millimeter and submillimeter instrumentation to be employed on the resurfaced 12-meter telescope and an eventual larger millimeter instrument. Improvements in existing millimeter receivers will depend on the development of lower noise Schottky diodes, whereas the success of future receivers will demand continued development and evaluation of SIS junctions. Emphasis will also be focussed on continued developments in VLBI technology to upgrade and improve the existing MkII processor as well as to assemble a prototype processor to meet the expanded needs of the VLBA. In the Central Computer Division, the principal task will be in acquiring and operating an expanded central computer facility depending on the outcome of a current Observatory-wide evaluation. The Engineering Division will be heavily committed in the planning for and construction of the VLBA.

EXPANDED COMPUTER CAPABILITY

The bulk of the Observatory's computing is provided by three systems: the VLA DEC-10 based system, the IBM central computer facility, and a number of VAX-based image processing systems. This capability is distributed throughout the Observatory and provides support in the areas of VLA, VLBI, single dish, telescope design, theory and engineering.

Each of these systems has been improved in the last year. The DEC-10 system was upgraded from a KI to a KL processor, increasing available capacity by a factor of 2 to 3. The IBM central facility was upgraded from an IBM 360/65 to an IBM 4341, representing a reliability improvement. The number of super-mini (mostly VAX) based image processors has been increased from 3 to 4. However, further increased capacity will be required in support of the VLA in the near term, and of VLBI on a slightly longer time scale. The current two IF channels used in the VLA will shortly be increased to four, doubling the data rate. The spectral-line system will be implemented in the next year, increasing the data rate much further, the exact factor depending on the amount of time spectral-line observing is scheduled. Significant increases are also predicted in VLBI processing as the number of stations per experiment increases.

If data processing is going to be avoided as a primary scientific limitation for VLA and possibly VLBI data, the NRAO must develop a major increase in computer capability over the next 5 years. This increase must be both in power and flexibility. To aid in planning for such, the NRAO recently sought the advice of an external group of computer experts. Based on the recommendations of this group, we have divided the computer development into near-term and next-generation systems. The near-term (1-2 years) involves mostly the VLA and includes the successful completion of the VLA "pipeline system", the further development of the AIP image processing system, and the upgrade of the VLA central system. The longer term (3-5 years) involves the development of the next generation computer systems. It includes a review of the role of the Observatory's various systems as well as a review of the extent to which processing in similar areas such as VLBI and VLA should be combined. The outcome will replace the Observatory's earlier plans which address primarily post-processing and general computing. We have undertaken this study and anticipate a proposal for the Observatory's next generation system in 1983. This study involves NRAO's central computer facility, the VLA DEC-10 based system, the image processing systems, and future VLB-related processing. Although purchase/rental tradeoffs have not yet been considered, a rental base of one to two million dollars per year is indicative of the class of system.

III. GREEN BANK OPERATIONS

Four divisions in Green Bank are devoted to the support of observations with the 300-foot and 140-foot telescopes.

Financial exigency during the interval since the last report led to a considerable reduction in force at Green Bank, with the resultant consolidation of several divisions into a leaner operational mode. Although there has been a corresponding reduction in several less essential services and a slowdown in production and new developments in some divisions, there are currently no plans to reestablish the former personnel levels.

Much of the success of NRAO in the past has been the result of its ability to provide the lowest noise systems available at certain popular spectral-line frequencies. Continued efforts to reduce the noise characteristics of the Green Bank receivers will be the primary goal of the Electronics Division during the planning period. Additionally, there will be an attempt to expand the capabilities of the 300-foot telescope by developing an appropriate broadband autocorrelator similar to that already operating on the 140-foot. Improvements to the telescopes themselves will also draw continuing attention. Although recent beam symmetry problems at the 140-foot have been solved, the telescope's high-frequency performance at large zenith distances will be further improved by laterally shifting the focus.

