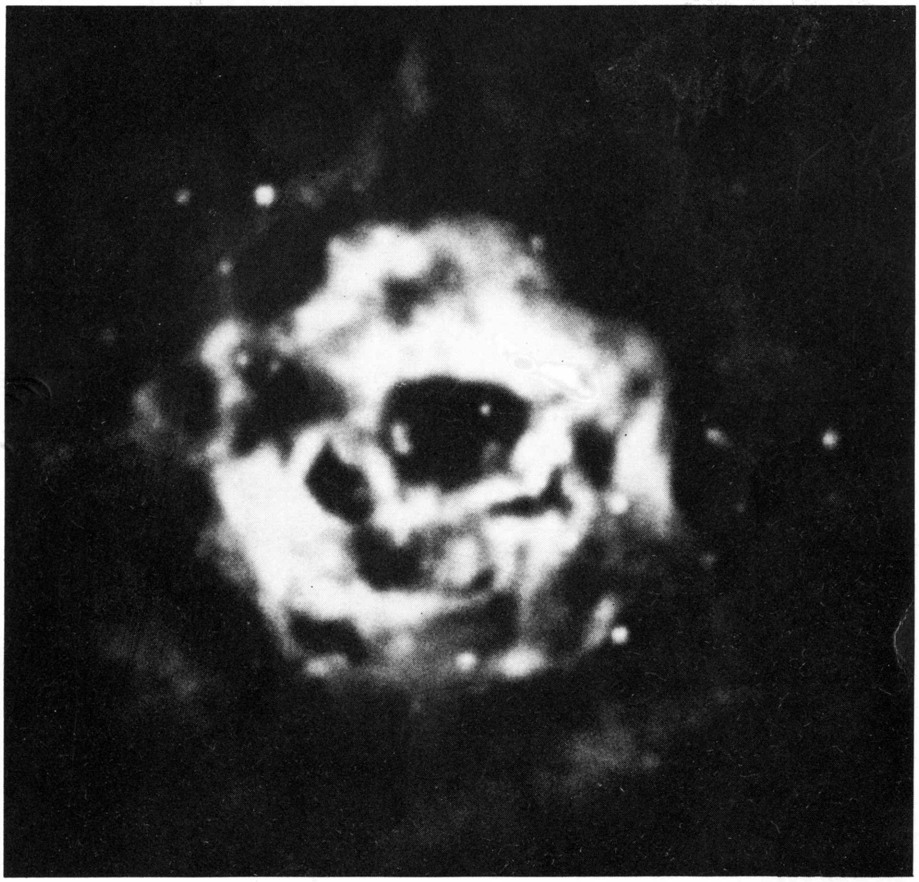
NATIONAL RADIO ASTRONOMY OBSERVATORY



NRAO

LONG RANGE PLAN 1989–1993

NATIONAL RADIO ASTRONOMY OBSERVATORY

LONG RANGE PLAN

1989 - 1993

MAY 1988

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1. INTRODUCTION

In 1987 more than 800 scientists and students from 190 institutions made observations with the telescope facilities at the NRAO in the course of their research. This is an increase of 13 percent in both number of visiting scientists and institutions represented in just one year. These numbers, and their derivatives, illustrate the extent to which radio astronomy is represented in contemporary astronomical research, and it illustrates the success which can be achieved via the NSF concept of national research facilities. The Very Large Array and the soon-to-be-completed Very Long Baseline Array, in particular, provide astronomers with such unparalleled sensitivity, angular resolution, and frequency coverage that we have every reason to expect that the recent expansive phase in radio astronomical research at the NRAO will continue. The challenge of the next five years will be to realize the full potential of this growth. The present long range plan, 1989-1993, addresses this challenge. The highlights of this plan are:

- Completion and full operation of the VLBA;
- Completion of the 75 MHz capability of the VLA, upgrading the L-Band receivers, and doubling the VLA resolution by construction of a link to the Pie Town VLBA antenna;
- Completion of the spectral processor, construction of a focal-plane array receiver, and development of off-axis L-band receivers for unblocked aperture observing for the 300-foot telescope;
- Improvements in receivers and feeds, construction of a 32 GHz receiver, and replacement of computers and telescope control systems at the 140-foot telescope;
- Expansion of the 8-beam, 230 GHz receiver to 32 beams, replacement of all Schottky mixer receivers with SIS mixer receivers, and completion of the control system and computer replacement program at the 12-meter telescope.

In planning the next five years of NRAO operation, considerable emphasis is given to facilities improvement and maintenance. Proper stewardship of the NRAO requires, for example, that the VLA rail track system be restored to its construction specifications and that the power distribution system be made safe and reliable. Such needs cannot be ignored. Also not to be ignored are opportunities to operate facilities in a more efficient and cost-effective manner. Here the consolidation of VLA and VLBA operations at the Array Operations Center building in Socorro using shared facilities and staff provides such an opportunity that will become a reality within the planning period. The operation of both arrays will benefit.

The role of the National Observatory transcends maintenance and operation of unique research facilities for the scientific community. Additionally, the NRAO provides a focus for development of new instrumentation, distribution of software algorithms for analysis and interpretation of astronomical data, and it coordinates the desire of the community 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 (HEMT) for microwave radio astronomy applications world-wide; photon-assisted tunneling (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.

