NATIONAL RADIO ASTRONOMY OBSERVATORY

LONG RANGE PLAN

1986-1990

April 1985

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I. INTRODUCTION

Advances in an observational science such as radio astronomy are predicated on our ability to "see," with increasing clarity, objects in the radio sky. Our vision, in this case, can improve only to the extent that the instruments we use are correspondingly improved. Thus, the mission of the NRAO in the planning period is to provide and continually improve radio astronomical instrumentation and techniques. It is precisely to this end that the present long range plan is developed.

In radio astronomy improved "vision" can mean the ability to see small details in large radio sources (higher angular resolution), the ability to see faint objects or features particularly in the presence of bright, nearby emission (greater sensitivity and dynamic range), and the ability to see the radio "color" of an object (frequency coverage). Together these parameters determine the quality of the pictures that the astronomer uses to gain insight into the nature of radio-emitting objects.

Recent experience has made it abundantly clear that sufficient improvements in any of the critical instrumental parameters leads to qualitative as well as quantitative changes in the science that is produced. Large increases in sensitivity, frequency coverage, and angular resolution provide not simply a clearer picture of familiar objects (although this is by no means to be minimized) but more important they provide an opportunity for entirely new classes of objects to be studied. For example, the extension of the frequency range of the 12-m telescope to 230 GHz with a sensitive receiver led to the discovery in three days of more circumstellar molecular shells than had been detected in the previous three years. The availability of low-noise GaAsFET amplifiers on the VLA provide a sufficient increase in sensitivity that the radio emission from supernovae in nearby galaxies can, for the first time, be studied virtually from the time of the stellar explosion. While it is hazardous to speculate what the next such landmark discovery may be, it is nevertheless worth emphasizing that major discoveries will be hastened by our determination and ability to implement technological improvements rapidly and continuously to our instrumentation.

II. PLAN OVERVIEW

The NRAO long range plan for the last half of this decade, 1986-1990, highlights the following four areas in which our support surely will be rewarded by abundant scientific returns:

(1) Continued operation accompanied by carefully considered growth of the major NRAO observing facilities at Green Bank, WV (the 140-foot and 300-foot telescopes); at Tucson, AZ (the 12-m millimeter-wave telescope); and at Socorro, NM (the VLA). Here the opportunities are most evident in areas of telescope sensitivity via improvements in receiver performance, frequency coverage, telescope efficiency, and spectrometer flexibility.

(2) Completion and initial operation of the 10-element Very Long Baseline Array (VLBA). This array, the Field Committee's highest priority ground-based astronomical instrument of the 1980s, will provide an unprecedented advance in high angular resolution studies of radio sources. The VLBA will allow astronomers to map the radio sky at milli-arc second resolution over substantially more than two decades of frequency (from 327 MHz to 86 GHz).

(3) A supercomputer for radio astronomical imaging. The definition of radio images produced by radio synthesis arrays, such as the VLA and VLBA, is limited by atmospheric phase fluctuations. Atmospheric "blurring" can be circumvented, and the sensitivity and dynamic range of the array increased by more than a factor of 100, using restoration and deconvolution algorithms that have been developed at the NRAO and elsewhere. This enormous gain in array sensitivity is readily realizable if access to supercomputer resources can be provided.

(4) New initiatives in response to the demands of the astronomical community. Specifically, following the recommendation of the Barrett Subcommittee of the NSF Astronomy Advisory Committee, NRAO has begun to consider the design of a millimeter-wave synthesis array to restore U.S. millimeter-wave astronomy to a competitive position vis-a-vis international endeavors in this field. In addition, we follow with interest those proposals being studied by NASA for radio astronomy in space in order to assess the appropriate participation, if any, of the NRAO in these ventures.

Each of the plans is amplified in the following sections.

III. OPERATION AND ENHANCEMENT OF EXISTING INSTRUMENTS

The major goal of the NRAO over the past years has been to provide the community with radio astronomical instruments having unique capabilities and to make those capabilities available to astronomers from all disciplines. Thus, the task involves not only developing state-of-the-art instrumentation but also making the telescopes straightforward to use and providing suitable data reduction facilities. All aspects of this program are important to the commitment of the Observatory to radio astronomy in this country. In the next five years we hope to maintain, and indeed extend, this commitment. To do so we present, by telescope, the major areas of scientific interest to be addressed and the anticipated instrumentation developments that the coming half-decade will bring.

A. The Very Large Array

By every measure the VLA has been the most powerful and the most scientifically productive instrument that the NRAO has constructed and operated. Since its first use in 1976 more than 2000 projects have been proposed and over three-fourths of them have received observing time. Many of the VLA users are not traditional radio astronomers, and their overwhelming demand for the instrument has been a strong endorsement of its capabilities in support of today's problem-oriented, multi-wavelength, inter-disciplinary astrophysics. The resolution capability of the VLA has given new impetus to radio studies of every class of object which is detectable in the short wavelength, X-ray, UV, optical and infrared spectral regimes. Direct comparisons of the spectral properties of individual objects are no longer restricted by resolution incompatibilities, and nearly all branches of astronomy have benefitted from VLA observations.

