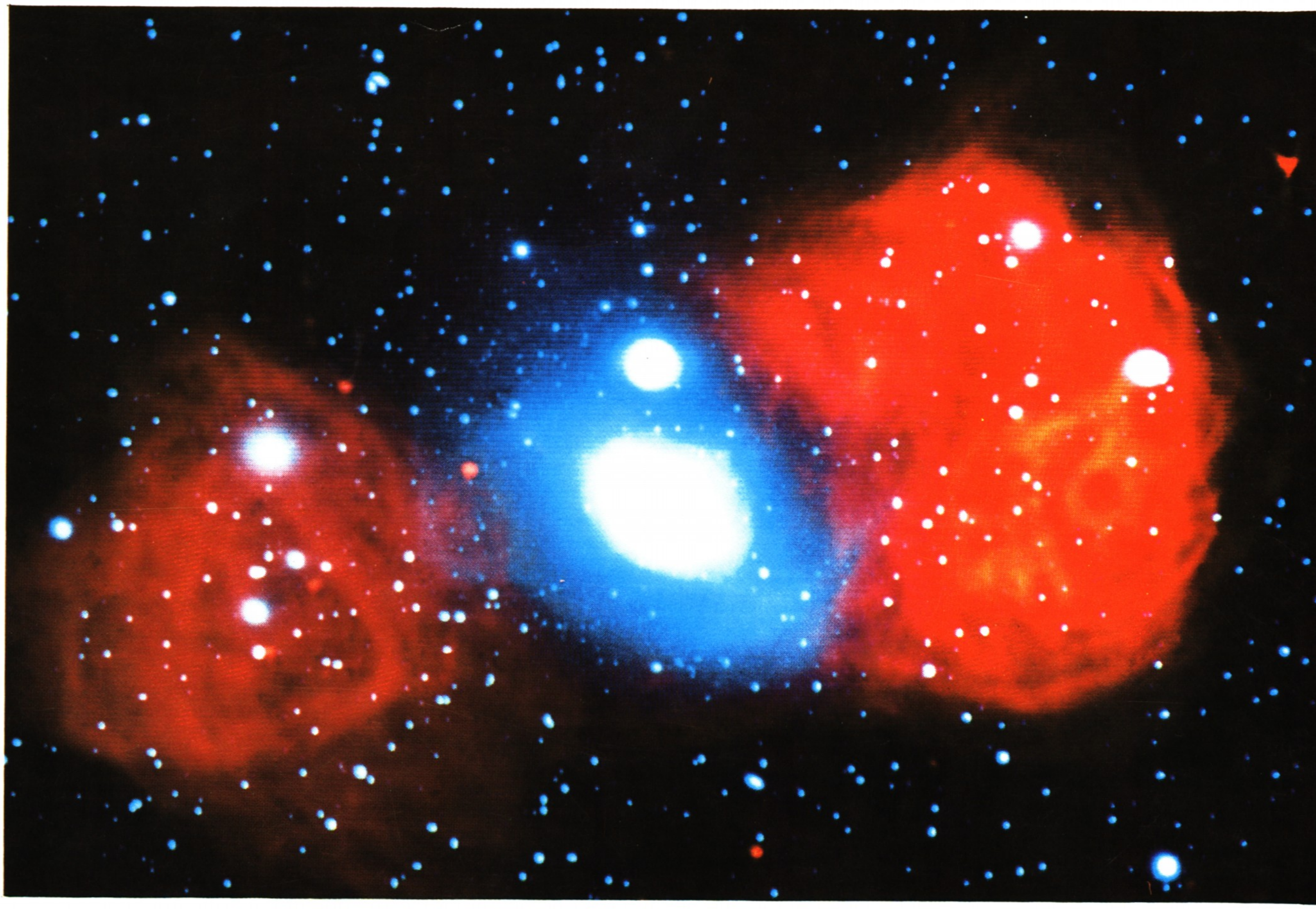
U4/GR Bk/

NATIONAL RADIO



ASTRONOMY OBSERVATORY

NRAO

LONG RANGE PLAN

1991–1995

Cover: The Radio Galaxy Fornax A

The cover photograph is a superposition of the VLA radio emission (shown as red) from the radio galaxy Fornax A and the visible light in the vicinity of NGC 1316 (shown as blue-white). The two main radio emitting lobes are produced by relativistic electrons in magnetic fields which have been transported hundreds of thousands of light years outward from the elliptical galaxy NGC 1316 which lies between the two regions. The energy for the relativistic flow apparently was provided by the gravitational capture of small galaxies by NGC 1316. The shock waves and trails of the infallen galaxies produce the features in the radio lobes seen as filaments and rings. The small galaxy near NGC 1316 may soon be captured.

Observation details:

Observers: E. Fomalont (NRAO), R. Ekers (Australia Telescope),
K. Ebneter and W. Van Breugel (U. California)

Frequency of 1.384 GHz; five hours of D-configuration and five hours of C-configuration

Resolution of 15"; field of view is 60' x 40'

NATIONAL RADIO ASTRONOMY OBSERVATORY

LONG RANGE PLAN - 1991-1995

April 1990

OCT 22 1990

NATIONAL RADIO ASTRONOMY OBSERVATORY

LONG RANGE PLAN - 1991-1995

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I. INTRODUCTION

The NRAO Long Range Plan for the years 1991-1995 is focussed on efforts to realize the promise of high resolution astronomical imaging at all wavelengths from 4 meters to 0.8 millimeters and to extend the reach of radio astronomy to unprecedented levels of sensitivity.

High resolution astronomical imaging is the province of synthesis astronomy. The Very Large Array and the Very Long Baseline Array are the foremost centimeter-wave synthesis telescopes in the world. In many ways the VLA and VLBA are complementary instruments. VLA images provide a record of the evolution and energetics of such objects as galactic nuclei, jets of relativistic particles, and protostars. The VLBA images will probe the physics underlying such phenomena. Completion and full-time operation of the VLBA is therefore important to the growth of our understanding of a wealth of astronomical objects. At short wavelengths, millimeter wavelengths, where thermal processes illuminate the sky, there is no high resolution synthesis imaging telescope comparable to the VLA. The Millimeter Array (MMA), which we propose to construct, beginning in 1994, will address this need. The MMA will provide images with a resolution comparable to that of the Hubble Space Telescope, doing so at millimeter wavelengths, where galactic nuclei and star-forming clouds are unobscured.

The thrust of many pioneering research programs depends on sensitivity, frequency agility, and special-purpose hardware. These needs have been incorporated as an integral part of the design of the Green Bank Telescope (GBT). For example, with the enormous GBT collecting area weak pulsars may be discovered throughout the galactic center region and the CO emission from extremely distant primeval and protogalaxies may be detectable. The clean beam of the GBT, which results from the unblocked design, will permit the studies of atomic hydrogen to reach levels more than an order of magnitude fainter than was possible in the past. Realizing these and other scientific goals of the GBT is an important part of the GBT design and construction project. Sensitivity, and the new science it brings, is recognized in the MMA project as well: the CO protogalaxies detected by the GBT will be imaged by the MMA with subarcsecond resolution, and the dust continuum emission from galaxies at epochs of formation as early as $z = 10$ will be detectable with the MMA.

The new instruments designed and constructed in the planning period not only set the stage for revolutionary advances in radio astronomy but they provide a comprehensive foundation for future scientific growth.

Planning for the next five years of NRAO operation also includes emphasis on the efficient operation of all instruments and user facilities. Consolidation of VLA maintenance and operation with VLBA operation and maintenance at the Array Operations Center in Socorro has already demonstrated the efficiency inherent in shared facilities and flexible task scheduling. Over the planning period the lessons learned will be further developed as the operation of the two arrays is merged into a single management structure.

Facilities maintenance at the NRAO will continue to receive attention so that the users and staff at the NRAO can be assured that all the equipment functions properly and safely. For the large structures, represented most particularly by the electrical power distribution system and 80 miles of rail track in the VLA, maintenance costs are substantial and the needs continuing.

Beyond the role of operation of unique research facilities for the scientific community, the NRAO provides a focus for development of new instrumentation, distribution of software algorithms for analysis and interpretation of astronomical data, and coordination of the astronomy community's needs for major new facilities. These various activities are also represented in the NRAO long range plan. Specifically:

- The NRAO Central Development Laboratory will further promote the design and development of ultra low-noise, high electron mobility transistor amplifiers for microwave radio astronomy applications; photon-assisted tunnelling (SIS) mixer development for millimeter-wave observations will be augmented.

- The Astronomical Image Processing System (AIPS) software will be optimized for the next generation of vector-parallel computers and operating systems. A separate program of basic research in image processing will be enhanced. The computational resources available for radio astronomical image processing will be made commensurate with the needs of the VLA and VLBA through implementation of the NRAO Array Computing Plan.

- Development of a single dish computing plan for the needs of the new Green Bank telescope and expanded capabilities of the 12-meter telescope.

- Working in concert with the community of millimeter-wave astronomers, the final design and initial construction of a national millimeter-wave array will be completed and major construction of the array started in this planning period.

- A program to expand and enhance the capabilities of the VLA will be the hallmark of the second decade of VLA operation. The VLA sensitivity will be improved at all frequencies by installation of a new generation of ultra low-noise receivers. The correlator and signal transmission system will be replaced by a new design which will increase the bandwidth by a factor of 20. Together, these improvements will enable research programs requiring twelve hours now to be completed in two hours or less.

- The end of this decade will see the union of the VLA and VLBA into a single instrument providing uniformly spaced data on baselines from 40 meters to 8000 kilometers.

II. THE MILLIMETER ARRAY

The Millimeter Array (MMA) is a versatile imaging instrument which emphasizes the following capabilities.

- Sub-arcsecond imaging at 115 GHz and higher frequencies;
- Wide-field imaging (mosaicing);
- Rapid imaging - "snapshots" of high fidelity;
- Sensitive imaging at high frequency ($\leq$ 350 GHz);
- Simultaneous multi-band operation;
- Comprehensive single dish observing.

Together these capabilities define a unique instrument. Astronomers using the MMA will explore scientific areas new to millimeter-wave research. Two examples are particularly illustrative: The combination of high sensitivity and sub-arcsecond angular resolution provided by the MMA at frequencies of 230 and 350 GHz will permit the photospheric emission from hundreds of nearby stars to be detected and imaged, the stellar radii to be determined, and the positions established to astrometric precision. The same combination of instrumental parameters will provide images, at a resolution superior to that of the Hubble Space Telescope, of the redshifted dust emission from galaxies at the epoch of formation ($z = 5$-10). Indeed, these "protogalaxies" will be the dominant source of background confusion at 1 mm at levels approaching 1 mJy.

High sensitivity implies that the total collecting area of all the individual elements in the array should be made as large as possible, while fast imaging is achieved by distributing the collecting area over many elements. The precise requirements of how many elements and the size of the individual antennas is then decided by minimizing the total array cost. Sub-arcsecond imaging places a constraint on the array dimension: $0\overset{''}{.}1$ at 230 GHz, for example, requires an array that includes baselines extending to 3 km. Finally, sensitive imaging at high frequency demands that the MMA be located on a high-altitude site with excellent atmospheric transparency. Considerations such as these have defined the design of the MMA. The unique imaging capabilities of the MMA are amplified below.

Rapid Imaging Capability. The MMA will be of special value for observations which must be completed quickly. Here "quickly" can mean within a few seconds, or perhaps a few minutes, or it may mean within a day or two. But, in any case, many vital projects must necessarily be finished in a time short compared with the time needed to physically move antennas. For this class of research it is not feasible to improve the u-v coverage by repositioning antennas--the phenomenon to be studied, the requisite atmospheric transparency, or the scale of the investigation requires short integrations.

The need for rapid imaging is most crucial for the construction of wide field mosaic images. One must be able to observe rapidly a raster of adjacent fields with sufficient instrumental stability and reliable enough calibration to enable one not only to image each field but also to combine all separate images into a coherent whole. Since the u-v coverage in each separate field must be good enough to produce a well sampled image even though the data extends over one or a few hour angle ranges, the "snapshot" capability of the array must be nearly complete. Excellent instantaneous u-v coverage is a prerequisite for an array to image wide fields.

Mosaics of wide fields are needed to address many questions regarding:

- the kinematics and chemical evolution of giant molecular clouds through the star formation stage;
- the gas content and distribution in galaxies; and
- the pressure of the hot (10^7-10^8 K) gas within clusters of galaxies.

Sensitive Imaging Capability at 230 and 345 GHz. A cornerstone for the science proposed for the MMA is its capacity to provide well-sampled, high resolution images at frequencies corresponding to the J = 3-2 and J = 2-1 transitions of the common molecular tracer CO and its isotopomers at the appropriate Doppler shifts. Spectroscopically, many important questions involve the spatial distribution and kinematics of molecular material. Such questions are best addressed by observations of strong lines of an abundant, and widely distributed, constituent. Carbon monoxide fulfills these requirements. In the continuum, observations at 250 and 350 GHz provide a high resolution, uncontaminated, view of the emission from thermal dust grains and solid surfaces. Owing to the steep spectral dependence of thermal emission, one can obtain this particular insight only by observing at wavelengths of one millimeter and shorter. A wealth of scientific opportunities is opened to astronomers given access to an imaging instrument at these wavelengths.

Wideband/Multi-Band Capability. The ultimate goal of astrophysical research is to reach an understanding about the nature and evolution of objects in the universe. Rarely is such an understanding reached with observations at only one particular wavelength. So it is perhaps not surprising that the scientific demands placed on the millimeter array emphasize wideband and multi-band capabilities. Wide bandwidths increase continuum sensitivity, while a true multi-band facility allows the astronomer to explore the relation of information in one band to that in another. Both capabilities are important to the scientific value of the MMA; together they make it unique.