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

Through these measures in the long-range plan we seek to increase and consolidate research opportunities for the science of the present and build to those required by the science of the future.

2. VERY LARGE ARRAY

The Very Large Array realizes the need for an imaging radio telescope that can provide radio "pictures" with a resolution similar to those obtained from optical telescopes. Recognition of this need is recognition as well that contemporary astronomical research has no wavelength boundaries but benefits from concerted work at all wavelengths. Thus, we expect the VLA to make important contributions to all the astronomical disciplines and this expectation is being abundantly fulfilled. More than 650 astronomers from 165 institutions use the VLA annually for their research on everything from the sun and planets to stars, galaxies, and quasars. The combination of VLA sensitivity, together with its angular resolution, multi-frequency capability, and flexibility to reconfigure, enables the VLA to reveal the full diversity of the radio sky. Future joint VLA/VLBA observations offer the prospects of a further increase in the quality of radio images and thus in our understanding of the physics of the radio sky.

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 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 high electron mobility transistors (HEMTs).

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.

Table 2.1 summarizes the parameters of the VLA receiver system.

TABLE 2.1. VLA RECEIVING SYSTEM

Frequency (GHz)	T_{sys}	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 97 kHz. 512-channel spectroscopy is supported in all bands.

FUTURE PLANS - ELECTRONICS

75 MHz (4 m) System - Four VLA antennas have been outfitted with simple dipole feeds to explore the feasibility of VLA observing at 75 MHz, and initial tests with this system have been encouraging. Full use of this frequency will await the next solar minimum. 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.

L-Band Sensitivity Improvements - Spectroscopic observations with the VLA at 21 cm are limited in sensitivity by the ten year old front end design, which provides 50-60 K system temperatures with all of the front ends in the same dewar. A more modern design based on HEMT amplifiers in independent dewars could shorten the input waveguide runs and allow cooling of the polarization splitters, reducing the system temperatures to about half their present values. This would reduce by a factor of four the observing time for 21 cm line observations of a given sensitivity. HI and OH spectroscopy of extragalactic objects will be the primary beneficiary of this improvement.

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 over microwave or fiber optics links. 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 the following further step.

Combined VLA-VLBA Imaging - The VLA and VLBA, used separately, only sparsely sample the spatial frequencies from 40 to 400 km, leaving a range of angular resolutions uncovered (with useful dynamic range) at any frequency. This "gap" is unfortunate because the most physically revealing observations of radio continuum sources of all kinds are those that determine how the Stokes parameters of the radiation vary with frequency over a wide frequency range at a fixed angular resolution. For example, wide-band spectral studies at fixed resolutions are required to understand electron transport in the sources. Faraday depth studies at fixed resolution are needed to assess thermal densities and magnetic field strengths. To explore the physics of any class of radio continuum source fully at 0.1 to 0.001 arcsecond resolution will require bridging this "gap" through combined VLA-VLBA imaging. It is planned to do this in three main stages: (a) linking the Pie Town VLBA antenna to the VLA as noted above; (b) providing additional VLBA backends at the VLA so that up to four VLA antennas can be used as the "inner elements" of the VLBA when the VLA is in its A configuration; (c) adding additional VLBA antennas in New Mexico and Arizona for use with either the VLA or the VLBA as appropriate for individual experiments. The long-term goal is to provide an array of at least 40 elements (27 VLA antennas, 10 VLBA antennas, plus three or more additional antennas) that can be divided into subarrays as required to obtain a "matched spatial filter" appropriate for each experiment that requires high resolution, wide field imaging. These ideas, of course, are not new: the VLBA configuration was centered on the VLA location specifically to allow synergy between the two instruments in the 1990's.

FUTURE PLANS - MAJOR MAINTENANCE

The VLA Rail Track System - The VLA rail track system consists of two standard gauge railroad tracks which run along each 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 interchange. There are about 80 miles of rail 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, not unusual for a railroad track.

The rail system currently has 800,000 feet of rail on the main line and 46,000 feet on the antenna spurs. There are 190,000 ties. 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 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 groups of rail ties. This has become serious because the rate of deterioration has accelerated beyond what would normally be expected, because the system was built with used ties. Ties that came from wet regions of the U.S. are deteriorating rapidly in the dry conditions of New Mexico.

Other major 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; and cleaning and dressing ballast.

The goal is to bring the VLA rail system back to its original construction specifications. An updated estimate based on our detailed inspection is that this will cost about $2,850,000 spread over five years. A detailed technical report outlining the plan to restore the track system to specifications was submitted to the NSF in March 1987. In 1987 a total of $150k was spent on track repairs, and budget constraints will have limited repairs to this amount in 1988 also. This level of effort only addresses the most seriously degraded sections of track, allowing reconfiguration of the VLA but neither halting nor restoring the general deterioration of the rail system.

<u>The Power Distribution System</u> - Electrical power is supplied to the antennas of the VLA by buried cable running along the arms, three cables 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.

Prior to November 1985 the VLA had no cable failures. There have been twelve failures since then. If the failure rate follows industry experience, in a few years the deterioration of the cables is predicted to lead to a very serious disruption of VLA operations. 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 several years. The total cost is estimated to be approximately $1.35M. About 25 percent of the cost is being borne by NASA as part of the Voyager/Neptune encounter project. During 1988 recabling of the VLA through C-array will be completed.