In the study of the galactic environment, the VLA will continue to investigate detailed dynamical and morphological interactions in star-formation regions and molecular clouds. HII regions provide important laboratories in which to probe the physical conditions of the interstellar material, and current studies will be extended to many more regions. Detailed analysis of the structure of ultracompact HII regions and the investigation of OH and H_2O maser sources promise to reveal much about small-scale, star-formation phenomena throughout the Galaxy.

The significant number of stellar programs carried out with the VLA has been noteworthy and is expected to continue at a high level (approximately 25% of the assigned telescope time). Future high-resolution studies of X-ray stars will search for periodicities and morphological changes. Planetary nebulae, mass-losing stars, and supernovae will continue to receive much attention, especially as the VLA observations are directly comparable with observations with similar resolution in other spectral regimes. This is also true for stellar objects which have not traditionally been of radio interest, such as T Tauri stars, normal A stars, red giants, and symbiotic stars.

Expanded studies of individual extragalactic objects are expected to take advantage of the ability of the VLA to provide equivalent angular resolution over a broad wavelength range as it is used in its various standard configurations. Programs requiring this capability are on the increase as the instrument spends greater amounts of time on detailed studies of individual objects. Very high dynamic range maps and polarization studies will be required to understand the physics and evolution of radio source structures such as jets and lobes. Dynamical studies of individual galaxies will be compared with numerical model simulations. Deep searches will investigate radio source evolution models and contribute to cosmological studies. Similar progress is expected in the study of clusters of galaxies and the nature of the microwave background.

Many modifications to the VLA have already been incorporated during its construction and early operation and have had a significant effect on the scientific productivity of the VLA. Additional improvements are planned during the next five years that will greatly enhance its capabilities to serve the varied requirements of its ever-widening astronomical clientele. These projects will potentially expand the wavelength coverage of the telescope, upgrade its sensitivity and performance at its present operating wavelengths, and provide for improved calibration and data-handling.

Extending the VLA frequency range down in frequency from the current 1.35 GHz limit appears to be best accomplished in the following three stages.

- 300-350 MHz receivers will be installed at prime focus on all antennas at the rate of approximately six antennas per year. Scientifically, this additional frequency range provides an opportunity for studies of those sources particularly bright at low frequencies (e.g., pulsars) and for objects as large as 60-90 arc minutes in diameter. Technically, the lower frequency allows us to experiment with restoration algorithms that will be necessary to remove ionospheric effects and the effects of confusing field sources: such algorithms will be indispensible if still lower frequency observations are to be attempted with the VLA.

- A 75 MHz capability for the VLA will be investigated. This will take two forms. First, a few antennas will be fitted with very simple dipole-type feeds to evaluate the efficacy of the restoration algorithms developed to handle the 327 MHz observations. If such algorithms, suitably modified, prove satisfactory for 75 MHz observations, then the goal is to construct a low-frequency synthesis interferometer on the plains of San Augustin. This array would comprise at least 27 fully steerable banks of antennas, sited near the current 'A' configuration stations. These would operate independently of the current VLA, except that the signals would be conducted by cable to the nearest 25-meter antenna for amplification and injection into the current waveguide transmission line. These signals will be extracted from the waveguide in the control building and recorded on tape for later correlation using a special-purpose correlator. This approach will allow data from days of good ionospheric behavior to be archived without losing any information from the large (30 degree) primary beam. VLA operations would be undisturbed by the 75 MHz array.

- A 610 MHz capability designed to fill the gap between 350 MHz and 1370 MHz will be installed on all antennas. In addition to improving the frequency coverage of the VLA, this frequency is supported on other telescopes around the world as well as being one of the primary VLBA frequencies.

The frequency range of the VLA will also be extended to higher frequencies. Neither the intrinsic accuracy of the VLA reflector panels nor the gravitational deformations of the antenna structure limit the VLA to the present highest operating frequency of 26 GHz. As there is considerable scientific gain to be realized by providing the capability to reach lines of the SiO molecular masers and the molecular tracer CS at 43 GHz, and since the telescopes will perform adequately at these frequencies, we intend to equip the antennas with suitable high-frequency radiometers. However, at 43 GHz the telescope pointing tolerance is sufficiently severe that thermal deformations leading to pointing errors will have to be greatly reduced; this will require that thermal insulation be applied to parts of the telescope structures.

Finally, the frequency agility of the VLA will be augmented in two ways. First, the addition of S-band, 2.2 GHz receivers will supplement the present broadband spectroscopic facility of the VLA. It will usefully complement the 20 cm band for cosmological studies by providing a large field of view but a much lower confusion-limit. It will also permit the VLA to be used in conjunction with the VLBA at an important VLBA frequency. Second, simultaneous observations at two frequencies, 5 and 14 GHz, will be provided by means of a dichroic reflector system. Such a facility is vital for the study of rapidly evolving sources such as flare stars and active regions on the sun.