The MMA Proposal - The instrument to realize these scientific capabilities has been defined by the NRAO in consultation with the user community and other technical experts. A summary of the MMA specifications is given below:

Array --

Number of Antennas	40
Total Collecting Area	2010 m^2
Total Resolution	$0\farcs07\ \lambda$ (mm)

Antennas --

Diameter	80 m
Precision	$\lambda/40$ at 1 mm
Pointing	1/20 beamwidth
Transportable	

Configurations --

Compact	70 m
Intermediate (2)	250, 900 m
High Resolution	3 km

Frequencies --

Emphasis on	200-350 GHz
Capability at	70-115 GHz; 9 GHz
Desirable	Simultaneous multi-band

Site --

High Altitude--suitable for precision imaging at 1 mm

A proposal to the National Science Foundation, that such an instrument be constructed, will be submitted in May of 1990. Major construction should begin in 1994 following two to three years of detailed design work. The total cost is expected to be approximately $120M. Operations could begin in 1998.

III. MAJOR CONSTRUCTION PROJECTS

VERY LONG BASELINE ARRAY

Introduction

Many of the most exciting subjects of modern astrophysical research, including active galactic nuclei and quasars, pulsars, molecular masers, and active stars such as SS 433, require high spatial resolution. Such resolution can be achieved only by using radio arrays with dimensions of thousands of kilometers. The Very Long Baseline Array (VLBA) will exploit techniques which have been developed for the VLA and VLBI and will form images with unprecedented angular resolution and quality. At its shortest operating wavelength, the array will have a resolution of a few tenths of a milli-arcsecond. This resolution corresponds to linear scales of an astronomical unit within the galaxy to a few parsecs for the most distant quasars and radio galaxies.

Together with the VLA, the VLBA will provide a wide range of brightness sensitivity and resolution from a few arcminutes (VLA D Array at 327 MHz) to 0.2 milli-arcseconds (VLBA at 43 GHz). The VLBA elements are located to optimize the image quality. The nine observing bands of the VLBA are designed to cover the radio astronomy continuum bands, to give a range of resolution, surface brightness sensitivity, and spectral information. The observing bands also include the main spectral lines of interstellar masers and the DSN bands commonly used for a variety of world-wide geodetic experiments.

Each of the ten elements of the VLBA is being designed to work at wavelengths as short as 3.5 mm. Initially the shortest wavelength receivers will be at 7 mm. The VLBA correlator facility will accommodate 20 inputs, so up to 10 additional antennas located throughout the world can be used to increase the sensitivity and resolution. It is anticipated that these external stations will adopt the VLBA recording standards, and that the VLBA Array Operations Center in New Mexico will become the coordinating center for much of the worldwide VLBI activity.

The operation of the VLBA will be under the control of an operator located at the Socorro Array Operations Center who will execute a planned program of observations based on proposals and review. Like the VLA, it is anticipated that the VLBA will be used by a wide range of scientists who are not required to have any particular expertise in radio interferometry. Observers will not need to be present at observing time or when the data are correlated. They may choose to monitor either activity from their home location via a remote computer connection. While this mode of observing has its well-known advantages and disadvantages, it is particularly suitable for the VLBA. With the VLBA there is little opportunity for scientific interaction either at observing or correlating time. Since the observers need not be present, the daily observing program may be adjusted to match the weather conditions or to exploit unusual scientific opportunities.

Data reduction and analysis will be based on the extensively used AIPS package. The data reduction facilities will be combined with those of the VLA at the Socorro Operations Center, to exploit the available hardware and software. The combined VLA/VLBA Operations Center will support all types of VLBA observing, including geodesy and geophysics. However, it is anticipated that, as has often been the case for VLA observations, many users will choose to do most or all of their analysis at their home institutions. We do not plan to provide sufficient <u>internal</u> computing resources to process all of the VLBA observations.

Project Status - March 1990

<u>Sites</u>. The following table gives the status of the ten antennas and associated sites.

Site	Status
Pie Town NM	operational
Kitt Peak AZ	operational
Los Alamos NM	operable, but not staffed for network support
Ft. Davis TX	operable, but not staffed for network support
North Liberty IA	outfitting underway; scheduled operable 7/90
Brewster WA	antenna 80% complete; outfitting to start 7/90
Owens Valley CA	antenna complete; outfitting to start 11/90
Hancock NH	site almost complete; antenna assembly to start 5/90
St. Croix VI	site 75% complete; antenna assembly to start 8/90
Mauna Kea HI	site lease imminent; antenna assembly to start 2/91

<u>Antennas</u>. Manufacture of the last two antennas was completed in late 1989. Assembly of the last antenna on its site is scheduled for 1991.

Tests to date indicate that the Pie Town antenna meets specifications, and, moreover, the specification of the primary reflecting surface accuracy has been exceeded. The combination of panel surface and panel setting accuracy was specified to be less than 180 microns rms, and the measured value is 145 microns rms. This means the goal of an array that can function at 3 mm wavelength should be achievable. Tests at 86 GHz in 1989 at Pie Town have further verified this result, and antenna efficiencies of 25 percent or better are predicted at this frequency with production subreflectors.

<u>Receivers</u>. The following table gives the measured amplifier noise temperatures and expected system noise temperatures for the nine receiving bands, along with status comments.

VLBA Frequency Bands and Noise Performance

Band	Tuning Range	Receiver Type	Input T(Phys)	T(Rx)	$T_{(Sys)}$
330 MHz	0.312 - 0.342	GaAsFET	300	30	90
610 MHz	0.580 - 0.640	GaAsFET	300	30	60
1.5 GHz*	1.35 - 1.75	HEMT	15	6	27
2.3 GHz	2.15 - 2.35	HEMT	15	8	28
4.8 GHz*	4.6 - 5.1	HEMT	15	13	30
8.4 GHz	8.0 - 8.8	HEMT	15	15	36
10.7 GHz**	10.2 - 11.2	HEMT	15	20	40
15 GHz	14.4 - 15.4	HEMT	15	25	46
23 GHz*	21.7 - 24.1	HEMT	15	35	66
43 GHz	42.3 - 43.5	HEMT	15	55	100

* First set of receivers to be installed at each site; others installed later in construction schedule. All bands except 43 GHz have been installed at Pie Town.

** Installed at Pie Town only.

These high-performance receivers are based on very reliable, cryogenically cooled, transistor-amplifiers developed at the NRAO Central Development Laboratory in Charlottesville. Each receiver is completely independent and self-contained, allowing for maintenance and repair at a central location by replacing entire receivers.

Maser Clocks. Sigma Tau Standards Corporation has delivered nine maser clocks. A tenth and an eleventh (as spare) are on order for delivery in 1990. The masers meet specifications (root Allan variance ≤ 2x10E-15 at 10E3-10E4 seconds, ≤ 1x10E-13 at 1 second averaging time). Two masers underwent careful environmental tests at JPL to determine their long-term stability. These test results essentially corroborated those of NRAO and the manufacturer.

Record/Playback Systems. Haystack Observatory has completed the first twelve data recording systems. One acquisition drive has been integrated into the control system digital laboratory at the AOC. Another is installed at Pie Town, where it has been used successfully to record MkIIIA data during Network runs in 1988 and 1989. A third recorder is being held at Haystack for further extensive tests with thin tape samples. Two systems will be equipped for playback application at the correlator laboratory in Charlottesville. A kit to be assembled at the AOC will constitute a third playback drive, again for the Charlottesville lab. An order for eight additional recorders was placed with Haystack for delivery in 1990-91. The narrow track headstacks used in these systems are being manufactured commercially by Honeywell.

It is hoped that the VLBA recorder/playback system and recording format will eventually become the world standard. A number of commercial VLBA recorders will be built for foreign institutions by Interferometrics, Inc., under license from NRAO, for deliveries starting in 1990. To ensure a smooth transition from the present MkIII standard, which is likely to take many years, the VLBA recorders are able to write MkIII tapes. However, there will be certain important limitations on bandwidth and number of channels for mixed standard operations.

Other Electronics. One set of initial-outfitting electronics required at each site has been completed and installed at Pie Town, Kitt Peak, Los Alamos, Fort Davis. One is ready for installation at North Liberty. The remaining equipment required is in routine production.

Correlator. The correlator is designed with inputs for 20 stations (each input accepts eight IF channels) to accommodate large global arrays in which the VLBA is combined with up to ten other stations. The 20 inputs also provide support for other special modes, including extremely wideband VLBA measurements using both station recorders in parallel and simultaneous correlation of two ten-station observations.

To implement such a large-scale system at reasonable cost, NRAO adopted an FX or spectral-domain architecture, based on a dual-purpose application-specific integrated circuit (ASIC). This chip functions as a radix-4 stage in the station-based FFT section. It also functions as a complex multiplier/accumulator in the baseline-forming section. Significant delays were encountered during the design and prototyping of the ASIC, arising from inadequate vendor support and a faulty basic product within which the design was to be implemented. These difficulties were overcome after a total delay of 13 months. Prototype chips are now undergoing extensive functional tests and appear to be satisfactory.

A subsection of the correlator, comprising seven station inputs, each two IF channels wide, will be constructed by the correlator group in Charlottesville. Completion is scheduled for the end of 1991. The size of this subsection is chosen to be sufficient for thorough testing before delivery to the Array Operations Center. The capacity of the subsection will also match the number of VLBA stations expected to be available when the array begins routine operation. Expansion of the correlator to its final configuration will be completed in Socorro.

Software. Software governing local station functions is essentially complete, but is being converted to run under a new operating system. astronomical observing routines are in the final stages of debugging. The converted software handles communications between stations and the Array Control SUN processor running under Unix. Software to handle the received data will be written during 1990. Routinely, the first four VLBA stations are controlled remotely from Socorro.

Much of the software required for imaging has already been developed and installed in AIPS. Development is proceeding on software to interface to the correlator and monitor data base for calibration and editing of data, and for the analysis of geometric data.

Operations Center. Construction of the Array Operations Center was completed in late 1988. This building houses VLBA activities as well as VLA operations staff whose presence is not required at the VLA site. The ability to house operations staff for both arrays in a common building is an important element in the operations plan.

Construction Schedule

The major milestones for the VLBA during the period of this Long Range Plan are:

1990

- Completion of North Liberty IA and Brewster WA stations, for a total of six stations complete;
- Delivery of remaining two maser clocks;
- Construction complete of all 4.8, 8.4 and 23 GHz receivers;
- Completion and delivery of data recording systems through acquisition drive No. 14 and playback drive No. 5;
- Array Control Computer operational.

1991

- Completion of Owens Valley CA, and St. Croix VI stations;
- Completion of subsection of correlator, with 7-station, 2-channel capability, and installation in the AOC;
- Completion of most receiver construction;
- Completion and delivery of data recording systems through acquisition drive No. 22 and playback drive No. 13.

1992

- Completion of the Hancock NH and Mauna Kea HI stations.
- Completion of the correlator;
- Completion of post-processing computers installation;
- Delivery of remainder of playback drives through No. 24;
- All stations operational.

Long Range Prospects

Millimeter-Wavelength Receivers. Each of the ten elements of the VLBA are the most precise antennas of this size in the United States. It is anticipated that they will be useful at wavelengths as short as 3.5 mm. Successful VLBI observations using millimeter telescopes have been demonstrated at this wavelength. By equipping the VLBA with 3.5 mm receivers, it will be possible to further improve the resolution by a factor of two. Ten of these receivers are estimated to cost a total of $500k or more, but there may be other costs required to upgrade the antenna pointing accuracy. It is too early in the project to evaluate these costs.

Intermediate Spacing Antennas. By using the VLA and VLBA together, it will be possible to partially bridge the gap between VLA and VLBA spacings. There are too few antennas to cover this gap adequately. The location of the New Mexico and Arizona antennas has been carefully chosen so that the addition of four more antennas in New Mexico will give a well-designed 41 element array with good (u,v) coverage from antenna separations of 40 meters to 8000 km. This is discussed later in the section on the VLA-VLBA Connection.

Space-Based Antennas. Extension of the VLBA to 3.5 mm will give essentially the highest angular resolution possible from the surface of the earth. At shorter wavelengths, instability of the earth's atmosphere becomes too extreme for correction by conventional VLBI algorithms. To increase high-frequency resolution even further, and to form images with high resolution at lower frequencies, it will be necessary to place at least one interferometer element in space. Two space VLBI projects, the Soviet Radioastron and Japanese VSOP missions, are in the planning stages. An assessment study for IVS (International VLBI Satellite), a more ambitious and longer range project, has been approved by the European Space Agency.

Unfortunately, there is no comparable plan by the United States to extend into space the VLBI techniques which have been developed in this country. NRAO scientists are, however, involved in the planning of the Soviet and Japanese missions and have been invited to contribute to their design and construction. We expect funds will be available from NASA to support this work.

Space VLBI requires an extensive ground array to provide a distribution of earth-space baselines. It is hoped that all the space missions will use the VLBA recording technology and that the VLBA will be used as the major ground support of the space VLBI programs. The VLBA correlator will be able to support space-based elements, although some software enhancements will be necessary. Additional hardware will also be required if incompatible recording systems are employed in recording data from these orbiting elements. Funds for these purposes will be requested from NASA should this become necessary.