<u>FUTURE PLANS - VLA/VLBA COMPUTING</u> - Both the quality and the quantity of images produced by the VLA now greatly surpass the original goals, as Table 2.2 shows.

TABLE 2.2. 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 Table 2.2 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 exciting but exceptionally computer-intensive scientific investigations can now be supported. Useful observing capabilities that are designed into the array hardware are now withheld from users, solely to avoid overloading the data reduction computers.

In order to rectify this situation, the NRAO submitted to the NSF in September 1987 a proposal, "Array Telescope Computing Plan," which leverages the VLBA computing budget and creates a joint VLA/VLBA computing environment suitable for the needs of both arrays. This Plan is discussed in Section VII.

3. 300-FOOT TELESCOPE

In September 1987 the 300-foot telescope celebrated its twenty-fifth year of continuous operation, dedicated wholly to astronomical research. About 50 observers use the 300-foot telescope each year. Constructed to provide U. S. astronomers with an aperture as large as that available elsewhere in the world for operation to wavelengths (originally) only as short as 21 cm, the characteristics of the 300-foot telescope most important to its astronomical uses now are:

- The large aperture yields high sensitivity ($\approx$ 1 K/Jy) and resolution as fine as 3 arcminutes at 5 GHz.

- This transit telescope can reach sources over a wide declination range ($-19° < \delta < +90°$) but with limited tracking in hour angle (4^m sec δ at high frequencies, 30^m sec δ at low frequencies). It is most efficiently utilized by survey programs covering many sources or large areas of the sky.

- Sensitive receivers provide continuous frequency coverage from 30 MHz to 5 GHz, the upper frequency limit of the telescope. The 1.3-1.7 GHz receiver (for HI and OH observations) is the most sensitive receiver on any radio telescope in the world.
- The 300-foot telescope in Green Bank is located in the National Radio Quiet Zone (NRQZ). Interference from fixed transmitters in the NRQZ is regulated by the FCC. An additional West Virginia statute even protects against electrical interference generated within some tens of miles of the Observatory, for example, motors or welders. Protection from man-made interference permits observations at frequencies outside of bands allocated to radio astronomy (observations of high-redshift spectral lines, for example) or with very wide continuum bandwidth.

PRESENT INSTRUMENTATION

Telescope Specifications

Diameter: 300 feet (91 m)
Pointing Accuracy: 10"
Sky Coverage: -19° to 90° declination
Sensitivity: 1.1 K Jy^{-1}

Two receivers can be mounted simultaneously on the telescope, both at prime focus. One receiver is fixed on-axis in a focusing feed mount while the other is mounted on a traveling feed which tracks position to increase the hour angle coverage available.

Receiver List

	Frequency Range	Amplifier Type	System
Single Beam:	25- 88	Transistor	300K
	110- 250	Transistor	250
	250-1000	Cooled Upconverter/ GaAsFET	45-85
	1000-1450	Cooled GaAsFET	35
	1300-1800	Cooled HEMT	18-23
	2900-3500	Cooled GaAsFET	25-35
	4470-5050	Cooled GaAsFET	25-35
Multi-beam:	1300-1500	4-channel GaAsFET	90
	2640-2750	4-channel GaAsFET	130
	4600-5100	14-channel Cooled GaAsFET	60

Note: All these receivers are shared with the 140-foot telescope.

FUTURE INSTRUMENTATION PLANS

Spectral Processor - A spectral processor is being built for the 300-foot telescope, with completion scheduled for early 1989. For spectroscopy, it will provide a maximum bandwidth of 40 MHz, 2048 channels, and 8 IF inputs. It will offer flexible configuration, e.g., two simultaneous 40 MHz IFs with 1024 channels for each. The timing circuitry involved in its autocorrelation can also be used for pulsar studies. An accumulator can average data synchronously with a pulsar's period. Furthermore, pulsar signals can be de-dispersed and their Faraday rotation removed. The processor will be able to recognize and reject RFI with a time resolution of $\geq$ 12.8 microsec. The primary scientific projects driving the need for a spectral processor are (1) redshifted hydrogen studies of external galaxies and (2) detailed studies of pulsar physics and the intervening medium that modifies pulsar signals.

Focal-Plane Array Receiver - A second project intended to enhance the usefulness of the 300-foot telescope is the construction of a focal-plane array of receivers. This is one project that could have been completed in 1988, but which has been stretched over the next two years because of insufficient equipment funds. The intent is to increase the effective hour-angle coverage of this "transit" telescope by continuously varying the amplitude and phase illumination. By mounting a 2 x 8 phased array of receivers on a structure which can track hour angle, the effective daily observing time may be tripled with high aperture efficiency and low coma. This is so advantageous that the array in progress may be only the first of several, each needed to cover a different frequency band. The first is designed to cover the band 400-500 MHz, with instantaneous bandwidths of 10 MHz. Presently, a source can be tracked for (10 sec δ) minutes on either side of transit before the telescope gain falls by half. With the focal plane array, that increases to $\pm$(30 sec δ) minutes/day. The major scientific objectives are (1) redshifted ($z = 1.8$-2.5) neutral hydrogen absorption studies in quasars and (2) pulsars whose steep spectra favor low frequencies.