The sensitivity of the VLA can be increased by factors as large as 2-6 at three of the present VLA operating frequencies through modest-to-major upgrades of the existing radiometers. The specific plans are as follows:

- 1.3-1.7 GHz. HI and OH imaging done in this frequency band at 1.4 and 1.66 GHz, respectively, are the most important classes of spectroscopic projects done with the VLA. Since such observations are always sensitivity limited, the need for improvement in radiometer performance here is most compelling. Presently, the VLA provides system temperatures of 50-60 K in this band. A significant fraction of the system temperature results from the decade-old receiver design which locates all front-ends in the same cryogenic dewar. This results in longer input waveguide runs than necessary and prevents polarization splitters from being cryogenicaly cooled. By adapting the VLBA receiver design to the VLA--cooled GaAsFET amplifiers in an independent L-band dewar--noise temperatures one-half the current values can be expected.

- 4.5-5.0 GHz. In many ways the 4.5-5.0 GHz system is the optimum VLA observing frequency. This frequency is high enough to avoid background source confusion at all VLA resolutions but not so high that there is significant degradation owing to telescope efficiency or atmospheric effects. As at 1.3-1.7 GHz noted above, if the 4.5-5.0 GHz GaAsFET receivers are mounted in a separate cryogenic dewar as in the VLBA design, a factor of approximately 2 improvement in system temperature is realizable.

- 22-25 GHz. Many important ammonia line experiments, such as observations of accretion disks, circumstellar material, distant star-forming complexes, and extragalactic ammonia, will benefit from the upgrade in K-band performance. The projected improvement at 24 GHz by a factor of 5-6 means a tremendous boost in speed and sensitivity. Experiments will be 20-30 times faster. Eight-hour experiments will then take only a little of over half an hour. Instead of one region per u-v track, 20-30 regions can be studied at once. This is a very significant step forward.

The present receivers for the VLA 1.3 cm wavelength band use cryogenically cooled mixers to obtain a system temperature of approximately 400 degrees Kelvin at the 22.2 GHz water line and up to twice this at the ammonia line frequencies. The NRAO Central Development Laboratory will develop an improved front-end amplifier for the 1.3 cm band that will reduce the system temperature to 150 degrees Kelvin. It will be either a GaAsFET amplifier or a HEMT (high electron mobility transistor) amplifier. The new receiver element will be installed in a cryogenic dewar ahead of or in place of the existing cooled mixer.

The sensitivity of the VLA can be improved not only by reducing the noise temperature of the RF front-end receivers but, for important classes of experiment, through modifications and upgrades to the telescope "back-end," the correlator and image-forming computers. The following four specific plans are noteworthy:

- Broadband Correlator. To observe large fields of view with high spatial resolution and high sensitivity, it is necessary to break the wide continuum bandwidth into several narrower frequency channels to avoid bandwidth smearing at the edge of the field. For wide field continuum mapping this will provide an increase in sensitivity of almost a factor of three. Some line projects requiring large bandwidth would also benefit by this modification.

To synthesize out to the first null of the primary beam at 21 cm wavelength in the A array, it is necessary to break the 50 MHz bandwidth into 64 channels. The current VLA correlator provides only four channels in 50 MHz when polarization data is required. However, by using analog filters ahead of the digitizer, the necessary number of channels can be obtained and the gain in sensitivity realized.

- Water Vapor Radiometers. At the higher VLA frequencies the array sensitivity to low-level emission in a field that does not contain a bright source (e.g., detection experiments) depends on the phase stability of the atmosphere. As the atmospheric phase errors worsen, the sensitivity is correspondingly diminished. In principle, these errors can be corrected in real-time by means of radiometric measurements of the fluctuating water content in the sky above each antenna.

- Ionospheric Measuring Device. The sensitivity of the VLA for linear polarization measurements at 20 cm is significantly, and at longer wavelengths seriously, limited by Faraday rotation in the ionosphere. Current methods of correcting for ionospheric Faraday rotation rely on knowing the electron content of the ionosphere as a function of time. Approximate values for the VLA, calculated from observations of geostationary satellites, are obtained from the World Data Center in Colorado. However, the only way to improve the accuracy of these values for the VLA longitude and latitude is to make appropriate measurements at the VLA.

- Deconvolution and Restoration Algorithms. Enormous gains in radio picture definition and dynamic range are achievable through the use of self-calibration algorithms. These methods require computer resources vastly greater than exist in present NRAO image processing systems and point to the need for Class 6 supercomputing resources. This is discussed in a separate section below and constitutes a major initiative of the NRAO in the planning period.

Between now and the time when the supercomputer is available substantial augmentation of the existing image processing facilities will be necessary at the NRAO.

B. The 300-foot Telescope

The 300-foot transit telescope operates principally as a survey instrument, accessing many sources per day as each in turn crosses the meridian of the instrument. Sensitivity to faint sources depends on the large collecting area, low-noise receivers, and integration times which may span many meridian crossings. The availability of this telescope over the years has been a powerful resource for innumerable large-scale surveys for galactic and extragalactic sources of varied character. Future surveys for low-luminosity pulsars, low-frequency variable sources, and of the velocities and structures of galaxies, clusters, and super-clusters will depend on continued improvements to the telescope and receiver systems. The wealth of fundamental data that the 300-foot provides in an environment unrestricted by competition from short-term, limited programs, is unparalleled in its contribution to large-scale programs which are otherwise difficult to schedule on other major telescopes in the U.S.