Bandwidth Improvements. Finally, the sensitivity of the VLBA will be limited by the bandwidth of the tape recording system. However, this is a rapidly developing technology. For example, Haystack Observatory recently demonstrated over one gigabit per second recording on a VLBA recorder equipped with three extra recording heads. It is likely that these and other very significant improvements in the sensitivity will be possible in the future. This will require upgrading the recording and playback systems.

Operating Plan

Operation of the VLBA presents a major challenge. The antennas are located at remote sites, widely separated from each other, but must operate in concert as a system comparable in complexity to the VLA. Achieving the high reliability of operation demanded by the investment in the array while keeping operations costs at a reasonable level is the goal of this plan. It has been carefully taken into account in the design of the array.

Cost considerations require keeping the staff levels at each of the ten sites to a minimum. The goal is the equivalent of two technician-level personnel at each site for maintenance of continuous, daily 24-hour operation. Subsystems are designed as modular units and those that fail will be exchanged for working units, with all repairs to be made at a central location.

Further economy of operation can be achieved if the operations teams at the central location have joint duties for both the VLA and VLBA. This was an important consideration in the choice of Socorro for the location of the VLBA Operations Center (AOC). It was also the rationale for the decision to make the AOC large enough to house all VLA staff whose presence was not required at the VLA site. The construction of a building larger than that required by VLBA needs alone was made possible by an appropriation of $3M from the State of New Mexico. The VLBA construction project is funding a matching $3M. We estimate the annual cost savings realized by joint operation of the VLA and VLBA in Socorro will be $1M annually.

The following table gives a summary of the annual operating costs of the VLBA in 1990 dollars. These costs are incremental to NRAO's existing operating budget.

Category	Cost ($1990)
Personnel (91 people)	$3.5M
Travel	0.2
Communications and Power	0.9
Materials and Supplies	1.6
Shipping	0.2
New Equipment	0.6
Total	$7.0M

The personnel estimates are based on the following plan and VLA experience.

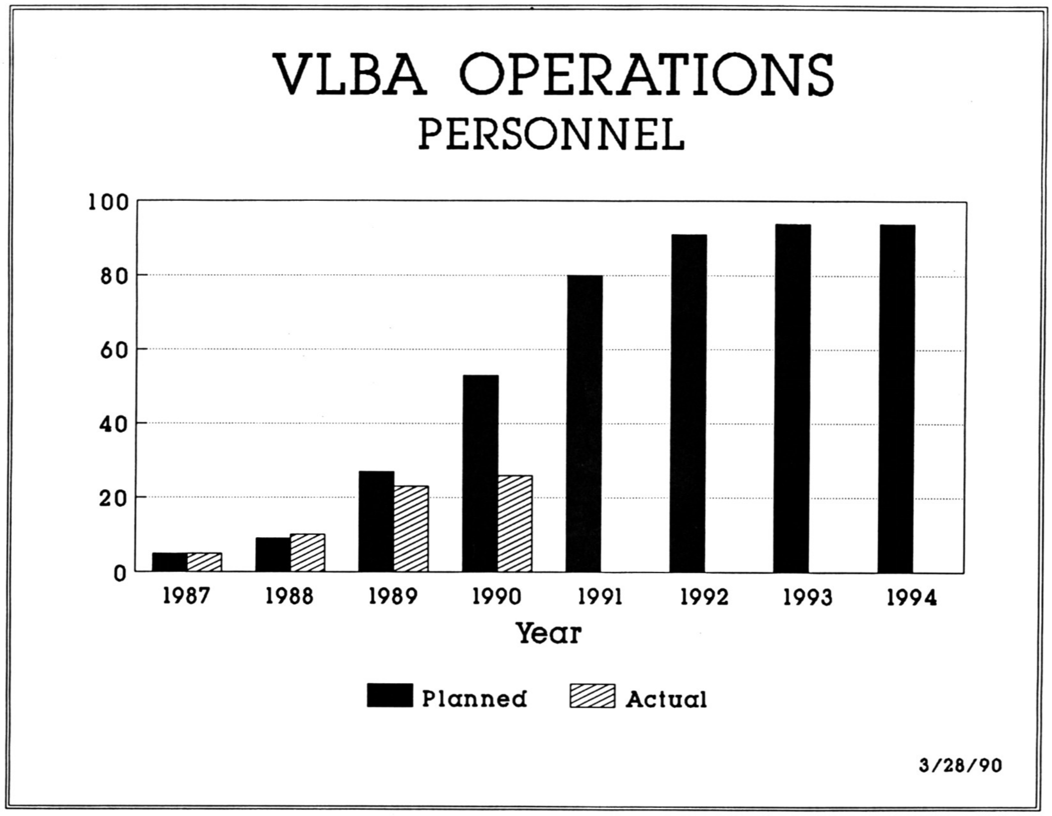
	VLA Alone	VLA & VLBA Combined
VLBA Site Technicians	-	20
Electronics	28	50
Antennas	25	33
Array Operations	13	27
Business	28	34
Computing	17	27
Scientific Services/ Management	17	28
Total	128	219

The difference is 91 additional personnel needed to operate the VLBA jointly with the VLA.

Full operation of the VLBA is not expected until 1992. Operations during construction are to follow this schedule:

- Addition of antennas to operations of the *ad hoc* network of the VLBI consortium as they are completed;
- Operation as a partially completed array in late 1990;
- Stand-alone operation including the correlator in late 1991;
- Full operation of the 10-element array in 1992.

The funding schedule for interim operations was planned to be a roughly linear ramp up to $7M in 1992 (in 1990 dollars) from a very modest start in 1987. The actual funds available for VLBA operations have been $0.2M (1987), $0.5M (1988), $0.9M (1989) and $1.275M (1990). See Figures 1a and 1b. This means that only the Pie Town and Kitt Peak antennas will be operated for the VLBI Network observing runs in 1990. Regular operation of these two antennas in VLBI Network runs checks out the system in actual observing by users, revealing problems early for timely correction. However, the delay in using the other sites as they become available limits the VLBI science that can be done during this period and puts difficult dislocations in what was to be a smooth growth in staff and operations funding.



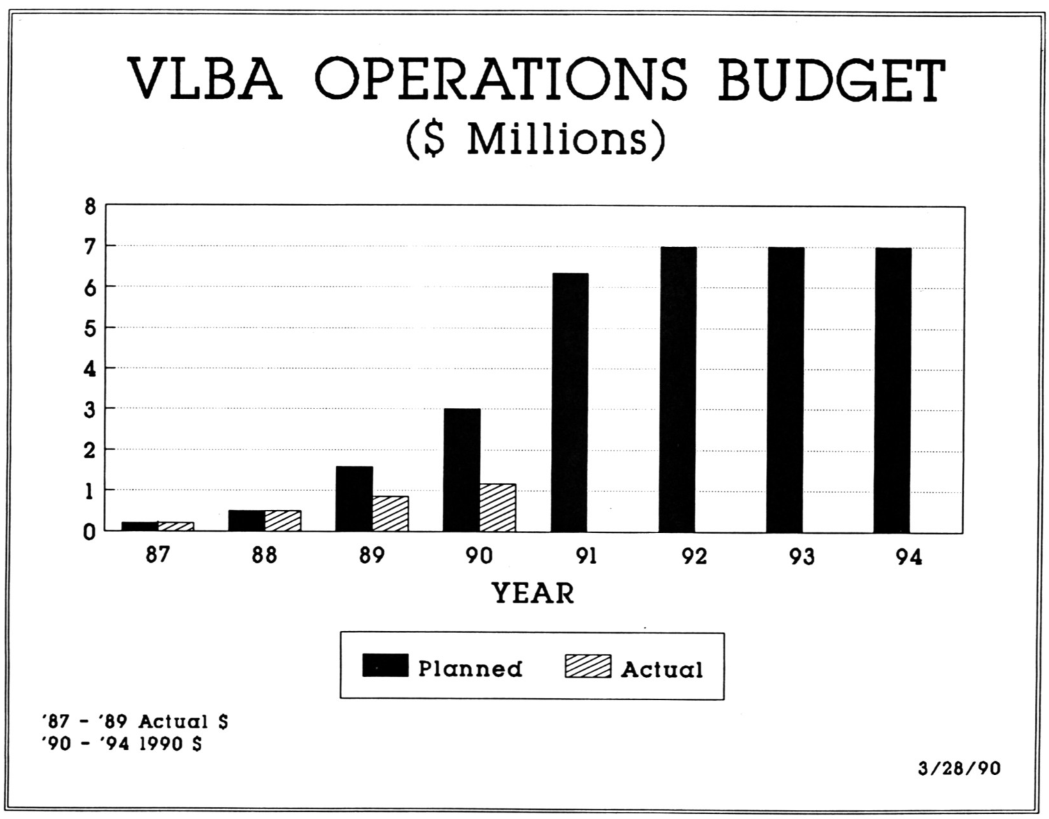


Figure III. 1a. VLBA operations staffing levels--plan compared with actual; Figure 1b same for operations budget levels.

THE GREEN BANK TELESCOPE

Following NSF approval of the Green Bank Telescope (GBT) project and the inital funding, an intense design effort began with the goal of producing a truly advanced concept for the telescope. The GBT will make major contributions to the study of the structure of the universe, the gas content of galaxies, solar and stellar phenomena, interstellar molecular clouds, star formation and stellar evolution, the evolution of galaxies, the solar system, quasars, active galactic nuclei and radio galaxies, the establishment of fundamental catalogues of radio sources, and the search for extraterrestrial intelligence. Its application to studies of galaxies is of particular interest. With its great sensitivity at decimeter wavelengths, it will be able to measure the redshifted hydrogen emission line of numerous galaxies, both in the field and in clusters of galaxies. Moreover, because it will have a large collecting area at wavelengths near 7 millimeters, it will be able to study effectively galaxies at high redshift, using the redshifted carbon monoxide emission line. For pulsars, the GBT offers enhanced capability because of its great collecting area, its ability to track horizon to horizon, and its location in the National Radio Quiet Zone. When used in conjunction with the VLBA or the proposed Soviet and Japanese space VLBI missions, the new telescope will provide a dramatic improvement in sensitivity for high resolution imaging of a many kinds of celestial objects. Last, it can be a passive element in bi-static radar astronomy of solar system objects.

At all wavelengths the sensitivity of the telescope will exceed by a substantial margin that of the 300-foot or the 140-foot. To maximize the performance of the GBT, and to ensure it will function as a world-class instrument well into the next century, two innovations have been adopted in the current design.

The first innovation is that the antenna will have an unblocked aperture. This design significantly reduces the level of distant sidelobes which confuse the measurements of faint hydrogen emission from the galaxy and which may also deteriorate continuum and spectral line observations as a result of solar or terrestrial interference. The improved performance is obtained by eliminating entirely the blockage caused by the subreflector and prime focus support structure. The absence of this support structure also reduces multiple reflections which often limit the effective sensitivity of spectroscopic measurements. Although this concept has been successfully demonstrated in smaller antennas, the GBT will be the largest antenna to utilize it.

The second innovation of the GBT is the active adjustment of its surface panels to correct the shape of the reflector for deformations induced by gravity as the elevation of the telescope is changed. The actuators will be set under computer control to positions given by a calibrated look-up table. The panels themselves will be manufactured with a specified surface accuracy of 75 microns. With the largest part of the gravitational deflection removed by this means, the GBT should work with good efficiency to wavelengths as short as 7 millimeters, under favorable conditions of wind and sunlight. At this wavelength the telescope will have a beamwidth of 18 arcseconds between the half-power points.

To ensure that the telescope will be able to address many of the important outstanding research problems, the design is also attempting to meet the following constraints:

- Sky Coverage. The GBT will be able to observe 85 percent of the celestial sphere (all declinations north of -45°) This includes the entire ecliptic plane; important molecular clouds; two-thirds of the galactic plane, including the galactic center; 85 percent of all globular clusters; and many nearby clusters of galaxies. Because it can track from horizon to horizon, it will undertake long integrations on faint sources, timing measurements of pulsars, and VLBI observations in conjunction with earth satellites or as an adjunct to the VLBA.

- Protection from Interference. The GBT will have as strong protection from man-made radio interference as is possible, since Green Bank is located in the National Radio Quiet Zone. This unique legal protection from interfering signals permits observations both at very low frequencies and at scientifically important frequencies outside the standard radio astronomy protected bands. The design of the GBT and its associated equipment will place high importance on minimizing or eliminating any new sources of RFI.

- Versatility. Ultimately the GBT will be equipped with receivers that allow nearly continuous frequency coverage from a frequency near 100 MHz to the highest frequencies supported by the telescope. The current design effort on the optics of the telescope attempts to make such frequency flexibility possible.

The project staff began the in-house design of the telescope in the late summer of 1989 under the leadership of D. S. Heeschen. In November, R. D. Hall joined the NRAO and became Project Manager. At present the preliminary design of the reflector backup structure is being optimized to have minimum gravitational deflection and minimum weight. Preliminary concepts of both the feed arm and the azimuth support structure have been proposed, and the design has started. The telescope's optics are at the final stage of study. The plan envisions two gregorian subreflectors, of diameters 8 meters and 3 meters for low and high frequencies, respectively. There will be easy access to the prime focus for low frequency systems or for multi-beaming systems.

Considerable effort is being expended in the design and development of systems to provide accurate pointing and surface control for the antenna. The manufacturer of the telescope will be expected to use good construction practices yielding tolerances that are sufficiently strict to enable the GBT to operate at a wavelength of 2 centimeters. Then, the necessary extra precision in pointing will be provided by a system now under development at NRAO. In addition, the necessary improvement in surface precision will be achieved by adjustment of the surface using an actuator system also developed here. The resulting design will be an affordable telescope that operates with good efficiency ($\eta_{aperture}$ = 50%) and pointing (rms error = 1".7 = 1/10 beam) at 43 GHz.