Unblocked Aperture Feeds - HI column densities and line profiles are most severely limited not by receiver sensitivity but by corruption from "stray radiation," i.e., emission coherent at the feed but which does not come in the main beam. Stray radiation is power in the far telescope sidelobes which are themselves the results of imperfections in the illuminated aperture attributable mostly to reflections off the feed legs. The solution to these problems is to observe with an inherently "clean" telescope. Fortunately, because the 300-foot telescope has only two feed support legs, there are large areas of the aperture unblocked to the east and west of the main axis. Experiments have shown that we can illuminate these parts of the dish and achieve a truly "clean" beam. (Beam efficiencies greater than 98.7 percent were demonstrated by observations at 5 GHz with an offset feed.)

Construction has begun on an off-axis, 21-cm feed to illuminate one unblocked portion of the antenna. When complete, a sky survey will be undertaken of the galactic HI north of -19°. Such a survey will characterize the distribution of Galactic HI, and Galactic kinematics, with an angular resolution, velocity resolution, sensitivity, and discrimination against spurious features which is unprecedented. It will be a time consuming survey: at 40 seconds integration per beam the telescope time required is 600/n days, with n being the number of feeds.

4. 140-FOOT TELESCOPE

The 140-foot radio telescope was designed and built to provide astronomers with a versatile instrument of reasonable aperture that could be adapted in conventional and unconventional ways to a wide range of astronomical investigations. The wisdom of this approach was rewarded shortly after the telescope began routine operation with the first discovery of a polyatomic organic molecule in the interstellar medium, formaldehyde. The instrumental capability of the 140-foot system exploited to advantage in this discovery--the ability to observe at a "non-standard" radio frequency with sufficient sensitivity--is precisely the same capability that led to the discovery nineteen years later, in 1988, of the cyanomethyl radical CH_2CN. In the intervening years the science progressed and dozens of other discoveries, large and small, were reported. There are larger telescopes than the 140-foot--there were larger telecopes in 1969 when formaldehyde was discovered--but there is no other which has contributed so much in so many different areas to centimeter-wave astronomy. With its constantly improving sensitivity, its versatility, adaptability, and reliability, the 140-foot has been, and continues to be, a unique research tool. Over 200 observers use the 140-foot telescope each year.

The characteristics of the 140-foot telescope most distinctive and most in demand by astronomers are:

- Frequency coverage. In 1987, research programs were conducted on the 140-foot telescope at frequencies from 25 MHz to 25 GHz. With very few gaps, sensitive state-of-the-art receivers are available throughout this frequency range. 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 full-time to radio astronomical research. Astronomers are encouraged to bring their own instrumentation and/or to experiment with unconventional observing techniques. The now "standard" spectroscopic observing procedures at the 140-foot--e.g., total power, nutating dual-beam--all resulted from users' experiments and experience.

PRESENT INSTRUMENTATION

Telescope Specifications

Diameter: 140 feet (43 m)
Pointing Accuracy: 7"
Sky Coverage: -46° to 90° declination.
Fully steerable. Tracking time is 2 hours or greater at all declinations.
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 means of 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.

Receiver List

Frequency Range	Amplifier Type	System Temp.
0.025- 0.088	Transistor	300 K
0.110- 0.250	Transistor	250
0.250- 1.0	Cooled upconverter/GaAsFET	45-85
1.0 - 1.45	Cooled GaAsFET	35
1.30 - 1.80	Cooled HEMT	18-23
2.90 - 3.50	Cooled GaAsFET	25-35
4.47 - 5.05	Cooled GaAsFET	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. The prime focus receivers, those at frequencies below 5 GHz, are shared with the 300-foot telescope.

FUTURE INSTRUMENTATION PLANS

HEMT Amplifiers - The fundamental amplification of the 140-foot Cassegrain receivers is a K-band maser tunable from 18-25 GHz.

Frequencies between 5-18 GHz are converted in frequency to K-band by one of three parametric upconverters that proceeds the maser. While giving wide bandwidth and frequency flexibility, the upconverters introduce a source of noise (and instability) that it would be advantageous to eliminate. Heretofore, no competitive wideband, lower noise alternative was available. However, with the successful development of HEMT amplifiers at the NRAO Central Development Laboratory, we have the opportunity to replace the 5-18 GHz upconverter portion of the Cassegrain receivers with wideband HEMT receivers operating at the signal frequency. Since the CDL HEMTs have a receiver temperature of approximately 1 K/GHz, these amplifiers are superior to the upconverter/maser receivers but they are inferior to the maser itself at its K-band signal frequency.

We plan to replace the upconverter receivers with HEMTs over the next few years, retaining the maser receivers. The present system temperature of the 140-foot Cassegrain receivers is shown as the solid line in Figure 4.1; the expected improvement with HEMT receivers at 5-18 GHz is shown by the dashed lines.

<u>Improved Feeds</u> - In August 1987, the first steps were taken to improve the 140-foot optics when a detailed holographic map was made of the primary mirror and, on the basis of this map, the surface panels were reset. At high frequencies the increased aperture efficiency (from 18 to 28 percent at 24 GHz) was reassuring. Further improvements in aperture efficiency will result when the figure of the secondary and tertiary mirrors are improved. More work on the feeds will reduce spillover, as well as the noise contribution of the feeds and waveguide. (At L-band more than half the total system noise of 18 K is a result of the feed and spillover.)