As a survey instrument the 300-foot telescope requires certain performance characteristics that are of lesser importance at the other telescopes. Specifically, the need is to frequently change observational parameters, start and stop observations and do so routinely, reliably and with minimal active intervention by observer or telescope operator. Unfortunately, this need is ill accommodated by the present 20 year-old DDP-116 control computer and manually-controlled Mark III autocorrelation spectrometer. Thus, the plan for the 300-foot telescope over the next five years is to correct these deficiencies and truly optimize its performance as a survey instrument.

A spectral processor is under construction which is a combination spectrometer and signal processor, designed to replace the Mark III autocorrelator and the Nicolet signal averager. It will improve on existing instrumentation in two major areas. Spectral-line observations will have greater resistance to interference since spectral estimates are produced once every 10 microseconds instead of once every 10 seconds as in the autocorrelator. This allows spectral estimates contaminated by radio frequency interference to be excised from the accumulated spectrum. The spectral processor will also increase the number of spectral channels, providing 2048 channels across 40 MHz bandwidth as compared with the present limit of 384 channels across 10 MHz bandwidth available with the Mark III autocorrelator. Secondly, the spectral processor will greatly improve data acquisition capabilities for pulsar observations at the 300-foot. As a pulsar dedisperser, it will allow high time-resolution studies of average waveforms and single pulses with full polarization information. Scintillation studies will be possible that employ a wide range of bandwidths and with spectral windows centered on different pulse components.

In addition to improving the survey operation and flexibility of the 300-foot telescope there are also plans to improve its performance at both high and low frequencies.

- Lateral Focusing. There is a significant north-south displacement of the focal point as the telescope is moved away from the zenith. Both defocusing and astigmatism cause a sharp drop off in the short wavelength aperture efficiency at zenith angles greater than about 20 degrees. This effect most severely degrades the high frequency performance of the 300-foot and markedly limits the sensitivity of 5 GHz sky surveys.

Using a special offset feed arrangement, we have measured the aperture efficiency as a function of declination at 5 GHz. The optimum feed position was found to move relative to the feed cabin in the sense that as the antenna is moved south the optimum feed position moves north. This offset feed scheme showed that the aperture efficiency could be improved at large zenith angles with the addition of a north-south receiver motion. Mechanical assembly of a movable feed to correct for this effect is underway.

- Adaptive Array Receiver. For low frequency observations the beam shape of the tracking feed receiver deteriorates when the feed is scanned off axis. For example, when the feed is two half-power beamwidths off axis the efficiency has already degraded by 10 percent. Tracking is consequently restricted to ten or twenty minutes (at 400 MHz) when the antenna efficiency is critical to the success of an experiment. To rectify this problem a feed array has been designed which is an array of dipoles. With appropriate combining networks the antenna beam of the traveling feed mechanism could be scanned over the full 17.4 degrees with minimal loss in gain. This receiver will cover an astrophysically significant frequency range not covered by other receivers and will permit observations of one source for more than an hour.

Finally, a sensitive new 300-foot telescope receiver is planned which will have the capability to make 5 GHz maps of the entire sky visible from Green Bank. Such a map would be the radio analog of the Palomar Sky Survey to be used by any astronomer to make radio "identifications" or set upper limits to the flux densities of any class of objects. The 7-beam, 14-channel receiver would allow the 300-foot telescope to cover the declination range 0 to 75 degrees in approximately 90 days and would resolve the sky into 10 million beam areas permitting detection of at least 200,000 sources stronger than 10 mJy. Each map would be an historical record of the sky so that successive maps will reveal variable sources. The proposed receiver consists of 7 dual-polarization feeds followed by 14 FET amplifiers, all mounted in a single dewar.

C. The 140-foot Telescope

In recent years a major effort has been directed toward improving the sensitivity and frequency coverage of radiometers on the 140-foot telescope. This has taken two forms: A maser/upconverter receiver has been installed at the cassegrain focus for observations virtually anywhere in the 5-25 GHz range; at lower frequencies, 1.3-2.0 GHz, an optimized GaAsFET prime focus receiver provides a system temperature of less than 25 K. These receivers have had a major impact on the scientific productivity of the 140-foot telescope. Detections of numerous weak transitions of molecular species have become routine; the fine-structure transition of the helium isotope ^{3}He, sought for more than a decade at the NRAO and elsewhere, has not only been detected but the telescope has proven to have sufficient sensitivity to allow this isotope to be used as a valuable probe of the physics of HII regions; OH "megamasers" have been seen in exceptionally distant galaxies. The frequency agility, large collecting area, and all-sky coverage of the 140-foot telescope ensure a continuing high demand for this instrument throughout the current planning period.