A development project has been initiated to attempt to extend the useful performance of the GBT to still higher frequencies. To improve the surface setting accuracy, a surface metrology system must be devised to measure the thermal distortions of the dish, which the gravitational look-up table does not address. A prototype system based on laser-ranging technology is being assembled. It could, in principle, form the basis of the further improvement in pointing required for operation above 43 GHz. It is hoped that by the time the telescope begins operation surface metrology and pointing systems will have been found which allow operation with useful efficiency and pointing accuracy to frequencies as high as 115 GHz.

A request for a proposal to design and construct the GBT will be issued in early June, 1990. The remainder of this calendar year will be spent in the evaluation of the proposals as well as in the continued design and development of the precision systems for which NRAO has the principal responsibility. The award of the contract, following appropriate NSF approval, will be made early in 1991. Work on the foundation will begin in Green Bank later in 1991. The detailed design and drawings should be completed in the summer of 1992. By then fabrication of certain parts of the structure will have begun, and site development will be complete. On-site fabrication and the early stages of assembly and erection will begin in 1992, and will last for approximately two years. During this time work will begin on the monitor and control system and on the associated electronics. Towards the end of 1994 the outfitting and testing of the antenna will start. The goal is to begin routine operations at the outset of 1995.

With the GBT operational in the last year of the present long range plan, 1995, we will cease operation of the 140-foot telescope as an NSF-funded visitor facility. At this time there will be a transition of the 140-foot operational and support staff to the GBT. The incremental operations cost of the GBT will therefore be kept to a minimum. However, the transition from a mature facility to a new and pioneering instrument will require some investment in augmentations to the telescope development staff. The costs are subsumed in the 1995 budget and personnel schedules in Chapter VI.

The two areas requiring most development work in the first year of GBT operations, and beyond, are (1) telescope electronics design and construction, and (2) telescope software. The enormous frequency range made accessible by the GBT--three orders of magnitude, from 100 MHz to 100 GHz--is a significant expansion on that available to the 140-foot telescope. To instrument the telescope properly with receiving equipment will require engineers and technicians having skills complementary to those of the existing staff. Perhaps even more important than front-end engineers are designers of digital signal processing hardware for the backend electronics. For its effective scientific utilization, the GBT should be equipped with a very wideband, flexible, multichannel spectrometer and pulsar processor. The design and fabrication of such a device will be a substantial challenge made only somewhat simpler by the development work that has gone into the VLBA correlator. Processing the data output from this and other GBT receivers will also require an increased effort commensurate with the increases in capabilities the new instrumentation provides over the 140-foot equipment. Software designers, scientists, and programmers with modern approaches to data management will have the responsibility to organize the data for the astronomer's review, analysis, and export.

IV. BASE PROGRAM

VERY LARGE ARRAY

Status of Present System. The Very Large Array is the ultimate radio astronomical tool for acquiring radio "pictures" across the full diversity of the radio sky with a resolution similar to or better than that obtained by the world's major telescopes at other wavelengths. Multiwavelength investigations of the broad range of astronomical objects from the sun and planets to stars, galaxies, and quasars are now no longer hindered by inferior resolution in the radio band. The combination of VLA sensitivity, angular resolution, frequency flexibility, and adjustable baseline configuration has propelled the instrument to the forefront of many non-traditional radio astronomical investigations in a way that was totally unpredicted by its designers. A full decade after its completion the size of the VLA user community and the annual publication rate continue to increase. Ground support follow-up radio observations for the Hubble Space Telescope and the NASA "Great Observatories" promise an even stronger user base in the future. Future joint VLA/VLBA observations offer prospects of a further increase in the quality of radio images and thus in our understanding of the physics of cosmic sources of radio emission.

Present Instrumentation

The VLA consists of twenty-seven 25-meter antennas arranged in a wye-configuration, nine antennas on each arm of the wye. The antennas are transportable along double rail track and may be positioned at any of 72 possible stations. In practice the antennas are rotated among four standard configurations which provide a maximum baseline along each arm of 0.59, 1.95, 6.39, and 21.0 km, respectively. Reconfigurability provides the VLA with variable resolution at fixed frequency.

The VLA supports six frequency bands, remotely selectable; the five upper bands by means of subreflector rotation. When the VLA became fully operational in 1981, receiving systems were supported at 1.4, 5.0, 14.4, and 22.5 GHz, with the fundamental amplification at all four frequencies occurring with a 5 GHz parametric amplifier--1.4 GHz was preceded by a parametric-upconversion to 5 GHz, whereas both 14.4 and 23 GHz were mixed down to 5 GHz for amplification. Since 1981, most of these systems have undergone major improvements. Presently,

- 1.4 GHz amplification is done at the signal frequency with a cryogenic GaAsFET developed at the NRAO Central Development Laboratory (CDL);

- 5.0 GHz amplifiers are nearly all CDL GaAsFETs;

- 14.4 GHz amplification is done at the signal frequency with CDL GaAsFET amplifiers;

- 23 GHz amplifiers are CDL HEMT units.

In addition, two new frequency bands have been installed.

- 8 GHz HEMT amplifiers have been added to all antennas. This X-band system was constructed with funding provided by NASA/JPL in support of the Voyager 2 encounter with Neptune.
- 327 MHz prime focus FET receivers were installed.

The table below summarizes the parameters of the VLA receiver system.

VLA Receiving System

Frequency (GHz)	T_{sys}(K)	Amplifier
0.308 - 0.343	150	GaAsFET
1.34 - 1.73	60	Cooled GaAsFET
4.5 - 5.0	60	Cooled GaAsFET
8.0 - 8.8	35	Cooled HEMT
14.4 - 15.4	110	Cooled GaAsFET
22.0 - 24.0	180	Cooled HEMT

The VLA receives two IFs with full polarization capability in continuum bandwidths ranging from 50 MHz to 195 kHz. Within certain total bandwidth limitations, 512-channel spectroscopy is supported in all bands.

Future Plans - Electronics

When the VLA went into operation in 1980, it gave an improvement in resolution, sensitivity, speed, and image quality of more than two orders of magnitude. Since that time, the VLA has been an extraordinarily productive scientific instrument, used by more than 1200 astronomers for a wide variety of investigations, including solar system, galactic, and extragalactic research. However, as a result of technological advances during the past decade, much of the instrumentation is seriously out of date. Major replacement and upgrading of the instrumentation is needed to keep the VLA at its current leading position among the world's radio astronomy facilities.

When designed in the mid 1970's, the VLA used state-of-the-art technology. Over the last fifteen years, however, there have been major advances in receiver sensitivity, correlator design, and the transmission of broadband signals which have already been incorporated into other new radio telescopes such as the VLBA, the Australia Telescope, and the Nobeyama millimeter interferometer. In its current configuration, the VLA can still observe radio sources which are two orders of magnitude fainter than has been observed by any other radio telescope. By using modern low noise radiometers, fiber optic transmission lines, and a broad bandwidth correlator, it will be possible to gain <u>another</u> order of magnitude improvement in sensitivity. New receivers are also needed at wavelengths not presently covered in order to extend both the spectral coverage and the range of sensitivity to low surface brightness observations.

The scheduled completion of the VLBA in 1992 will give a milli-arcsecond imaging capability to complement the arcsecond capability of the VLA. There still remains, however, a gap in the range between the largest spacings of the VLA (up to 35 km) and the smallest spacings of the VLBA (about 200 km). The baselines between Pie Town and the VLA and between Los Alamos and the VLA lie in this gap. The location of these VLBA antennas was chosen in part to partially cover this range of spacings. However, the addition of four new antennas is needed to give good image quality, with a resolution about an order of magnitude greater than that of the VLA. This will permit scaled observations at a fixed resolution between about 0.01 arcseconds to 0.1 arcseconds over a wide range of frequencies.

Receiver Upgrade and Addition Program

The receiver upgrade and addition program will be described here. The program to expand the bandwidth of the VLA by replacing the correlator and substituting fiber optics for the waveguide is described in a later section, as is the addition of antennas to fill the intermediate spacings between the VLA and VLBA.

Completion of 327/75 MHz Capability. The P-band (327 MHz) system is "complete" only in the sense that all 28 antennas have P-band receivers installed and operational. However, only four antennas have RFI shielding installed on their B-racks. Without this shielding the self-generated RFI environment provides a strict limit of 3 MHz on the useful P-band bandwidth and hence on the array sensitivity at this frequency. As a result the basic sensitivity of the VLA at 327 MHz compares unfavorably to that at 20 cm, for example, even when account is taken of the steep spectrum of many cosmic non-thermal sources. RFI shielding must be installed on all antennas before P-band observations can reach their potential sensitivity and fidelity using bandwidths of 12.5 and perhaps even 25 MHz.

Eight VLA antennas have been outfitted with simple dipole feeds to explore the feasibility of VLA observing at 75 MHz. Initial tests with this system have been encouraging. A 100:1 dynamic range image of the radio galaxy Cyg A at a resolution of 20 arcseconds has been made. Future research programs will include the studies of steep-spectrum components of radio galaxies and quasars, the haloes of normal galaxies, the spectra of more compact sources, imaging of supernova remnants, searches for steep-spectrum galactic sources such as millisecond pulsars, studies of diffuse HII in absorption against the nonthermal background, flare stars, interstellar propagation effects, and solar system objects.

Receiver Upgrades and Additional Bands. New receivers based on cooled low noise HEMPT amplifiers are needed to lower the system temperature at all bands except 3.6 cm where these devices already exist. The proposed receivers are based on designs already implemented at the VLBA. With the current VLA design, there is a large contribution to the system temperature from the uncooled polarizer located at the base of each feed, plus the waveguide runs to the common cryogenically cooled first-stage amplifier. Advances in cryogenics now allow each polarizer to be individually cooled, together with the first stage amplification within the same dewar. The required cryogenic capacity is already in place. This approach has been taken with the VLBA receivers and with the VLA's new 3.6 cm system where these devices are already installed as a result of the VLA's participation in the Voyager Neptune encounter. The resulting system temperature at this band of 35 K makes this by far the most sensitive of all the VLA's observing bands. Implementing both the above items will improve the sensitivity of the VLA by over a factor of two at the 2, 3, and 18-21 cm bands and by nearly a factor of three at 1.3 cm.

L-Band Sensitivity Improvements. Spectroscopic observations with the VLA at 21 cm are limited in sensitivity by the ten year old frontend design, which provides 50-60 K system temperatures with all of the front-ends in the same dewar. Twenty centimeter sensitivity is the most important commodity to the nearly 15 percent of VLA users who study extragalactic HI; the high system temperature is the greatest impediment to their research. The solution to this situation is replacement of all the L-band receivers with HEMT amplifiers in independent dewars as is done on the VLBA antennas. Currently one VLA antenna is equipped with a VLBA style L-band receiver. A program is in progress to completely equip the VLA with these receivers by the end of 1993. In 1990, we hope to have seven antennas finished.

C, Ku, and K-Band Improvements. The improvement to the L-band system sensitivity that can be achieved by the installation of VLBA-style receivers applies equally well to the C, Ku, and K-band systems (6, 2, 1.3 cm, respectively). These three bands must be upgraded simultaneously as there is insufficient space to allow the present large four-frequency dewar to remain in place while each of its frequencies is upgraded to a separate VLBA-style receiver. (The L-band feed location is sufficiently far from the dewar to allow separate replacement of that frequency, as outlined above.)

The following table shows the expected improvements.

Potential VLA Receiver Improvements
System Temperature (K)

Frequency (GHz)	Present VLA	Achieved VLBA	Integration Time Ratios
1.3-1.8	60	25	5.8
4.5-5.0	60	25	5.8
14-15	110	48	5.3
22-25	180	85	4.5

The improvement in observing efficiency is dramatic. Alternatively, the limiting flux density sensitivity that can be achieved in long but reasonable integration times, and thus produces new kinds of science, drops by a factor of roughly two.

Receiver Upgrade - New Bands. For observing programs that combine VLA and VLBA data, or even include both arrays simultaneously, having the same frequency bands available on both arrays is highly desirable. That means adding 2.3 GHz, 43 GHz, and 610 MHz to the VLA. The 610 MHz and 2.7 GHz bands are intended to fill in the gaps in existing coverage, while the 43 GHz system will improve the resolution by a factor of two. The additonal frequencies are all important for continuum studies of spectral shape as well as the effect of Faraday rotation and depolarization which are tied to specific critical frequency regimes that are determined by source physics; for pulsar work where the critical frequencies of observation are determined by the spectra and dispersion; and for unique spectral lines such as SiO at 43 GHz. A schedule for doing so, together with estimated costs, is given in the following table, both for these new bands and the improvements to existing bands already discussed.

VLA Receiver Upgrade Schedule (M$)

Frequency (GHz)	1990	1991	1992	1993	1994	1995
1.3-1.8	0.2	0.4	1.2			
4.5-5.0 14-15 22-25			3.0	3.0		
2.3				2.5		
43					4.0	
0.61						3.5

The L-band system work done in 1990 has been included in the current Research Equipment Plan as the top priority for the VLA. The other costs in the above table for L-band and all other frequencies have been put into the VLA Receiver Upgrade line of the budget projection table.