<u>32 GHz Receiver</u> - The more precise setting of the telescope primary mirror achieved in August suggests that it may be possible to extend the useful frequency range of the 140-foot to the atmospheric window at 32 GHz. If so, measurements of the microwave background anisotropy and the Sunyaev-Zeldovich effect stand to be the principal beneficiaries, although an increased frequency range for spectroscopy also could be exploited. Figure 4.1 illustrates the system temperature which appears feasible with a HEMT amplifier at 25-32 GHz (dashed line).

5. 12-METER TELESCOPE

The NRAO 12-meter telescope began as the 36-foot telescope, and the 36-foot telescope is where millimeter-wavelength molecular astronomy began. 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 as the 12-meter (in 1984). Subsequently, the scientific program has evolved from one

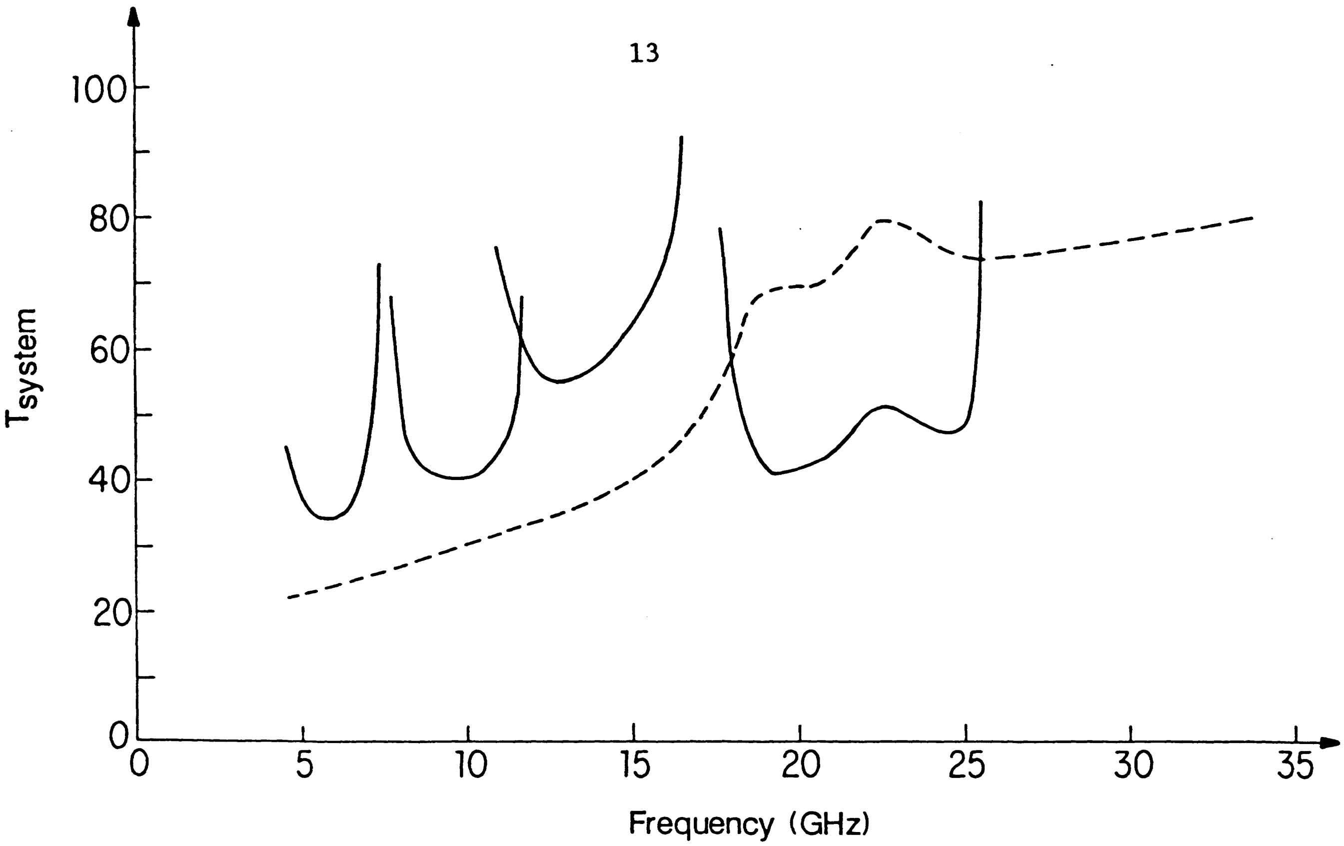


Figure 4.1. System temperature of one of the Cassegrain receivers on the 140-foot. The solid curves show the present performance with the upconverter/maser receiver. The dashed line is the expected system temperature with HEMT amplifiers at all frequencies.

dominated by observing programs in astrochemistry to one with concentrations in molecular clouds and galactic star formation, evolved stars, and, more recently, studies of external galaxies as well. 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. (per channel)
70-115	Schottky	350-500 K
90-115	SIS	80-150
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: All single beam receivers have 2 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 increase further the flexibility, frequency resolution agility and to accommodate the 8-beam receiver, a hybrid filter bank/autocorrelator is under construction. It will be on the telescope in the fall of 1988. Its instrumental parameters are as follows:

- 8 independent IF sections;

- 1536 spectral channels (can be split into 8 sections);

- 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 2 continuously between 1.56 MHz and 24 kHz.