Future gains in sensitivity at the 140-foot telescope are realizable from additions to the available receivers, computers and spectrometers as well as from improvements to the telescope structure.

- A second 5-25 GHz maser/upconverter receiver is nearly complete. Once a polarization splitter is fabricated the two 5-25 GHz receivers can be used simultaneously to receive opposite polarizations, thereby doubling the sensitivity of the telescope throughout this frequency range.

- An optimized 2-5 GHz GaAsFET receiver similar to the very low noise 1.3-2.0 GHz receiver is being constructed. A system temperature of less than 30 K is anticipated and, if achieved, it will become possible to map the 9 cm line of the important molecular tracer of diffuse gas, CH, throughout the Galaxy.

- The high-frequency performance of the 140-foot telescope rapidly degrades as one observes off the meridian owing to a lateral defocusing. Tests have shown that tilting the subreflector can offer a significant increase in aperture efficiency over a wide range of hour angles. Modifications to the present subreflector mount and nutation mechanism are planned to provide the necessary tilt and to realize this improvement.

- The control and analysis computers at the 140-foot telescope are rapidly becoming obsolete principally owing to their 16-bit architecture. To achieve needed flexibility and commonality with telescope control systems elsewhere in the Observatory (so that software can be shared) an upgrade to 32-bit architecture machines is desirable.

- A copy of the 300-foot spectral processor/spectrometer will be made for the 140-foot telescope in order to improve interference excision and expand interactive spectral line observations.

D. The 12-meter Telescope

The recent resurfacing of the NRAO millimeter wave telescope on Kitt Peak has resulted in three major telescope improvements which directly affect the quality of the observations made with it: Greater surface accuracy for higher efficiency operation at high frequencies, increased surface area and, accordingly, increased sensitivity to small sources; and improved pointing accuracy and stability. The increased competitiveness of the telescope has given rise to a flood of new proposals for telescope time which exploit the improved angular resolution and wavelength coverage now available. For the study of the ubiquitous CO molecule in a wide variety of objects, the improved angular resolution of the telescope at the J=2-1 line at 230 GHz is critical. Projects are just beginning which probe the detailed morphology and dynamics of the CO molecular components of circumstellar shells, regions of star formation where energetic bipolar outflows are detected, and in a wide variety of external galaxies. Newly sensitive observations of additional transitions of known molecular species in the interstellar medium and in dense molecular clouds will probe more thoroughly the physical conditions in such environs. In addition, prospects are quite good for detecting new species and adding to our understanding of the chemistry of the interstellar medium. More sensitive observations are planned for objects in the solar system, galactic dust clouds and globules. Further improvement in continuum measurements of extragalactic sources, compact objects, and QSOs are anticipated which will lead to more refined variability studies as well.

Ongoing improvements in all the 12-meter receiver systems will play an equally important role in the effectiveness of the facility to contribute to the above scientific studies. Progress is expected in a number of instrumental developments to insure that this continues unabated through the last half of the decade. Receiver sensitivity to the low-intensity, narrow, millimeter spectral lines which are emitted by cold, spatially extended astrophysical sources is dependent on improvements in Schottky-barrier diodes and SIS junctions which are the critical components of the NRAO millimeter-wave receivers. The NRAO will continue to emphasize work on these devices in parallel with research at other institutions.

Other instrumental developments include a 345 GHz spectral-line receiver for observations of the J=3-2 CO transition. This and other important molecular species have transitions in the 870 micron atmospheric window. A simple receiver is being constructed to evaluate the performance of the telescope and the suitability of the site for observations at 345 GHz.

Development of sensitive SIS receivers that require very little local oscillator power provide an unprecedented opportunity for a two-dimensional array of focal plane receivers to be constructed. Since spectroscopic observations of extended sources are so important in dynamical and morphological studies of regions in the interstellar medium, both in the Galaxy and in extragalactic objects, an efficient multi-beam receiver can greatly increase telescope effectiveness. Two such SIS multi-beam arrays are planned, one at 115 GHz for the CO(J=1-0) line and the other for the CO(J=2-1) line at 230 GHz. Each such receiver will consist of eight separate focal plane receivers that will permit mapping observations to be completed in one-eighth the time previously needed.

However, to fully realize this marked increase in mapping speed it will be necessary to expand the spectrometer to accommodate the eight data channels and to make corresponding enhancements to the computing resources. Present plans include the following:

- A hybrid filter-bank/digital autocorrelation spectrometer covering 2.4 GHz bandwidth and separable into eight separate sections each with 256 channels across 300 MHz bandwidth is under construction. This spectrometer will be suitable for the 8-element receiver arrays.

- To handle the increased data rate, the antiquated PDP-11/40 control computer will be replaced with a PDP-11/44 computer. The 11/44 will serve as host to a distribution of dedicated microcomputers that actually do the instrument control.

E. Operating Equipment and Facilities Maintenance

Large investments in capital equipment at all the sites, whether for buildings, telescopes or computers, impose a maintenance burden which may be (1) frequent and incremental or (2) episodic and appreciable. The former are appropriately included within normal operating budgets. The latter, having a time scale between events longer than a given budget year, need to be planned for individually. Neither, however, can be forgotten.