With the continuing advent of low-noise radiometers and improved telescope control and data acquisition systems, it is foreseen that the current backlog of observing time on Green Bank's two telescopes will probably be maintained. As two of the largest single dishes in the U.S., this backlog of observing requests remains a high 10 months. The 300-foot telescope, as a transit instrument, is primarily in demand as a survey instrument to study large classes of objects--individual galaxies, clusters of galaxies, or selected groups of radio sources with specific spectral, morphological, or brightness properties such as pulsars or low-frequency variables. As receiver sensitivities improve, fainter classes of these objects will come within the range of the instrument. Anticipated demand for the 140-foot telescope is expected to concentrate on spectral-line studies of dark clouds, and star formation regions, including new molecular line searches. Spinoffs will include an understanding of the dynamics and the interstellar chemistry of these regions. The 140-foot will probably also remain much in demand for VLBI investigations right up until the time when the VLBA is completed. As the number of well-equipped VLBI stations increases, the 140-foot VLBI program will encounter increasing observing pressure.

Green Bank staff levels will remain roughly constant during the planning period except for occasional augmentation to carry out specific instrumentation studies.

IV. MILLIMETER-WAVELENGTH OPERATIONS

Now that the 36-foot telescope is in the process of being resurfaced with an improved 12-meter surface, increasing demand for the instrument is anticipated for several years to come. Modifications to the backup structure as well as a vastly improved surface tolerance will combine to greatly improve the observing efficiency down to wavelengths as short as 1 mm. As plans for the 25-meter telescope have been somewhat delayed by the confused budget outlook for several years running, the 12-meter telescope will fill an important role in maintaining a millimeter capability during an era of increased scientific excitement in the field. The 12-meter will be phased out of operation once a future large millimeter-wave facility is available.

The current staff level of 22 people in Tucson will be sufficient to continue adequate support for the 12-meter telescope. With support from the Central Development Laboratory, the Tucson-based group will focus on bolometer and spectral receivers for the short end of the millimeter-wave range in order to supplement existing receivers and to prepare for the eventual needs of a large millimeter-wave facility in the future.

V. VLA OPERATIONS

Experience gained in the beginning years of VLA operation has borne out earlier predictions that the instrument would receive strong usage by groups other than traditional radio astronomers. The system has been developed and will continue to be developed as one that is "friendly" to experienced and inexperienced observers alike. The multi-wavelength approach to astrophysical problems is now a reality and will continue to dominate future research trends as the Space Telescope and other satellite-based instruments are brought into regular use. Observing pressure on the VLA in support of future space-based observations is expected to increase dramatically from current levels throughout the decade of the 80's. The capacity of the VLA is far in excess of its design goals and because of the great number of users that it has served, its current staff level is only marginally adequate. Efficiencies have in large part resulted from efforts to standardize map processing techniques and to promote their use at non-NRAO data processing centers. The observing pressure created by future technical innovations will be partially offset by an increasing use of remote observing. However, a modest increase in the number of VLA operations' personnel is expected in order to meet the added growth anticipated in the system's capacity.

VI. GENERAL AND ADMINISTRATIVE

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. The viability of future radio astronomical research in large part depends on our ability to respond as rapidly in these areas as time, money, and manpower will allow.

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. The VLA - An instrument the size of the VLA with approximately $80M invested capital is never really fully completed. Changing technology demands that additional outlays continually be made in order to maintain the instrument's technical viability as well as to preserve the initial investment. Even during the construction phase, far-reaching technical and design modifications were adopted and led the instrument's current capacity. During the planning period it is foreseen that additional VLA instrumentation expenditures will be approximately $1.5M annually. Projects are already underway to add low-noise preamplifiers at 21, 2, and 1.3 cm to increase the sensitivity at these wavelengths. Further expansion of the instrument's spectral coverage could be made with the addition of two low-frequency receivers at 600 MHz and 300 MHz to enable the VLA to study faint sources with steep spectral indices. Another modification designed to expand the versatility of the instrument is the addition of a second master local oscillator whereby two spectral subarrays could operate simultaneously. Another major costly addition includes a dichroic system of dual-frequency feeds to allow simultaneous 6-cm and 2-cm observations. The addition of 3-cm and 11-cm receivers on a few antennas would also provide a rapid method for the reliable determination of microwave spectra.