Increased Angular Resolution. Many types of radio sources have physically interesting structures that are barely resolved with the VLA but which do not require VLBI resolution. These include galactic circumstellar sources, compact HII regions, bipolar outflow sources, filaments and knots in supernova shells, filaments and knots in extragalactic jets, and "hot spots" in the lobes of radio galaxies and quasars. For nonthermal sources one cannot simply increase the resolution by increasing the frequency, as brightness sensitivity is also essential. Studies of Faraday depth or of radio spectra must also be done at given frequencies to address given physical questions. The ability to vary the VLA's configuration to obtain "scaled arrays" has been vital to its success as an astrophysical instrument--but this capability is restricted to resolutions of 1 arcsecond or lower at 20 cm and to 5 arcseconds or lower at 90 cm. We can increase the angular resolution of the VLA by linking it to the Pie Town VLBA antenna. This has recently become more feasible as a result of the installation of an AT&T commercial optical fiber west along U.S. 60 from Socorro that passes both the VLA and Pie Town. We will investigate use of this link. To complete the system, the delay, fringe-rotation, and control systems for the VLA must also be expanded. In so doing, we will double the resolution of the VLA for northern sources, but the imaging quality at this resolution will be of low fidelity. True imaging requires additional antennas, as discussed in the description of the VLA-VLBA connection program.

12-METER TELESCOPE

The NRAO 12-meter telescope began as the 36-foot telescope, the telescope responsible for the birth of millimeter-wavelength molecular astronomy. Following a period of explosive growth in this new area of astronomical research, during which most of the dozens of molecular species known to exist in the interstellar medium were first detected at the 36-foot, the telescope's reflecting surface and surface support structure were replaced and the 36-foot was re-christened in 1984 as the 12-meter. Subsequently, the scientific program has evolved from one dominated by observing programs in astrochemistry to one with concentrations on studies of molecular clouds and galactic star formation, evolved stars, and, more recently, studies of external galaxies. The 12-meter is the only millimeter-wavelength telescope operated full-time as a national facility. More than 150 visitors make use of the telescope annually. It offers users flexibility and the opportunity to respond quickly to new scientific developments. Low-noise receiving systems at a wide range of frequencies are maintained and operational reliability throughout is emphasized. The development of multi-beam receivers has inaugurated a new era of high speed source mapping on angular scales complementary to those of the millimeter-wave interferometers.

Present Instrumentation

The basic specifications of the 12-meter telescope, its site, receivers, and spectrometers are given below:

Telescope Specifications

Diameter: 12 m
Astrodome with slit
Pointing accuracy 5"
Effective surface accuracy: 50-60 μm rms
Aperture efficiency = 49% at 70 GHz
45% at 115 GHz
25% at 230 GHz
15% at 345 GHz

As many as four receivers are mounted simultaneously at offset Cassegrain foci on the telescope. Receiver selection is by means of a rotating central mirror and can be accomplished in minutes.

Receiver List

Frequency Range (GHz)	Mixer	SSB Receiver Temp. (K) (per polarization channel)
70-115	Schottky	350-500
90-115	SIS	80-150
200-240	SIS	200-400
200-240	Schottky	500-700
240-270	Schottky	1200
270-310	Schottky	1200-1500
330-360	Schottky	1800-2200
Eight-beam Receiver		
220-240	8-Schottky	500-700

Note: The 200-240 GHz SIS receiver has been tested successfully on the telescope and will be available for routine use in the fall of 1990. All single beam receivers have two orthogonal polarization channels. Receiver temperatures include all receiver optics.

The following filter bank spectrometers are maintained so that the astronomer will have access to the proper frequency resolution for a particular astronomical observation.

Resolution (kHz) per channel	Number of channels	Number of filter banks
25	256	1
30	128	1
100	256	1
250	256	1
500	256	1
1000	256	2
2000	256	2

Note: All filter banks except the 25 and 30 kHz units can be divided into two 128-channel sections to accept two independent IF channels. The 25 kHz filters use the spectrum expander.

To enhance the telescope's spectroscopic capability and to accommodate the 8-beam receiver, a hybrid filter bank/autocorrelator is now available. Its instrumental parameters are as follows:

- maximum total bandwidth options:

  1 x 2400 MHz
  2 x 1200 MHz
  4 x 600 MHz
  8 x 300 MHz

- frequency resolution (per channel): variable in steps of two continuously between 1.56 MHz and 24 kHz.

Future Instrumentation Plans

Most millimeter-wave spectroscopic studies of star formation, interstellar chemistry, galactic and extragalactic composition, etc., require observations of a number of molecules in a number of transitions, occurring at many different frequencies. These studies can be carried out most expeditiously, and most thoroughly, if high-sensitivity receivers are available for all the atmospheric windows, and if a high-speed imaging capability is available at the most important wavelengths. Together, these requirements define the focus of the long range plans for the 12-meter.

All the developments described here are of immediate relevance to the 12-meter telescope, and most are equally relevant to the MMA.

One-millimeter Imaging SIS System

Millimeter-wave telescopes inevitably have small beams, and, hence, with the usual single beam system, true imaging of large fields is particularly difficult and time-consuming. For large-scale imaging, the smaller diameter of the 12-meter telescope compared, e.g., with the IRAM 30-meter telescope in Spain, is no disadvantage. We plan to provide a powerful imaging system at our optimum wavelength of 1.3 mm.

To this end, we have already developed an 8-feed Schottky mixer system. This has been interfaced to our new 1536 channel hybrid spectrometer, and was made available to observers during the 1989-90 season. At this stage the full versatility of the hybrid spectrometer is not yet available--budget considerations have caused us to implement a cut-down compromise design. We hope that funding will enable us to complete this project according to the original specifications.

During 1990-91, we will upgrade the eight Schottky mixers to use SIS devices, thereby giving us state-of-the-art sensitivity in all feeds. We plan to have a 32-feed SIS system operational during 1994. The key to this development is the backend electronics. We have started developing a prototype acousto-optic spectrometer, which will eventually become an 8-spectrometer system to extend the usefulness of the 8-feed system. In addition, we will initiate shortly a project for a new 32-section digital spectrometer for the full imaging system planned with the 32-beam SIS system. The digital system will provide the full resolution and bandwidth versatility required for both galactic and extragalactic observations. Of course this puts severe demands on the computer hardware and software. We are in the process of updating our real-time telescope control system (both hardware and software) to allow support of these future developments. Planning has begun for a multi-workstation environment at the telescope to support data analysis of the 8-beam imaging system. The data acquisition rate will have increased by between 1 and 2 orders of magnitude. A great deal of new computer hardware and software development will be required in the next three to four years.

Single-Beam Systems

Receivers. NRAO has traditionally provided receivers equalling or bettering any others in the world, and this is particularly true at mm wavelengths. A prototype closed cycle 4.2 K system capable of holding several SIS receivers sharing the same dewar has been completed. This will enable, by the early 1990's, a complete set of state-of-the-art dual-channel SIS receivers to be operational over the entire range 70-360 GHz. The arrangement of several receivers sharing the same dewar is extremely effective in terms of cost, manpower, and in operational demands. These will equal or better the sensitivity of any existing receivers in the world.

To enhance further the flexibility and data acquisition efficiency, we are exploring the possibilities of simultaneous observations in different frequency bands through the use of beam splitters. This would be an important development for the future MMA.

Antenna Improvements

Pointing. Especially with the new 12-meter shaped subreflector (a project carried out in cooperation with the University of Texas), operation of the 12-meter telescope at the highest frequencies (360 GHz) is becoming important. This puts a more critical demand on the pointing characteristics of the telescope. In order to improve the pointing, we have implemented the following in the past year: real-time monitoring of movements of the focus assembly using a laser and quadrant detector and an improved focus (Sterling) mount offering more freedom of movement and more precise control. We expect to implement additional instrumentation (inclinometers, strain guages, temperature sensors), replacement of feed legs with a carbon-fiber design giving less temperature dependence and less aperture blockage, and a sun screen to reduce thermal distortions of the telescope during daytime operation. We have conducted successful experiments with an auxiliary optical pointing system, observing stars optically as an aid to better understanding of the pointing characteristics of the telescope. We intend to explore a higher level of automation, with the possibility of offset guiding on optical stars to give accurate tracking of weak radio sources.

Active Secondary Optics. Further improvements in the aperture efficiency of the 12-meter can only be accomplished through active, correcting optics. The primary reflector has been "tweaked" to the extent possible and the shaped subreflector has made further substantial improvements, however, the 12-meter exhibits significant gain-elevation correcting optics. The primary reflector has been "tweaked" to the extent possible and the shaped subreflector has made further substantial improvements, however, the 12-meter exhibits significant gain-elevation defects owing to the distortion of the primary reflector and backup structure under the force of gravity as the telescope moves through its range of elevation angles. Since the shaped subreflector must be configured for a given elevation angle, active optics are required to remove the gain-elevation effects. Two options are available: active adjustment of the primary reflector (such as with the GBT and Keck optical telescope), or active adjustment of the secondary (or tertiary) optics. Adjustment of the primary may produce the overall best results, but it is costly and would require significant down-time for the 12-meter. Active secondary optics (e.g., a deformable subreflector) is the best option for the 12-meter. It is technically feasible, more economical, and would result in no telescope down-time (i.e., it could be developed totally in the laboratory). Considerable expertise in this area exists among the 12-meter staff and in the Tucson astronomical communitity. This project will be initiated shortly.

Future Plans

In addition to continued improvements in the 12-meter, the Tucson staff expects to play a growing role in the development of the Millimeter Array. As the MMA project develops, there will be the necessity for real hardware design, prototyping, and testing, including multi-band, millimeter and submillimeter-wave receivers, digital spectrometers, and continuum backends. The Tucson staff is essential to this aspect of the MMA development work.

We have also outlined two future projects. With current budget constraints, we are unable to realize our plans, but should the financial climate change in the coming years then the following projects should be considered for support:

A New 15-Meter Millimeter-Wave Telescope. A disparity currently exists between the antenna performance--in terms of diameter, surface accuracy, or both--of U.S. millimeter wave telescopes and those of other countries. Assuming even optimistic funding and development time scales for the MMA, this disparity is likely to persist for most of the next decade, unless steps are taken quickly. Hence, we propose to purchase a copy of the IRAM 15-meter telescope, which already exists. The Swedish-ESO SEST project has shown that this design can provide an operational installation within two years. We estimate the cost to be approximately $6M capital expenditure. This cost is small enough that the project is easily justifiable as an essential stop-gap measure that should have only positive impact on the much larger MMA project. The instrumentation, frontend and backend, would be transferred from the 12-meter telescope. Operation of the 12-meter by NRAO would be phased out so that operating costs of the new telescope would be covered by the existing funds allocated to the 12-meter. A higher, developed site in Arizona would be chosen, and both the site and the new antenna would support efficient operation into the submillimeter region.

The requirement that the replacement telescope be placed in operation quickly essentially precludes NSF funding, given the current combination of tight budgets, heavy demands on the NSF for other projects, and the long process of review and prioritization. For this reason no funds have been included in the table in Chapter V of this Plan. An alternate plan is under consideration, modeled after the Kitt Peak WIN telescope, that would secure the replacement telescope with funds assembled privately by a group of universities. NRAO would operate the telescope until the MMA was completed and then turn the operation of the 15-meter telescope over to the university group.

Arizona Array. This is a plan for a millimeter-wave VLBA, filling the gap between the proposed NRAO MMA and existing millimeter-wave VLBI operation. The initial baselines would be from 70 km up to nearly 200 km. The first stage of this project would be operation using existing mountaintop telescopes in Arizona, with optical links and real-time correlation of signals. The longer term aim would be for an array of about ten dedicated antennas, e.g., duplicates of the MMA antenna design, using mainly developed sites but filling in more UV coverage over a range of baselines from 10 km to 200 km. The first stage of this project could be implemented for approximately $1M, with some additional manpower.

140-FOOT TELESCOPE

The period 1991-94 represents an extremely important transition era for the 140-foot telescope. The major goals for it during this period are (1) to build momentum toward the Green Bank Telescope in the centimeter-wavelength, single-dish research community and (2) to stay at the forefront of telescope instrumentation so the move to the GBT proceeds smoothly.

Major Research Goals

The first goal, nurturing and strengthening the single-dish research community, will be achieved by relying on the unique versatility of the 140-foot telescope. Some of the characteristics that make it distinctive and therefore in demand by astronomers are:

- Frequency coverage. With very few gaps, sensitive receivers are available throughout the frequency range 100 MHz to 25 GHz. Often the Green Bank receivers define the state-of-the-art in radio astronomy.

- Stable spectral baselines. Detection of broad, weak, spectral features may be limited by instabilities in the RF/IF systems to a greater extent than by receiver noise. Exceptional care is taken to minimize these effects.

- The telescope is accessible. The 140-foot telescope is dedicated fulltime to radio astronomical research. Astronomers are encouraged to bring their own instrumentation and/or to experiment with nonconventional observing techniques.

The now "standard" spectroscopic observing procedures at the 140-foot--e.g., total power, and nutating dual-beam--all resulted from users' experiments and experience.

- Simultaneous dual-frequency operation. Between 8 and 25 GHz astronomers can observe at two different frequencies simultaneously. This permits reliable comparison of two molecular species or two lines of a single species.

- High-time resolution. The spectral processor provides a unique combination of large bandwidth and number of channels for detailed study of pulsars. It also provides interference rejection, essential to observations at frequencies below 1 GHz.

- National Radio Quiet Zone (NRQZ). The 140-foot telescope enjoys the unique protection of the NRQZ. Green Bank remains one of the few sites where observations over the range 25-250 MHz remain possible. Frequencies > 250 MHz are also interference-free by comparison with the RFI environments of other radio observatories.