Among the needs in the latter category that must be addressed in the current planning period are the following:

- General Test Equipment. Much of the Observatory's laboratory equipment is antiquated and needs to be replaced. Some critical equipment such as spectrum analyzers and network analyzers are simply not available.

Other Major Operating and Major Maintenance:

<u>VLA</u>

--Major maintenance to the railroad track and rail beds
--Road paving
--A motor generator to protect computing equipment from power line fluctuations
--Machine shop and vehicle maintenance facilities

<u>Green Bank</u>

--Road paving
--Telescope painting
--Major mechanical improvements to telescope structures

<u>Tucson</u>

--Fabric replacement cover for the telescope dome
--Erection of a pre-fabricated dormitory building on the mountain to replace the 20 year-old "temporary" mobile homes used as observer residences.
--Storage building on the mountain

IV. THE VERY LONG BASELINE ARRAY (VLBA)

A. Construction and Operations

The present planning period, 1986-1990, will see the construction of the Very Long Baseline Array, ten precision 25-m diameter antennas located throughout the United States from Puerto Rico to Hawaii, that will allow images of radio sources to be constructed with an angular resolution better than one thousandth of an arc second. Equipped with radio receiving systems covering assigned radio astronomy bands in the frequency range 327 MHz to 86 GHz, the VLBA will provide an unprecedented opportunity for astronomers to study radio sources over a broad range of resolution and surface brightness. Realization of the scientific potential of the VLBA is the principal challenge of the NRAO in the next half-decade.

VLBI observations made with existing radio telescopes have already given a fascinating glimpse into the heart of quasars and galaxies, but the nature of the central energy source remains a mystery. With the VLBA it will be possible to see in detail the dynamics of the energy generation process. Of particular interest will be the apparent faster-than-light motions arising from the explosive ejection of relativistic material from quasars and galactic nuclei.

The high resolution of the VLBA will also enable it to extend the range of direct distance measurements by trigonometric parallax. Observations of proper motions will be possible both throughout our Galaxy and in other galaxies. This will open up an exciting range of astrometric problems, including galactic structure and rotation, and earth rotation.

Even within our own Galaxy there are a variety of very compact radio stars of interplanetary dimensions that can be studied by the VLBA although they are unresolved by conventional radio telescopes. One of the most important problems in galactic astronomy is to understand the life cycle of stars. Clouds of molecular OH, H_2O, and SiO are often found in regions where stars are formed and in the atmosphere of very old stars. They are excited by the stellar radiation field and may act as interstellar masers. High-resolution radio images made with the VLBA will be able to probe the dynamics and magnetic fields in these regions on a scale of astronomical units to parsecs and give information on the birth and death of stars.

The VLBA will also be used for a broad range of problems in physics and geophysics, as well as for astronomy and astrophysics. Because the spacing of the interferometer fringes depends on the separation of the antennas, precise analysis of the received signals enables one to measure the antenna separations with very high accuracy. This measurement has a variety of applications to geodesy and crustal dynamics (plate tectonics). In addition, since the directions of the baselines connecting individual elements can also be determined from celestial observations, the VLBA may also be used to locate the instantaneous position of the Earth's rotation axis and the wandering of the poles. Accurate determination of the rate of the Earth's rotation (time) and a better evaluation of the rate of its slowing down will also be feasible.

The operation of a radio telescope with elements dispersed over 8000 km presents a number of unique problems. All of the elements of the VLBA will be controlled via dedicated telephone lines from an Operations Center in Socorro, NM. The VLBA will operate using a preplanned program under the control of a central computer, which will simultaneously monitor the performance of the antennas and receivers as well as the meteorological conditions at each site. An array control operator will be present at all times at the Array Operations Center (AOC) to intervene when necessary and to carry out various bookkeeping tasks. From time to time brief samples of the received signal at each antenna will be sent to the AOC via the telephone lines and correlated in nearly real-time to check that all components of the array are functioning properly.

Normally, each antenna will be unattended, but a technician/operator will be available at each site for inspection, routine maintenance, and the simpler unscheduled repairs. The local staff will also update the operating systems at the local control computer, change the data tapes, and ship them to the AOC, and be responsible for security, for emergency intervention, and for routine start-up and shutdown procedures.

The AOC will provide for major maintenance and repair requiring personnel with special skills, special equipment or major replacement parts. However, since it is planned to build much of the electronics in modular units and to replace complete modules in the case of failure, most such replacements can be easily performed by the local site personnel. Defective modules will be returned to the AOC for repair.

B. Consolidation of VLBA and VLA Operations

The VLBA in many ways is the logical extension of the VLA to still greater telescope spacings (higher angular resolutions). The receiving equipment, data handling, and image formation tasks are identical in the two instruments. For this reason, there are considerable economies to be realized if the two instruments are operationally consolidated. In particular, shared personnel will allow each operation the access to a larger pool of technical and scientific expertise than would be available to either instrument alone. Maintenance facilities can be shared.