Much of the OOE funds for the VLA will be earmarked for computer-related expenditures in recognition of the key role they play in processing the rapid flow of VLA data. The presently nonmaintainable system discs on the MODCOMP synchronous computers need to be replaced and upgraded and future maintenance and upgrading of the DEC-10 system is expected. With the completion of the pipeline processor, there will be a need during the planning period for a large mass store device as the throughput of spectral-line data will soon overrun our current data archiving capabilities. Much of the pressure on the DEC-10 system for map processing has been alleviated with the addition of VAX systems for asynchronous data analysis. In the light of ongoing studies to evaluate future computing needs at the NRAO, it may become advisable to add an additional VAX system sometime during the planning period.

2. Millimeter Wavelengths

As the 12-meter telescope goes into full operation, demand for telescope time to take full advantage of its improved short wavelength efficiency will require continued NRAO emphasis on developing new and improved millimeter radiometers. The pace of millimeter-wave astronomy accelerates as efforts are being focussed on extragalactic molecules, interstellar chemistry, and the energetics of star-forming regions by many new and powerful telescopes worldwide. It is essential that the NRAO maintain state-of-the-art instruments for the 12-meter telescope at least through the planning period. Major efforts currently stress the development of low-noise receiver components--Schottky diodes and research on SIS junctions. The NRAO continues to evaluate its efforts in these areas in light of rapidly advancing technology.

3. VLBI Support

The NRAO remains committed to the support of VLBI observing with both MkII and MkIII terminals. Nearly 30 percent of the observing time on the

140-foot telescope is devoted to this effort, and a significant amount of the OOE funds will be allocated for VLBI system improvements. Development of a prototype VLBI receiver to include the most common VLB frequencies is planned. This will consolidate the VLB effort at the 140-foot by replacing the current number of non-VLB specialized receivers. It would possibly also be of use at other VLBI network stations. Progress in the widespread employment of MkIII processors is dependent on future technical advances in the use of high-information density media. Work on a new state-of-the-art processor possibly incorporating video cassette technology will take place during the planning period.

4. Centimeter and Decimeter Wavelengths

Along with the continuing efforts in Green Bank to upgrade existing receivers and integrate low-noise systems into operation, work on other system components is planned. Further improvement of the high-frequency performance of the 140-foot telescope at large zenith distances is dependent on a lateral focussing device which automatically will follow the shifting focus. A pulsar signal processor is needed which increases the signal sampling rate over existing devices and provides greater flexibility for time resolution, multiple frequency polarization, and the rejection of interference. These development efforts will parallel ongoing investigations of feed designs, reflector improvements, and overall telescope sensitivity.

VIII. CONSTRUCTION AND INSTALLATION

(a) The Very-Long Baseline Array Radio Telescope

Exciting scientific and technical advances that have occurred in recent years in the field of Very Long Baseline Interferometry (VLBI) have illustrated the need for a national instrument dedicated to the requirements of this emerging field. The NRAO has collaborated with the VLBI university-base community in submitting a proposal for such an instrument to the National Science Foundation. Strong endorsement for a dedicated VLB Array was included in the Field Committee Report on "Astronomy in the Decade of the 80's", where it received a first priority rating among ground-based projects.

The technical feasibility of VLBI has been amply demonstrated since its inception just over a decade ago. Existing antennas separated by baselines of continental extent in connection with high-time resolution recording devices and extremely stable reference-frequency maser clocks have facilitated astronomical studies with resolutions heretofore unattainable. Detailed studies of the very central portions of galaxies and quasars have revealed core-jet morphologies with structures as small as 10^{16} cm and commonly exhibiting superluminal motions. Applied to objects in our own galaxy, the VLBI technique has provided fundamental knowledge on the dynamics of OH and H_2O maser activity in young star-forming regions as well as in the circumstellar environment of older mass losing late-type stars. The spatial structures of other stellar objects, such as the Algol binary system, SS 433 and the Galactic Center, have been probed in a search for further clues to their peculiarities. Geodetic studies of the Earth's rotational parameters have benefitted from the application of VLBI techniques.

Although many exciting pioneering discoveries have already been made with existing VLBI systems, these only serve to accentuate the need for a dedicated VLBA which is designed to overcome the inadequacies of the present ad hoc system. The VLBA would provide major improvements in sensitivity, resolution, operating wavelength range, and image quality. Proper aperture synthesis observations require the number, distribution, siting, instrumentation, and scheduling of antennas to be specifically geared to the design goals of the instrument. Without existing limitations in all these specifications, the scientific impact of a dedicated VLBA will be overwhelming.