The major areas of scientific research envisioned for the 140-foot telescope during 1991-94 are pulsars, large scale structure of the universe, spectroscopy, and very long baseline interferometry (VLBI). The focus of pulsar research has shifted to the search for and study of millisecond and binary pulsars. The 140-foot telescope's sensitive receivers, relatively interference-free environment, spectral processor, and full-sky coverage (particularly to the Galactic Center) make it competitive with any existing radio telescope. The figure (Fig. 2) shows a one-hour integration at 1.67 GHz of PSR1745-24, an eclipsing binary pulsar in the globular cluster Terzan 5. This is the highest frequency at which the pulsar has been detected. The plasma causing the eclipse is therefore probed to a greater depth than at lower frequencies.

Some of the same advantages that enable world-class pulsar research also equip the 140-foot telescope to make HI redshift measurements of galaxies necessary to map supergalactic structures in all three dimensions. Spectroscopic research has shifted toward studying particular objects--circumstellar shells, HII regions, dark molecular clouds, etc.--over as broad a frequency range as possible, i.e., surveying in frequency space. In this way, new spectroscopic features are discovered that require laboratory studies to identify, a reversal of the early years of astrochemical research. As one example of new discoveries, various ^{13}C isotopes of HC_5N have been detected. VLBI also continues to rely on the sensitivity of the 140-foot telescope.

Present Instrumentation

Telescope Specifications

Diameter:	140 feet (43 meters)
Pointing Accuracy:	7"
Sky Coverage:	-46° to 90° declination.
Fully steerable. Tracking time is 3 hours at d = -45°, 7 hours at -30°, 10 hours at 0°, and 13 hours for all d > 20°.	
Sensitivity:	0.26 K Jy^{-1}
Surface Accuracy:	0.7 mm (rms)

Receivers at frequencies lower than 5 GHz are mounted at prime focus. Two high frequency maser/upconverter receivers are mounted at the Cassegrain focus. Both Cassegrain receivers cover the entire range 5-25 GHz and may be used simultaneously at frequencies above 8 GHz by a polarization splitter mounted on the optical axis at the Cassegrain focus. When both Cassegrain receivers are used simultaneously, they can be tuned independently throughout the range 8-25 GHz. In this way true simultaneous dual-frequency observations may be conducted.

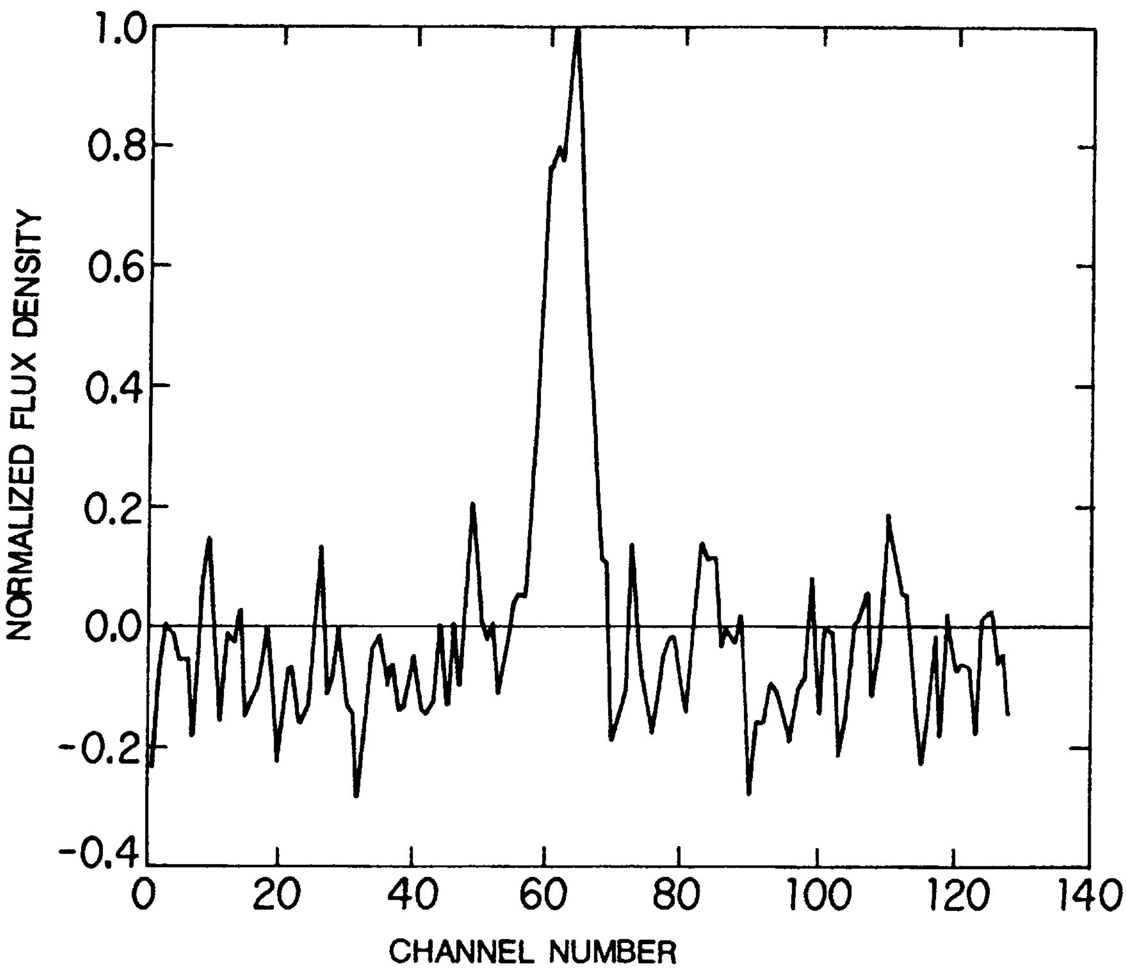


Figure IV. 2. Pulsar 1745-24 at 1.67 GHz. The peak flux density is about 5 mJy. The period is approximately 11 msec. Eclipsing occurs at slightly different phases in the period than at lower frequencies, using a plasma diagnostic.

Receiver List

Frequency Range GHz	Amplifier Type	System Temp. (K)
0.025 - 0.088	Transistor	300
0.110 - 0.250	Transistor	250
0.250 - 1.0	Cooled upconverter/GaAsFET	45-70
1.0 - 1.45	Cooled GaAs FET	35
1.30 - 1.80	Cooled HEMT	18-23
2.90 - 3.50	Cooled HEMT	25-35
4.47 - 5.05	Cooled HEMT	25-35
4.70 - 7.20	Upconverter/Maser	30-50
7.60 - 11.20	Upconverter/Maser	35-80
12.0 - 16.2	Upconverter/Maser	50-80
18.2 - 25.2	Maser	35-60

Note: All receivers are dual polarization.

Future Instrumention

As mentioned for the 140-foot telescope at the outset, the second major goal is to continue instrumental development. Electronics instrumentation proceeds incrementally. Engineers must work through every stage to stay at the forefront. It is therefore critical, if the GBT is to enjoy state-of-the-art instrumentation, to prevent any gaps in development between now and the time when the GBT starts operation. It is also true that instruments built henceforth, while initially for the 140-foot telescope, should be done in such a way that they can be transferred to the GBT. Planned developments consistent with these goals include:

Cassegrain Receiver. New receivers for the 140-foot Cassegrain system are currently under development. Cooled HEMT amplifiers have been constructed by the Central Development Lab to cover the 25-35 GHz frequency range (Ka band) and to replace the upconverter series over 5-18 GHz. The 18-25 GHz (K band) masers will not be altered. Two independent receivers are being built to receive orthogonal polarizations. We expect more uniform gain response and improved noise temperature vs. frequency using transistor amplifiers, as well as better stability and reliability. A few gaps in frequency coverage will be eliminated.

The Ka band capability will be new for the astronomical community. We plan to install one such receiver for winter 1990/91 observing. The 5-18 GHz capacity will be implemented in 1991.

Spectral Processor. The spectral processor is in use for pulsar observations at the 140-foot telescope. Previously pulsar observers had supplied their own specialized equipment for online data processing. The spectral processor makes this capability available to the general community. Its second 1024 channels will be added by fall 1990. Software enabling spectral-line observations should be available by the end of 1990. For spectral line observations, the main advantage of the spectral processor over the Model IV autocorrelator will be higher tolerance to interference and twice as many IF inputs (8 instead of 4). A few comparative specifications are given in the following table.

	Model IV Autocorrelator	Spectral Processor
IF Inputs x Bandwidth	4 x 80 MHz 4 x 40 4 x 20 4 x 10 4 x 5 etc.	 2 x 40 MHz 4 x 20 8 x 10 8 x 5 etc.
Total Number of Channels	512 @ 80 MHz 1024 < = 40 MHz	2 x 1024
Approximate Relative Sensitivity	0.81	~ 0.7 with 2048 chan > 0.9 with effectively 1024 channels
Time Resolution	10 sec	25 μs @ 4 x 512 12.5 μs @ 4 x 256 Depends on bandwidth
Approximate Sidelobes on Narrowband Interference	-20 dB	-40 dB Depends on Taper Fn
Integration Modes	Total Power Switched Power Pulsar Synchronous Spectral	Total Power Switched Power Pulsar Synchronous Time or Spectral Time/Freq Matrix Dedispersed Time

<u>800-MHz Receiver</u>. The oldest receivers for the 140-foot telescope are those for frequencies less than 1 GHz. With the intensified interest in pulsar research, which is definitely signal-to-noise limited, the need for improved sensitivity is apparent. The same receiver could be used for HI absorption-line searches in highly redshifted quasars. We plan to construct a cooled HEMT amplifier receiver with a feed designed to minimize spillover for the band 800-840 MHz. This band has little interference at Green Bank. The receiver will use fiber optics throughout. This will enable the rf signal to be transmitted to the control room before a local oscillator signal is mixed with it to produce an IF signal. Other innovations will be full computer control of receiver functions. Work will begin in 1990 and be completed by late 1991.

L-Band Receiver. The band 1.0-1.7 GHz will be in greatest demand on the GBT initially, since it serves HI, VLBI, pulsar, and continuum observers. It also represents an optimum band for conducting major surveys, either for pulsars or for galaxies at great distances. We therefore propose another iteration of improvement to the receiver that is presently radio astronomy's best. This work will span 1991-92.

Dual S/X Receiver. No receivers operable in the band 1.8 to 3.0 GHz exist for the 140-foot telescope. Some continuum observations, particularly of pulsars, have requested a capability near 2.3 GHz. In addition, the frequencies of 2.3 and 8.4 GHz have become standards for geodetic and astrometric VLBI. Using a design worked out for the Green Bank interferometer at the request of the Naval Observatory, we intend to construct a frontend permitting simultaneous S- and X-band observations.

450-MHz Receiver. The band 450-500 MHz is useful for both pulsar research and for searches for primordial galaxies. As in the case of the 800-MHz receiver, the technology in the present Green Bank package is more than a decade old. We intend to improve significantly the sensitivity by using the same techniques as for 800 MHz. Advantages of fiber optics not mentioned in discussion of that receiver include freedom from electrical pickup, especially lightning, and relaxed requirements on the distance between the telescope and its instrumentation. Work on the 450 MHz receiver could commence in 1992 or 1993.

Present Computing Capability

NRAO-Green Bank is presently served by a Local Area Network (LAN), using Ethernet connections to distribute computing power across the site. Observers, for instance, can analyze data being acquired at the 140-foot telescope with equal ease from the telescope's control room, the Jansky Lab, or, if they have a PC and modem, from their residence hall room. The same data set can be accessed by more than one observer in a team. Different observers time-sharing the 140-foot telescope in the course of a single day can simultaneously analyze their separate data sets. In addition, an Internet connection has been installed that connects the Green Bank LAN to other computers in any locale. Thus evolution toward completely remote access is well underway.

Data analysis software is currently an advanced version of POPS. It runs on SUN workstations and Masscomp computers at the Observatory. There is also a PC version that observers can use and maintain at their home institutions.

Future Computing Capability

The transition to accessibility must be completed during 1991-94. Instructions to control computers on site, e.g., observing schedules, and file transfers of data from the site must be easily interchanged over national networks. This work will require additional workstations in Green Bank to assure complete network reliability, greater data storage capacity (probably on optical disks), and high-bandpass communications lines (probably fiber optics). These improvements are ongoing throughout the period as available technology evolves.

The data analysis software will be upgraded to UNIPOPS, providing greater functionality and compatibility at all NRAO sites. This installation will take place in 1990. Simultaneously, a new FITS reader and writer will be installed, consonant with recently defined international standards. In 1991 work will begin on the more powerful packages needed for the high-volume output of multi-beam receivers and spectrometers with > 10,000 channels anticipted for the Green Bank Telescope. This development work will include an examination of both commercially available software and analysis packages in use at other observatories. It, too, will be an ongoing activity throughout 1991-94.

V. FACILITY MAINTENANCE, UPGRADING, AND EXPANSION

MAJOR MAINTENANCE

The past several years of very restricted budgets have severely limited the Observatory's ability to keep up with maintenance requirements. Some of the needs, such as the VLA track and electrical power systems, have attracted widespread attention. Others, although, less visible, are also important. At present, NRAO allocates what funds it can to maintenance on the basis of urgency--safety and impact on operations being the criteria. This level must be increased, by several million dollars spread out over the next five years, if we are to catch up.