FUTURE INSTRUMENTATION PLANS

Multi-Beam Receivers - The 8-beam 220-240 GHz Schottky receiver has been tested on the telescope and performs perfectly. It provides two rows of four 30" beams separated by 80". The beam shape for all beams is diffraction limited, the telescope illumination is complete, and the sensitivity is as expected from the receiver noise.

Full implementation of the multibeam receiver awaits completion of the hybrid filterbank/autocorrelator now expected in the fall of 1988.

The eight receivers are all Schottky mixers. Upgrade to SIS mixers from the NRAO Central Development Laboratory is anticipated once the SIS devices and 4K cryostats can be fabricated.

On a somewhat larger time scale, we are working toward an array of 32 independent SIS receivers at 230 GHz on the 12-meter. Development of a flexible and inexpensive spectrometer is crucial to this initiative.

SIS Receivers - Observational experience at frequencies greater than 300 GHz has been most favorable throughout the winter of 1988. Nine submillimeter programs, involving 18 astronomers and 27 days, have been scheduled on the telescope this winter. With a new subreflector shaped for the 12-meter at the University of Texas using holographic maps of the 12-meter surface, the aperture efficiency at 345 GHz has been improved by at least 50 percent. The Kitt Peak site appears to be adequate for submillimeter observations four months a year. The combination of telescope improvements, operational ease, and successful operation in 1988 promotes submillimeter astronomy at the 12-meter. Receiver performance will be addressed in the near future, with a change to SIS mixers expected.

Intermediate Baseline Millimeter/Submillimeter Array - The existence and proximity of large millimeter-wave and optical telescopes in southern Arizona presents the opportunity for these elements to be combined into an interferometric array for observations at millimeter and submillimeter wavelengths. Using radiative LO and IF links originating from the 12-meter telescope, one could create a connected interferometer made up of the Kitt Peak VLBA antenna, the MMT, and the Arizona/MPI 10-meter telescope in addition to the 12-meter. Other, smaller telescopes could, of course, be included as well. However, even with the four elements mentioned above, such an interferometer would provide baselines from 300 m to 180 km and a resolution of several tens of milliarcseconds. Such a cooperative array would: (1) permit scientific investigations of stars, star-forming regions, and extragalactic objects at an angular resolution not represented either by the existing millimeter interferometers or by conventional VLBI networks; (2) encourage technical development for the millimeter-wave array project (MMA); and (3) define the scope of millimeter-wave science at sub-arcsecond resolution.

6. 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 that 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 to give an imaging forming instrument with unprecedented angular resolution and image quality. At its shortest operating wavelength the resolution is a few tenths of a milli-arcsecond, corresponding 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 continuous range of brightness sensitivity and resolution from a few arc minutes (VLA D Array at 327 MHz) to 0.2 milli-arcseconds (VLBA at 43 GHz). The VLBA elements are located so as to optimize the image quality. The nine observing bands of the VLBA are designed to cover: the main spectral lines of interstellar masers; the radio astronomy continuum bands, to give a range of resolution, surface brightness sensitivity, and spectral information; as well as 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, although initially the shortest wavelength receivers will be at 7 mm. The VLBA playback facility will accommodate 20 inputs, so that up to 10 additional antennas located throughout the world can be used to further 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 preplanned 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 individual scientists who do not have any particular expertise in radio interferometry. Individual observers will not need to be present at observing time or when the tapes are correlated, but may choose to monitor either activity from their home location via an external terminal and display. While this mode of observing has its well known advantages and disadvantages, it is particularly suitable for the VLBA as there is little opportunity for scientific interaction either at observing or correlating time. Since the observer 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 operating center, to exploit best the available hardware and software. The combined VLA/VLBA Operating Center will support all types of VLBA observing, including geodesy and geophysics, but it is anticipated that as in the case of the VLA, many users will choose to do most or all of their analysis at their home institution, and we do not plan to provide sufficient internal computing resources to process all of the VLBA observations.

PROJECT STATUS - MARCH 1988

Sites - The following table gives the status of the ten antennas and associated sites.

Site	Status
Pie Town NM	operational
Kitt Peak AZ	antenna done; electronic outfitting 50% done
Los Alamos NM	antenna done; electronic outfitting beginning
Ft. Davis TX	antenna 75% done; electronics 50% built
North Liberty IA	site construction done; antenna assembly beginning
Brewster WA	site construction done; antenna under manufacture
Owens Valley CA	site development beginning; antenna authorized
St. Croix VI	site acquisition expected soon; antenna authorized
Mauna Kea HI	site acquisition in process
Peterborough NH	site to be acquired - spring 1988

Manufacture of the last two antennas will be authorized in early 1989. Assembly of the last antenna on its site will begin in early 1990. No further changes are anticipated in the contract with Radiation Systems, Inc. for the antennas. All of the antennas will be completed by 1991, and full operation of the VLBA is expected by the end of 1992.