The sub-millarcsecond resolution, image quality and sensitivity of the VLBA will open up the study of a wide variety of extragalactic, compact energetic sources from quasars to ordinary galactic nuclei. Following the evolution of individual parsec size-scale objects, the prevalence of superluminal motion, and the relation between compact and extended source components, will significantly add to our understanding of the energetics of these objects. Coupled to this will be detailed high-resolution absorption-line studies of the distribution and kinematics of neutral hydrogen in galaxies and quasars. In the Galaxy many more star-forming and late stellar-evolution regions will come under the scrutiny of VLBA and improved galactic-scale astrometry will be an important result. Fainter stellar objects, such as flare stars, will be sampled at longer wavelengths, while the ability of the VLBA to adequately sample low-declination sources will enable expanded studies of the galactic center with a resolution of a few AU. The VLBA will also open up the study of the origin and stability of the small-scale irregularities in the interstellar medium and their relation to interstellar shocks and cosmic rays. In general, where the current VLBI investigations have merely scratched the surface, the VLBA will be able to probe deeply in a broad range of problems in physics and geophysics as well as in astronomy and astrophysics.

The proposed Array will consist of ten elements within the USA, with locations chosen to optimize the image quality and to provide a reasonably smooth extension of VLA resolutions. The VLBA elements will use 25-meter high-efficiency steerable paraboloids designed to work well at wavelengths as short as 7 mm. The short wavelength receivers will employ maser preamplifiers at the secondary focus for state-of-the-art low system-noise temperatures while cooled GASFET amplifiers will be used in the receivers operating from 2 cm to 20 cm. GASFET amplifiers are envisaged for the 50-cm and 90-cm prime focus receivers. Independent, stable, hydrogen-maser oscillators will be used to maintain phase coherence over the VLBA.

Operation of the VLBA will require central computer control via leased telephone lines from an array Operating Center. Technician/operators only will man each site and major maintenance and repair will defer to the Central Service Center where a large group of engineers, technicians, and mechanics will be stationed.

(b) VLA Outrigger Antenna

In order to improve the available resolution of the VLA by a factor of five, the addition of an outrigger antenna at a distance of about 100 km from the array is foreseen. Not only would the extra resolution capability be useful as an extension of the power of the VLA for sources with a large range of size scales, but it would fill a gap intermediate between VLA and VLBI resolutions. Both instruments would thus complement one another from the arcsecond to milliarcsecond resolution regimes to enable a thorough analysis of the interdependence of physical phenomena at diverse size scales. Currently there are resolution differences of two orders of magnitude between the two telescopes.

The outrigger antenna, 15 meters in diameter, would be located approximately 100 km from the VLA on the southern end of the SW arm and linked by microwave communication to the VLA.

To a certain extent the priority of this project depends on the details of the proposed VLBA. An outrigger antenna would not be of high priority if the VLBA were planned and constructed with a sufficient number of short baselines to adequately cover this resolution regime. As funding, construction, and siting plans for the VLBA progress, the need for a VLA outrigger antenna will be reevaluated.

(c) <u>VLA - VAX Building Addition</u>

Depending on the outcome of the long-range computer plan now under development at the NRAO, there may arise the need for additional post-processing space at the VLA. Two VAX systems, serving up to four users simultaneously, are currently located at the VLA site. If additional VAX systems are allocated for use at the VLA, the current laboratory space would be inadequate.

(d) <u>Major Computer System</u>

As discussed in Section II under Expanded Computer Capability, the Observatory's plans for long-range implementation of next generation computer systems are under study. Although the exact details of components, configuration, or location will not be known until the completion of the study, it is clear that something will have to be done to update the current system, and approximately $1.5M per year for 1985 and beyond should be allowed for.

(e) <u>Millimeter Wave Facility</u>

Beyond the current installation and operation of the 12-meter dish, the role of the NRAO in providing national millimeter-wave facilities is quite uncertain. Plans for a future millimeter-wave facility are still active at the NRAO. Funding levels and years have not been specified.