Very Large Array

The VLA Rail Track System. The VLA rail track system consists of two standard gauge railroad tracks which run along each 13-mile arm of the array. During operations the antennas rest on concrete foundations 100 feet from the main rail line. Each station is connected to the main line by a short spur rail line and a track intersection. There are about 80 miles of (single) track in the system. The combined weight of the transporter plus the antenna is about 300 tons. With 24 wheels on four trucks, this gives a loading of 50,000 pounds on each of the 12 axles, a high but not unusual load in the railroad industry.

The track system currently has about 800,000 feet of (single) rail on the main line and 46,000 feet in the antenna spurs. There are 190,000 ties and 72 intersections. The entire track system was constructed with used materials. The rail, for example, dates from 1902 to 1956.

Since the VLA began full operation in 1980, the rail system has received inspection and a modicum of upkeep. Now, at roughly ten years of age for much of the system, more major maintenance is required. The main, but not the only, problem is a deterioration of the rail ties. This has become serious because the rate of deterioration has accelerated beyond what would normally be expected. In particular, those ties that came from wet regions of the U.S. are deteriorating rapidly in the dry conditions of New Mexico. A second major concern is the deterioration of the spur intersections. These intersections are the weakest elements in the system. Other maintenance items in the track system besides the ties are: replacement of clogged ballast; realigning, gauging, and upgrading antenna spur lines; replacing bad rail sections; repairing and smoothing joints; and cleaning and dressing ballast.

Rail maintenance is now done by a four-man VLA rail crew augmented by seasonal help. In the past year a tie extractor and a surplus ballast tamper have been added to the rail maintenance equipment. Tie replacement is continuing at about 3500 ties per year. The condition of the rail system is gradually improving. Over the next few years, while the tie maintenance program continues, increased effort will be made in aligning the spurs and redesigning and rebuilding the intersections. This last item is the major cost share of the rail maintenance program.

The Power Distribution System. Electrical power is supplied to the antennas of the VLA by buried cable running along the arms--three cables, one for each phase, per arm, operating at 12.45 kV. These cables were installed between 1974 and 1980. The type of cable selected was highly recommended and in wide use throughout the U.S. by electric utility companies. The extruded polyethylene insulation on these cables is now known to be subject to failures which increase rapidly in rate with cable age. Experience with the cable at the VLA is following the industry-wide pattern.

Polyethylene cable deteriorates with age owing to a process known as "treeing." A "tree" is a growing channel which propagates through the insulation, probably due to ion or electron bombardment. The number and size of trees in a cable is primarily a function of time in service, operating electric field strength, and the presence of manufacturing impurities. As treeing progresses, the dielectric strength of the insulation deteriorates until voltage surges due to switching transients or nearby lightning strikes break down the insulation and the resulting arcing produces a ground fault. The only solution is to replace the power cables. Steps to slow the cable degradation and minimize the disruption of operations will allow the cable to be replaced over many years. The total cost is estimated to be approximately $1.35M. About 25 percent of the cost has been borne by NASA as part of the Voyager/Neptune encounter project, and all cable has been replaced to the ends of the C-configuration at NASA expense. For 1990, the goal is to finish the recabling out to the end of the B configuration. This will represent the completion of 30 percent of the array, but leaves 420,000 feet of cable yet to be laid. At present installation rates it would take six to seven years to finish recabling. Funds to double the installation rate are included in the major maintenance line of the budget projections table at $150k per year.

Other maintenance needs at the VLA comprise a long list of smaller items: overhaul of antenna transporters and installation of new transporter control systems, overhaul of electrical generators and upgrading of electrical power system controls, rebuilding of waveguide manholes, bringing fuel storage tanks into compliance with new regulations, replacement of machinery and selected vehicles, and improvement of painting facilities. The VLA site road system is badly in need of maintenance. The large "cherry-picker" crane needs to be replaced.

Green Bank

Many of the maintenance requirements at Green Bank are related to environmental/health considerations. The sewage treatment plant must be modernized. The water tower must be painted inside and out, and a water filter system installed. Asbestos must be removed from the old 300-foot telescope control building. The recreation area requires a new well. Various buildings require new roofs. Finally, superficial cracks in the concrete of the 140-foot telescope pedestal must be grouted and sealed.

12-Meter Telescope

Within two or three years the fabric covering on the 12-meter telescope dome must be replaced. The estimated cost approaches $400k. Other 12-meter telescope needs include replacing the trailers that house visitors, adding a sun screen to the dome to prevent damage by the sun and wind, and repaving the road.

ARRAY TELESCOPE COMPUTING PLAN

Since the original design goals were specified in 1969, the power of the VLA for imaging radio sources has increased steadily. The following table gives the changes in selected image parameters.

Development of VLA Imaging Power

	Goal 1969	Achieved 1980	Achieved 1988
Speed (images per day)	3	200	200
Image Size - Routine (pixels)	128x128	512x512	1024x1024
Image Size - Maximum (pixels)	512x512	1024x1024	4096x4096
Spectral Line Channels (full array)	-	8	512
Dynamic Range - Routine	100:1	500:1	2,000:1
Dynamic Range - Maximum	100:1	2,000:1	100,000:1
Maximum Sensitivity (mJy)	0.1	0.05	0.005
Resolution (arc seconds)	1	0.1	0.07

Each increase shown in the above table has required computing resources beyond those originally anticipated. The growth in demand for computing resources has outstripped our ability to provide them within the annual operating budgets of NRAO. Only a small fraction of the scientific investigations that are exciting but exceptionally computer-intensive scientific investigations can now be supported. The operation of the VLBA is expected to increase the computing demand by 65 percent over the demands of the VLA alone. In order to rectify this situation, the NRAO submitted to the NSF in September 1987 a proposal, "Array Telescope Computing Plan," which creates a joint VLA/VLBA computing environment suitable for the needs of both arrays.

The essence of the plan is the recognition that the imaging burden of the synthesis arrays covers a broad spectrum: some observations require only modest computing resources while others may require the full power of a large supercomputer. Given this distribution, the design of the appropriate computing facility for VLA/VLBA imaging incorporates hardware resources which span the same spectrum from the modest to the very powerful. Doing this is cost-effective and leads us to a plan for a computing facility which is a combination of computers, of varying computational capacity, loosely coupled together.

From a careful estimate of the mix of scientific programs that we expect to be run on the VLA and VLBA, once the latter is fully operational, we conclude that 60 percent of the total projected computing demand will originate from VLA users, with the remaining 40 percent coming from VLBA users. But only 10 percent of the VLA projects and one percent of the VLBA projects account for over 70 percent of the computing demand. These computing intensive projects will be handled at supercomputer centers, either national (NSF) facilities or other supercomputer centers where NRAO users have access. NRAO does not plan to operate a supercomputer center itself. The outline of the computing plan is shown schematically in Figure 3.

Data from the remaining 90 percent of the array telescope projects will be processed at an NRAO computing facility, or at the user's home institution, or most likely, at some combination of both. We have assumed in this plan that the burden of processing the data from these projects will be shared equally between NRAO and user home institution facilities. The NRAO facility is to consist of a networked set of second-generation mini-supercomputers, high performance imaging workstations, and a mass storage and archive system.

The software plan for the proposed computing system has three elements:

- Continued development and support of AIPS for use at NRAO and export to other facilities, including supercomputer centers and user home institutions;
- Research in image processing, including new algorithm developments that will be incorporated into AIPS;
- Code optimization for efficient use of the machines available.

In 1988 the Array Telescope Computing Plan was reviewed by the NSF Division of Astronomical Sciences and received highly favorable reviews by our (anonymous) colleagues in astronomy and computer science. Nonetheless, the plan was not funded owing to overall budget limitations within the Astronomy Division. In the meantime the total world-wide computing resources devoted to VLA image processing and AIPS *outside the NRAO* continues to increase. The NRAO now provides only one-fifth of the total computing power dedicated to data processing in AIPS whereas in 1986 it provided one-half. The results of the latest (December 1988) AIPS site survey revealed that computing resources equivalent to two Cray X-MP processors running full-time are dedicated to AIPS. In a very tangible way, this demonstrates the enormous computing needs of astronomers engaged in radio astronomical imaging. Unfortunately, it is also sobering to realize that two full-time Cray X-MP processors are but one-sixth of the dedicated resources we estimate in the computing plan that are required by astronomers using the VLA and VLBA to process data for projects that do not require the power of a large supercomputer. Radio astronomy is seriously under-computed. The need for the realization of the computing plan remains urgent.

The Observatory has updated the Array Telescope Computing Plan. An Addendum to the Array Computing Plan re-examines the scientific needs, reviews the hardware implementation, and reassesses the plan for software and algorithm development. The basic philosophy of the Plan remained the same following this review. The incremental equipment and costs associated with implementation of the computing plan are included in the budget schedules.

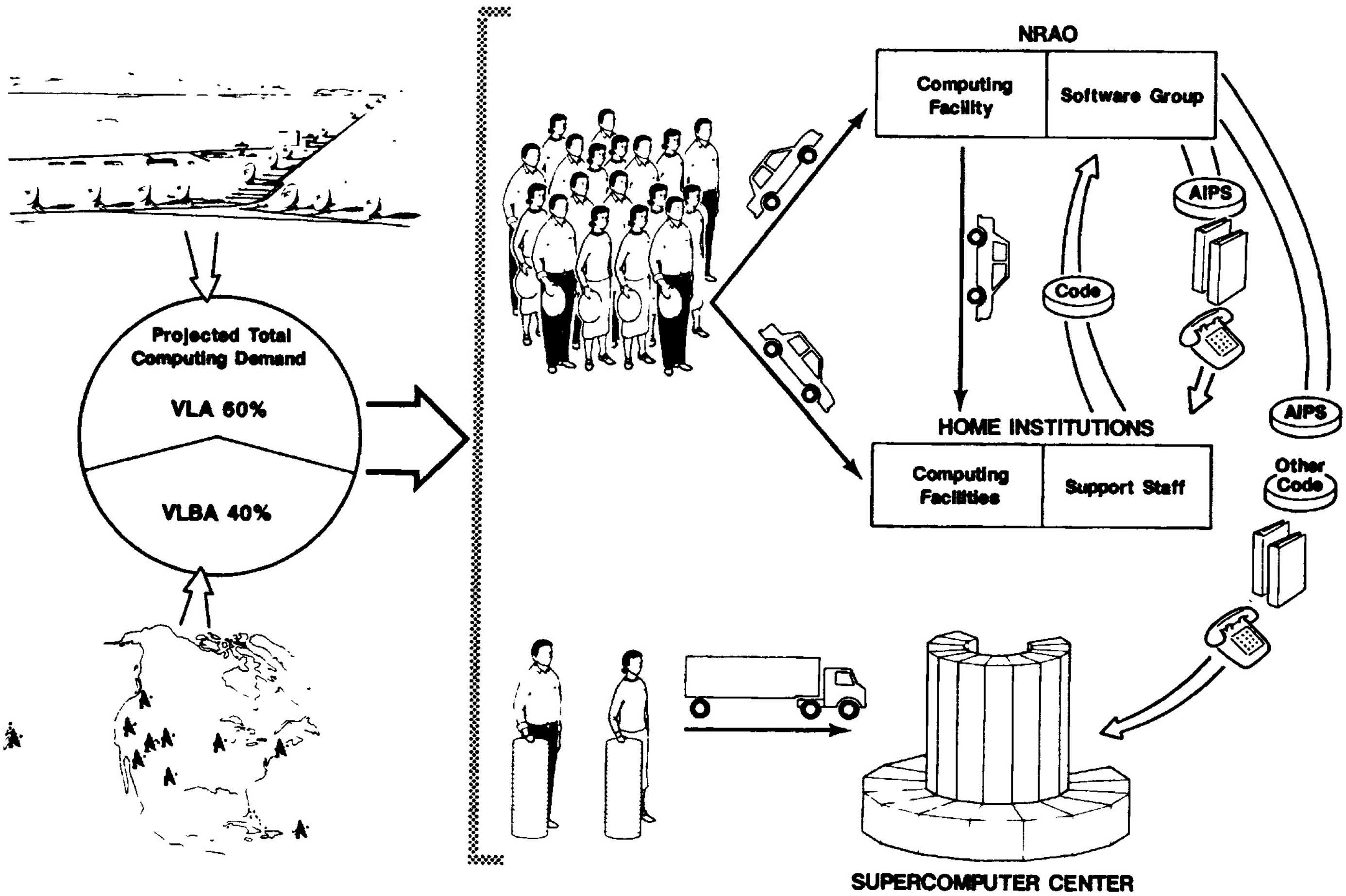


Fig. V. 3. - An illustration of the main features of the Array Telescope Computing Plan. The off-line computing requirements of the VLA and the VLBA will be met by computers at the NRAO, at users' home institutions, and at supercomputer centers. The data processing needs of about 90% of the users will be met at the proposed NRAO facility and/or at their home institutions. A few users with extremely computer-intensive projects will take their work to supercomputer centers. The NRAO will directly support computing outside the Observatory by exporting and documenting AIPS and other code, and by communication with staff at our users' institutions and at supercomputer centers. Code developed at user institutions will also be imported for inclusion in the NRAO distributed packages.

VLA CORRELATOR UPGRADE

The VLA provides a maximum bandwidth of 100 MHz, obtained by a pair of separately tuned, 50 MHz wide IF bandwidths. These bandwidths were set by technological limitations current some fifteen years ago and can now be greatly expanded. In conjunction with greatly improved IF transmission capability, a full 1 GHz bandwidth, in each polarization, can be implemented. A 2 GHz capability is also possible in the future. The new correlator will make the VLA a much more powerful and flexible spectroscopic instrument. It will allow more spectral resolution and targeted spectral coverage of up to eight frequencies with the same observing band.