Beneficial economies such as these provide a compelling motivation for the NRAO to consider merging the VLA and VLBA operations. Since the VLBA Array Operations Center, the AOC, will be located on the campus of New Mexico Institute of Mining and Technology in Socorro, NM, it is entirely feasible to consider moving the VLA control from the Plains of San Augustin to Socorro also. In this case both arrays could be controlled from a common site, even a common console, with the VLA telescopes linked to the AOC by means of a microwave link. From an operational standpoint such a consolidation is very attractive--problems with either array could be diagnosed and repaired quickly--and from an administrative standpoint consolidation simplifies both operations.

The present long range plan includes the funds necessary to provide an addition to the VLBA AOC building in Socorro with sufficient office space to accommodate VLA operations.

V. A SUPERCOMPUTER FOR RADIO ASTRONOMICAL IMAGING

In recent years astronomers have made increasing use of synthetic aperture radio telescopes, such as the VLA, to obtain ever higher angular resolution and sensitivity. Since the image-forming optics of such instruments are computers, major improvements can be made even after construction of the telescope hardware is finished. This flexibility has led to a dramatic increase in scientific productivity since both the quality and quantity of the images produced by the VLA now greatly exceed the original goals of the VLA.

This increase in productivity of the VLA has come at the cost of greatly increased computer usage, but the available computer resources have not kept pace with demands. At this time, only a small fraction of those exciting scientific investigations which are very computer-intensive are being pursued.

When the VLA was originally proposed in 1971, it was expected to produce images in which the ratio between the brightest features and the faintest believable features would be limited by various errors to 100:1 dynamic range). The two main effects which cause this limited dynamic range in synthesis arrays are: (1) incomplete measurement of the coherence of the wavefront due to the finite number of antennas and limited observing time; and (2) wavefront collimation errors due to the spatially and temporally varying refractivity of the atmosphere above the array (i.e., "bad seeing"). In recent years two new techniques, deconvolution and self-calibration, have been developed which can correct for both of these sources of error. Their use has greatly increased the quality of the best VLA images from the 100:1 dynamic range specified in the VLA proposal to over 10,000:1, but at the cost of greatly increased computation time. The impact of self-calibration has been even greater in VLBI where true imaging of objects, at resolutions up to a thousand times greater than thatavailable with the VLA, is now possible.

In 1984, almost 600 observers from 140 different institutions used the VLA to conduct their research. On the basis of these projects and the demands for other projects which are not feasible with the present inadequate computer resources, the NRAO has estimated future demand for data processing. Similar estimates have been made for the VLBA. From this analysis of present needs it is concluded that the future computer demands for image formation and enhancement will exceed the present total capacity of the NRAO by more than a factor of 25. These requirements imply a need for continuous computer capacity of at least 60 Megaflops. This is 100 times greater than the power of the current NRAO image processing system and can be provided by one relatively large supercomputer. The supercomputer needs a large, fast access memory and the best achievable disk I/O performance in order to facilitate the processing of the large VLA and VLBA images.

A supercomputer has four great advantages for NRAO over multiple array processors (the only other plausible technical option):

> Its high performance allows the largest processing calculations to be performed in a reasonable amount of time.
>
> It provides a unified environment of software, CPU, arithmetic pipelines, memory and I/O devices, all assembled and supported by a single vendor and optimized for highest performance from the total system.
>
> It supports high level languages using compilers which automatically utilize the pipelined vector hardware.
>
> It provides a direction for growth to allow for future needs.

NRAO has concluded that acquisition of a supercomputer is the most direct and straightforward approach to its data processing problem, since the required sustained throughput of at least 60 Megaflops cannot be achieved by any other hardware, except through a great deal of replication. Furthermore, the dominance of vector operations such as the FFT in the VLA task-mix ensures that the special properties of a suitably configured supercomputer can be exploited effectively.

As remarked in the Curtis Report to the NSF, lack of access to supercomputers has inhibited activity in certain scientific fields. This situation certainly occurs with synthesis radio telescopes. The best astronomers, conscious of computer limitations, will simply turn to other problems and the potentially most imaginative and most important problems in radio astronomy may not be studied. For observations which are just feasible with the present resources, the long turn-around time inhibits both experimentation with data analysis methods and investigation of unusual effects. Limited computer resources which increase the barrier between the scientist and his observations artificially arrest scientific progress. Cognizant of this, the NRAO seeks to acquire a supercomputer for VLA and VLBA image construction.

VI. NEW INITIATIVES IN RADIO ASTRONOMY

A. Millimeter Wave Synthesis Array

When it became apparent that the proposed 25-meter millimeter-wave telescope would not be funded, the NSF established a sub-committee of the Astronomy Advisory Committee to investigate new U.S. initiatives in millimeter-wave astronomy. The report of this subcommittee, chaired by A. H. Barrett, was issued in April, 1983. It recommended that the following three initiatives be pursued simultaneously:

> the initiation of a design study of a mm-wavelength aperture synthesis array with a minimum usable wavelength of 1 mm, an angular resolution of 1 arc-second, or better, at a wavelength of 2.6 mm, and a total collecting area of 1000-2000 square meters;
>
> construction and operation of 10-meter class submm-wavelength telescopes at dry sites;
>
> support of astronomical research and development of mm- and submm-wavelength technology relevant to astronomy.