With the exception of a problem known as "azimuth-wobble," the Pie Town antenna meets specifications. Most important, 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 μm rms. The measured value is 145 μm rms. This means the goal of an array that can in principle function at 3 mm wavelength is possible. The "azimuth-wobble" is being diagnosed and appears to be caused by a combination of factors associated with the azimuth track: unevenness of the rail surface, grouting technique, and possibly other factors. Corrections will be made by the manufacturer in the early antennas, and succeeding antennas are not expected to show the problem.

Receivers - 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 Input Type	T(Phys)	$T(R_x)$	T(Sys)	Comment
330 MHz	0.312 - 0.342	GASFET	300	30	90	Production
610 MHz	0.580 - 0.640	GASFET	300	30	60	Production
1.5 GHz*	1.35 - 1.75	HEMT	15	7	27	Production
2.3 GHz	2.15 - 2.35	HEMT	15	8	28	Prototype
4.8 GHz*	4.6 - 5.1	HEMT	15	10	30	Production
8.4 GHz	8.0 - 8.8	HEMT	15	16	36	Production
10.7 GHz	10.2 - 11.2	HEMT	15	20	40	Pie Town only
15 GHz	14.4 - 15.4	HEMT	15	30	52	Production
23 GHz*	21.7 - 24.1	HEMT	15	60	92	Prototype
43 GHz	42.3 - 43.5	SIS	3	40	77	Development
43 GHz	42.3 - 43.5	HEMT	15	90	127	Development

* 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.

These high-performance receivers are based on very reliable, cryogenically cooled, transistor-amplifier technology developed at the NRAO Central Development Laboratory. 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, Inc., has delivered four maser clocks and delivery is expected soon on two more. The masers meet specifications (root Allen variance ≤ $2x10^{15}$ at 10^3-10^4 seconds, ≤ $1x10^{-13}$ at 1 second averaging time). Two masers are undergoing careful environmental tests at JPL to determine their long-term stability.

Record/Playback Systems - Haystack Observatory has completed the first two recorder systems. One is being integrated into the control system hardware in the digital lab at the VLA prior to installation at Pie Town. The other is being held at Haystack for further system tests prior to shipment. Two more systems are being built as "pre-production" models before beginning production run manufacture of the remaining 18 systems. NRAO will build several major subsystems for these production units. Haystack has begun a prototype of the first playback system. The correlator requires 24 of these for full capacity operation.

It is anticipated that the VLBA recorder/playback system and recording format will eventually become the world standard. To ensure a smooth transition, which is likely to take many years, from the present MKIII standard, the VLBA recorders will be 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 all associated electronics required at each site has been completed and installed at Pie Town. Equipment for succeeding sites is in routine production.

Correlator - The correlator implements an FX, or spectral-domain, architecture. In October 1987 all aspects of the correlator were thoroughly reviewed, including the major hardware elements and control software, modes and performance tradeoffs, playback interface and data format, model tracking algorithms and accountability, expandability and future inclusion of data from orbiting antennas, subarray capabilities, cost, and construction schedule.

Design of the correlator is based on a dual-purpose VLSI chip using a specialized complex floating-point number representation. This chip functions as a radix-4 stage in the station-based FFT section, and also serves as a complex multiplier/accumulator in the baseline-forming section. An extensive preliminary chip design has been completed and analyzed through several simulations, and a request for proposals was recently issued for final design support, prototyping, and fabrication.

A subsection of the correlator, with seven station inputs out of the eventual twenty, and two of the final eight baseband channels, is expected to be completed and tested by mid-1990. At that point the subsection will be moved to Socorro and the initial subarray of VLBA antennas then complete will begin stand-alone operation. Replication of modules to expand the correlator to its final configuration will then continue in Socorro.

Post-Processing Software - Software governing local station functions is complete. Astronomical observing routines are logically complete and the software is being written and debugged. Software to communicate between stations and the Array Controller MicroVax exists in a rudimentary form; the Pie Town antenna has been 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.

Construction of the Array Operations Center is proceeding on schedule, with completion expected in summer/fall of 1988. This building will also house 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 as follows.

1988:

- Correlator chip ordered, correlator construction begun;
- Array Operations Center construction finished.

1989:

- Completion of the Los Alamos NM, Ft. Davis TX, North Liberty IA, and Brewster WA stations, for a total of six stations complete;
- Delivery of all hydrogen maser clocks;
- Construction complete of all 1.5, 4.8, and 23 GHz receivers;
- Delivery of two Data Acquisition Systems and prototyping of Play Back System complete;

1990:

- Completion of St. Croix VI and Owens Valley CA stations;
- Completion of subassembly of correlator, including 7-stations and 2-data channels;

1991:

- Completion of Mauna Kea HI and Peterborough NH stations;
- Completion of all receiver construction;
- Completion of post-procerssign computers installation;

1992:

- Completion of correlator;
- Delivery of all Data Acquisition Systems and Play Back Systems;
- All stations operational.

LONG RANGE PROSPECTS. As currently designed, the VLBA will give a vast improvement in sensitivity, resolution, image quality, frequency agility, spectral resolution, and time discrimination over current VLBI facilities. But even further improvements are possible.