Virtually all current observing is sensitivity-limited, if not in total intensity then in polarization. The planned improvement in sensitivity of up to an order of magnitude will make possible a wide range of programs and studies not now possible. In particular, it will further expand the emphasis of the VLA on targets of astrophysical interest rather than the strength of their radio flux. One of the greatest impacts of the VLA has been its speed which has allowed the study of meaningful samples of objects in acceptably short observing periods. For short "snapshot" observations, the bandwidth increase may be used to increase the speed by an order of magnitude or by using bandwidth synthesis to greatly improve the image quality.

The increased bandwidth will greatly benefit imaging of large objects, especially at high resolution. Bandwidth synthesis, in which the visibilities generated by a spectral line correlator are individually gridded for the image, will be used to obtain a spread in the effective baseline for any pair of antennas corresponding to the range of frequency used. The new correlator will also mean greatly increased sensitivity and field-of-view as the current correlator forces drastic reduction in sensitivity in order to obtain wide fields of view.

A 1 GHz correlator may be implemented using eight pairs of oppositely polarized IFs, each 125 MHz wide. These IFs need not be contiguous, so that at higher frequencies, where much more than 1 GHz of tuning is available, different frequencies of particular interest can be utilized. The 125 MHz wide IFs would be digitized at the antennas, and the digital signals sent to the correlator through optical fiber links. Recent technical advances in high speed digital circuitry may also permit sampling of up to 2 GHz bandwidth before sampling.

One gigahertz bandwidths will not, in general, require new antenna feeds since all bands except 20 cm and 90 cm already allow this bandwidth. There are, however, great rewards in redesigning the 20 cm feed to allow both greater efficiency and wider tuning range, especially below the current limit of 1250 MHz, to allow high redshift searches of HI. To better observe the molecular transitions of ammonia, a wider bandwidth feed at 1.3 cm is desirable. However, increasing the bandwidth to 2 GHz would require new feeds at all bands.

The VLA correlator is based on a custom designed ECL circuit that has since found widespread use in other radio astronomy applications. By modern standards, however, the bandwidth and spectral resolution of the VLA is correlator limited. This has greatly restricted the kind of research done with the VLA due to the inability to do wide field imaging and high spectral resolution line searches, such as looking for redshifted hydrogen. The present correlator only supports a 100 MHz (in each polarization) IF bandwidth, which limits the sensitivity to continuum sources.

Modern correlator design, based on the FX approach, removes these limitations and is especially suited to arrays with large numbers of elements, such as the VLA. The VLBA correlator is being built on this architecture. The new VLA correlator might provide 1024 channels of spectral resolution in each of the eight pairs of IFs being returned from the antennas. Full polarization will be available with the same number of channels except with perhaps a reduction to 512 channels when using the full 1 GHz bandwidth.

Although a 27-station correlator is needed to support the VLA, the design will permit the easy expansion to 33 stations necessary to support Pie Town and Los Alamos as well as the four proposed new antennas. In the interim it will be possible to replace one of the VLA antennas with the one at Pie Town in order to exploit the added resolution available for some types of observations that correlate the Pie Town antenna together with 26 VLA antennas.

In order to distribute 2 GHz, or even 1 GHz, of bandwidth from each antenna (two polarizations, each 1 GHz), the current waveguide transmission system needs to be replaced with a modern fiber optic link. This will also permit a further expansion in order to allow future expansion to even wider bandwidths and to allow inclusion of signals from other, more widely dispersed antennas. For the first stage, a fiber optics link will replace the waveguide connection between the VLA elements and will connect the Pie Town VLBA antenna to the VLA correlator.

In the second stage of the project, a fiber optics link will be run to the Los Alamos VLBA antenna as well as to the four new antennas at intermediate spacings between the VLA and the VLBA.

VLA-VLBA CONNECTION

The proposed VLA-VLBA connection will close the "intermediate resolution gap" which will make possible for the first time "scaled array" observations with the same angular resolution at different frequencies. The interpretation of radio observations depends on measuring how all the Stokes parameters vary with frequency over a wide band at a fixed resolution. These observations lie on a vertical line in Figure 4, and without filling in the "intermediate resolution gap," are possible only at a resolution of about 3 arcsec.

The doubling of the VLA resolution made possible by the use of the Pie Town antenna, of the VLBA resolution by the addition of 3 mm receivers appears modest compared with the very large increase in resolution which these instruments already have over other instruments. However, a factor of two in resolution can be critically important to many types of observations. For example, it reflects the difference between a site with "good" optical seeing (~ 1 arcsec) and one which is truly superb (≤ 0.5 arcsec), for which optical astronomers will go to remote sites to achieve. With the addition of four new antennas, and by using the Los Alamos VLBA antenna as well, the imaging capability of the VLA will be improved by nearly an order of magnitude.

For many astronomical problems, the VLA does not have adequate resolution, and the VLBA will give good imaging properties only on angular scales greater than those which correspond to the minimum spacing of about 250 km. Between 35 and 250 km, roughly corresponding to angular resolutions of 0.01 to 0.1 arcseconds at centimeter wavelengths, there is gap in antenna spacing corresponding to resolutions of interest to a wide range of astronomical problems and which is particularly important for studies of stellar and extragalactic sources. The required intermediate spacings may be implemented to a limited extent by providing the necessary communications between the existing VLA and VLBA antennas, but high quality imaging requires the construction of new antennas to provide the missing spacings intermediate between the VLA and VLBA.

The location of the Pie Town and Los Alamos VLBA antennas was chosen to partially sample this range of spacings, and so that the later construction of four additional antennas located at Dusty NM, Bernardo NM, Vaughn NM, and Holbrook AZ could provide complete imaging on these intermediate scales.

The following modes of operation will be possible with the combined 33 element array and may be implemented in stages.

- Using several VLA antennas independently with the entire VLBA to provide short-baseline data for VLBA imaging, by placing up to four VLBA backend systems at the VLA site. Each VLBA backend would allow a VLA antenna to participate independently in observations with the full VLBA using both polarizations at 100 MHz bandwidth. By dividing the available IF channels between several VLA antennas, more than four VLA antennas could be used simultaneously with the VLBA at narrower

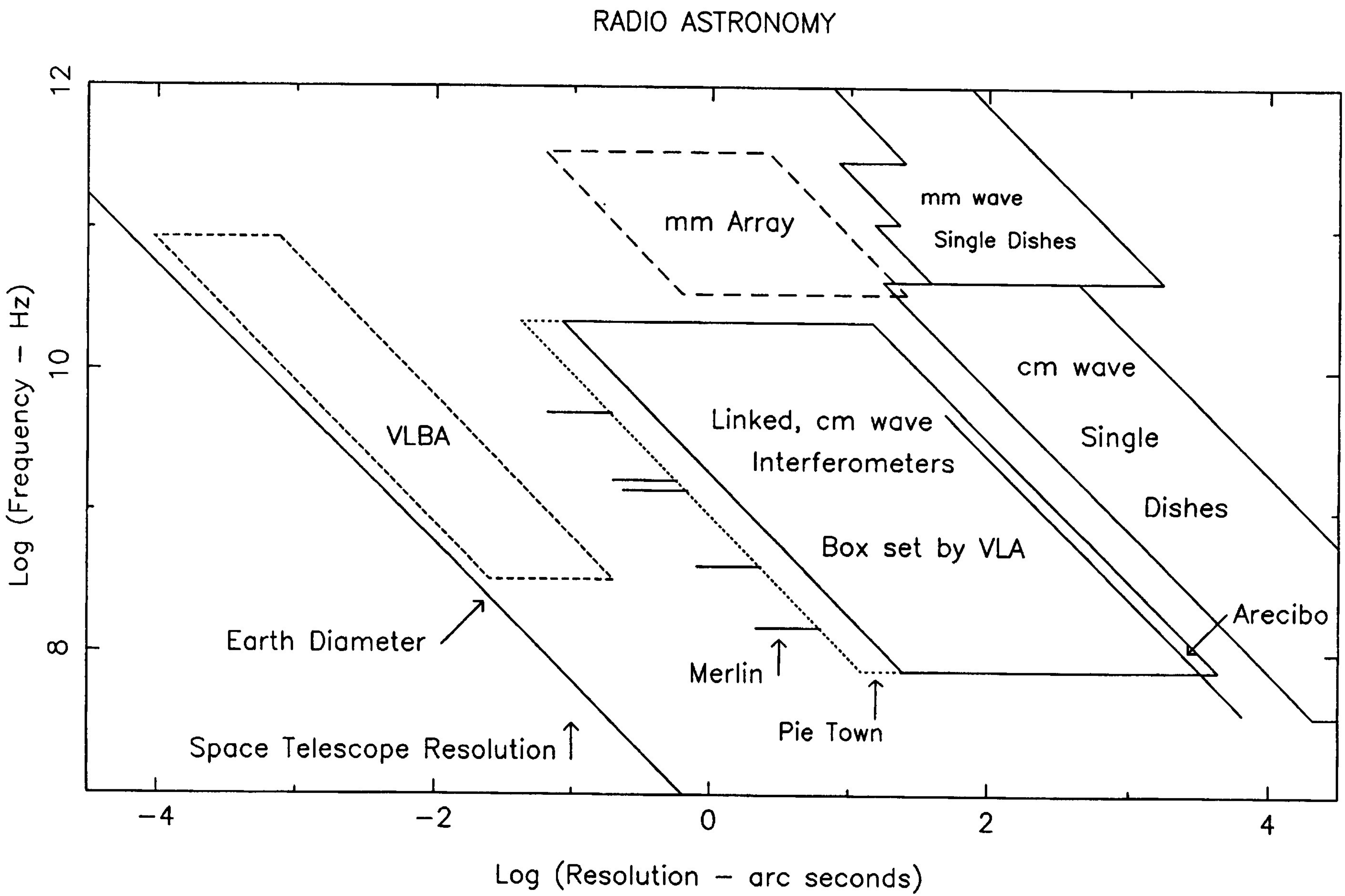

RADIO ASTRONOMY
12
10
8
Log (Frequency – Hz)
mm Array
mm wave
Single Dishes
VLBA
Linked, cm wave
Interferometers
Box set by VLA
cm wave
Single
Dishes
Arecibo
Earth Diameter
Merlin
Pie Town
Space Telescope Resolution
−4
−2
0
2
4
Log (Resolution – arc seconds)

Figure V.4

bandwidth for experiments in which inner uv coverage is more critical than sensitivity per baseline. Processing would be done at the VLBA correlator, which can handle up to 20 stations. This first step requires equipping four VLA antennas with VLBA recording systems, but does not involve the construction of any new antennas.

- The Dusty, Bernardo, and Pie Town antennas together form a 70 km extension of the VLA, while the Vaughn, Holbrook, and Los Alamos antennas extend the array to a total of 250 km. These six antennas could be operated together with the VLA as a real time, fully phase stable array to extend the resolution of the VLA by nearly an order of magnitude. This mode exploits the superb sensitivity of the VLA. Alternately, by using tape recorders at four VLA antennas, the VLBA will be able to image sources up to an order of magnitude larger than at present. In this mode the sensitivity is less than that of the real time expanded VLA because of the bandwidth restriction imposed by the tape recording system.

V. BUDGET PROJECTIONS (M$)

	1990	1991	1992	1993	1994	1995
Operations						
Base Operations	17.537	18.600	20.300	22.800		
VLBA Operations	1.272	2.300	5.000	7.600	35.100	37.200
Major Maintenance (1)	----	0.600	1.100	0.900		
Array Computing Plan (2)	----	0.600	1.600	2.600		
Total Operations	18.809	22.100	28.000	33.900	35.100	37.200
Equipment						
Research & Operating	0.391	0.900	1.100	1.500	1.600	1.800
Array Computing Plan (3)	----	2.100	2.000	3.000	----	----
VLA Receiver Upgrade ($16M)	----	0.400	1.500	5.500	4.000	3.500
Total Equipment	0.391	3.400	4.600	10.000	5.600	5.300
Total Operations & Equipment	19.200	25.500	32.600	43.900	40.700	42.500
Construction						
VLBA ($85M)	10.700	11.500	6.800	----	----	----
GB Telescope ($75M) (4)	4.410	69.580	----	----	----	----
Millimeter Array ($120M)	----	1.000	2.000	5.000	30.000	30.000
VLA Correlator Upgrade ($20M)	----	----	----	1.000	9.500	9.500
VLA - VLBA Link ($31M)	----	----	----	----	----	9.000

PERSONNEL PROJECTION (Full Time - Year End Ceiling)

	1990	1991	1992	1993	1994	1995
Base Operations	279	283	310	316		
VLBA Operations	36	55	80	91	427	442
Array Operating Plan	-	6	13	20		
VLBA Construction	60	50	7	-	-	-
GB Telescope Construction	12	12	14	15	17	-
Millimeter Array	-	5	10	20	50	50
Work for Others	10	10	13	14	14	14
Personnel Total	397	421	447	476	508	506

NOTES:

1) Incremental to on-going maintenance which includes routine minimum-level VLA track system and electrical cable replacement.
2) Incremental operations costs beyond those budgeted for computing in VLBA operations.
3) Incremental equipment costs beyond those budgeted for computing in VLBA construction.
4) Tables show NSF obligations; actual NRAO expenditure schedule - 63.6M ('91), 2.4M ('92), 2.0M ('93), 1.8M ('94).