The NRAO has begun investigating the first initiative, the design of a millimeter-wave synthesis array. Technical and scientific working groups are in the process of attempting to define the technical parameters of an array that would provide a unique capability in millimeter-wave astronomy. The expectation is that these efforts will converge toward the end of the planning period and culminate with a proposal for funding of such an array.

B. Radio Astronomy in Space

Two NASA/JPL proposals for radio astronomical observations from space are very much in the planning stage. One, the Large Deployable Reflector (LDR), is a 15 meter class submillimeter/infrared telescope initiative. The second is an orbiting VLBI antenna, QUASAT, that is intended to be correlated with ground-based antennas in order to provide VLBI baselines in excess of one-earth diameter and more complete (u,v)-coverage. Although neither plan currently involves the NRAO directly, it is possible that the Observatory may wish to participate in the future. We follow these proposals with interest.

VII. CONSOLIDATION OF CHARLOTTESVILLE ACTIVITIES

The Charlottesville Edgemont Road building has served as NRAO headquarters since 1965 when the NRAO expanded from Green Bank. As the NRAO staff increased during the VLA planning and development years, the need for expanded electronics laboratory facilities became acute, and temporary space was leased in an office building a mile away. The leased space, now occupied by the Central Development Laboratory, has recently been expanded to house the Charlottesville VLBA design and planning activities. Space at the Edgemont Road office is still at a premium with expanded data and image processing operations occupying what were formerly electronic laboratories. The artificially imposed separation of technical development activities from the scientific activities at Edgemont Road is a regrettable consequence of expansion that could be rectified in a variety of ways.

There are presently four somewhat disparate NRAO activities in Charlottesville:

- the Scientific Staff;
- the NRAO Central Administration;
- the Astronomical Image Processing System (AIPS) Group; and
- the Central Development Laboratory.

The location of each of these groups in Charlottesville is largely the result of the historical evolution of the Observatory over the course of the last two decades. While each group has been demonstrably productive over this time, it is difficult to argue that the productivity of any one group is a symbiotic consequence of the presence of the others.

The operation of separate sites, even those separated by only a mile, imposes an unnecessary burden on the Observatory manifested principally through redundant facilities. Here, as with the VLA and VLBA activities, economies can be effected through consolidation. However, unlike the situation in New Mexico, the four Charlottesville activities are so disparate, it is not necessary, or perhaps even desirable, to consolidate and co-locate any or all of them in Charlottesville or in any other single place.

We recognize consolidation of NRAO activities to be a worthwhile goal. There are, however, a number of ways of achieving this goal, all of which will require relocation and/or building construction monies. The plan is to consolidate Charlottesville activities by 1990, either in Charlottesville or a new location, possibly moving some of these activities to other existing sites. A necessarily crude estimate of building and moving expenses has been included for 1989 in the budget projection.

04/01/85

Long Range Budget and Personnel Projections (1985-1990)

Budget Estimate (M$)	1985	1986	1987	1988	1989	1990
I. OPERATIONS						
Existing Operations	17.1	17.1	18.1	19.0	20.0	21.0
New Operations (VLBA)	-	-	0.5	2.0	3.5	5.0
New Operations (Sc)	-	-	1.6	1.7	1.8	1.9
Total Operations	17.1	17.1	20.2	22.7	25.3	27.9
II. EQUIPMENT						
Research & Test Eqpt.	0.1	0.4	1.2	2.0	2.2	2.5
Operating Equipment	0.1	0.1	0.3	0.3	0.4	0.5
Sc Upgrading	-	-	-	1.0	1.0	1.0
Total Equipment	0.2	0.5	1.5	3.3	3.6	4.0
Total Operations & Eqpt.	17.3	17.6	21.7	26.0	28.9	31.9
III. CONSTRUCTION & DESIGN						
VLBA	9.4	11.5	17.7	18.0	14.2	-
VLA Building (Socorro)	-	-	2.0	-	-	-
Supercomputer	-	-	18.8	-	-	-
Hdqtrs/Lab Consolidation	-	-	-	-	4.0	-
Millimeter Array	-	-	-	0.5	1.5	10.0
Total Construction & Design	9.4	11.5	38.5	18.5	19.7	10.0
TOTAL PLAN [1]	26.7	29.1	60.2	44.5	48.6	41.9

PERSONNEL ESTIMATE	1985	1986	1987	1988	1989	1990
Existing Operations	331	320	322	323	324	325
New Operations (VLBA)	-	-	10	30	50	70
New Operations (Sc)	-	-	17	18	19	20
Total Personnel [1,2]	331	320	349	371	393	415

1. Does not include NSF funds or personnel for operation of Green Bank interferometer.
2. Does not include any personnel hired directly into construction projects.

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