Millimeter-Wavelength Receivers - Each of the ten elements of the VLBA are the most precise antennas of this size in the United States, and it is anticipated that they will work well at wavelengths as short as 3.5 mm. Successful VLBI observations have already been demonstrated at this wavelength, and by equipping the VLBA with 3.5 mm radiometers it will be possible to further improve the resolution by a factor of two. This is equivalent in optical astronomy of moving from a "good" site to a "superb" site. These radiometers are estimated to cost a total of $200k, but there may be other costs required to upgrade the subreflectors and antenna pointing accuracy. It is too early in the project to evaluate these needs.

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 adequately cover this gap, but the location of the New Mexico and Arizona antennas has been carefully chosen so that the addition of three or four more antennas in New Mexico will give a well designed 40-41 element array with good (u,v) coverage from 40 meters to 8,000 km. This was discussed above in the section on future VLA plans.

Space-Based Antennas - Extension of the VLBA to 3.5 mm will give essentially the highest feasible resolution possible from the surface of the Earth. At shorter wavelengths, irregularities in the Earth's atmosphere cause deterioration of the images. To improve the resolution even further, it will be necessary to go into space. At least three space VLBI missions are being currently planned. These are:

the ESA QUASAT mission;
the Soviet RADIOASTRON mission; and
the Japanese VSOP mission.

Unfortunately, there is no comparable plan by the United States to exploit further the VLBI techniques which we have developed in this country. NRAO scientists are, however, involved in the planning of the ESA and Soviet missions and have been invited to contribute to their design and construction. It is hoped that 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, and it is expected that all of 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 is the only large VLBI correlator being developed, and we have discussed its use in support of the space missions. Although the correlator is being designed to allow for a space-based element, some additional hardware will be needed at an estimated cost of about $500,000, which may be available from NASA.

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. It is likely that very significant improvements in the sensitivity will be possible in the future, but this will require replacing the entire recording and playback system.

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 at the same time keeping operations costs at a reasonable level is the goal of this plan. It has already had a profound effect on the design of the array.

Cost considerations require keeping the staff levels at each of the ten sites to a minimum. The goal is two technician-level personnel at each site for maintenance of continuous, daily 24-hour operation. It follows immediately that all subsystems must be modular. Units 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, to the extent possible, have joint duties for both the VLA and VLBA. This is much of the rationale behind the choice of Socorro for the location of the VLB Array Operations Center (AOC). It is also the rationale behind the decision to make the AOC large enough to house all VLA staff whose physical presence is 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 paying 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 1987 dollars. These costs are incremental to NRAO's existing operating budget.

Category	Cost ($1987)
Personnel (95 people)	$3.1M
Travel	0.2
Communications and Power	0.8
Materials and Supplies	1.2
Shipping	0.2
New Equipment	0.5
Total	$6.0M

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

	VLA Alone	VLA & VLBA Combined
VLBA Site Technicians	-	20
Electronics	28	51
Antennas	25	33
Array Operations	13	27
Business	28	36
Computing	17	28
Scientific Services/ Management	17	28
Total	128	223

Difference is 95 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 sub-array in late 1990;
- full operation of the 10-element array in 1992.

The funding schedule for interim operations was scheduled to be a roughly linear ramp up to $6M in 1992 from a very modest start in 1987. Actual funds available for VLBA operations have been $0.2M (1987) and $0.5M (1988). That means that the Kitt Peak and Los Alamos antennas will not be operated for the VLBI Consortium observing runs in 1988; only Pie Town is available to support these runs. While the regular operation of Pie Town in VLBI Consortium runs does check out one system in actual observing by users, revealing problems early for timely correction, the delay in using the other sites as they become available hurts VLB science and puts difficult dislocations in what was to be a smooth growth in staff and operations funding. Moreover, it will delay the testing of many of the new features of the VLBA.

7. ARRAY TELESCOPE COMPUTING PLAN

In September 1987, NRAO submitted an Array Telescope Computing Plan to the Foundation. This is the result of a reassessment of the projected computing needs of both the VLA and VLBA and a study of hardware developments in the computer industry. The plan entirely replaces the earlier concept, "A Supercomputer for Radio Astronomical Imaging," presented in the spring of 1985.

Instead of a single supercomputing facility at NRAO for all array telescope data processing, we now envisage a combination of various size computers, loosely coupled together. The outline of this new concept is shown in Figure 7.1.

Sixty percent of the total projected computing demand is estimated to originate from VLA users, with the remaining 40 percent coming from VLBA users. But only 10 percent of the VLA projects and 1 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 will not operate a supercomputer center itself in this Plan.

Data from the remaining 90 percent of the array telescope projects will be processed at an NRAO computing facility, or at the users home institution, or most likely, at some combination of both. The NRAO facility is to consist of a loosely coupled set of second-generation mini-supercomputers, high performance imaging workstations, and a mass storage and archive system. Figure 7.2 illustrates this system, to be located in Socorro NM in the new Array Operations Center currently under construction.

The software plan for this proposed system has three elements:

- continued development and support of AIPS for use at NRAO and export to other facilities, including supercomputers and user home institutions;

- research in image processing, including new algorithm developments that will eventually be incorporated into AIPS;

- code optimization for efficient use of machines available.

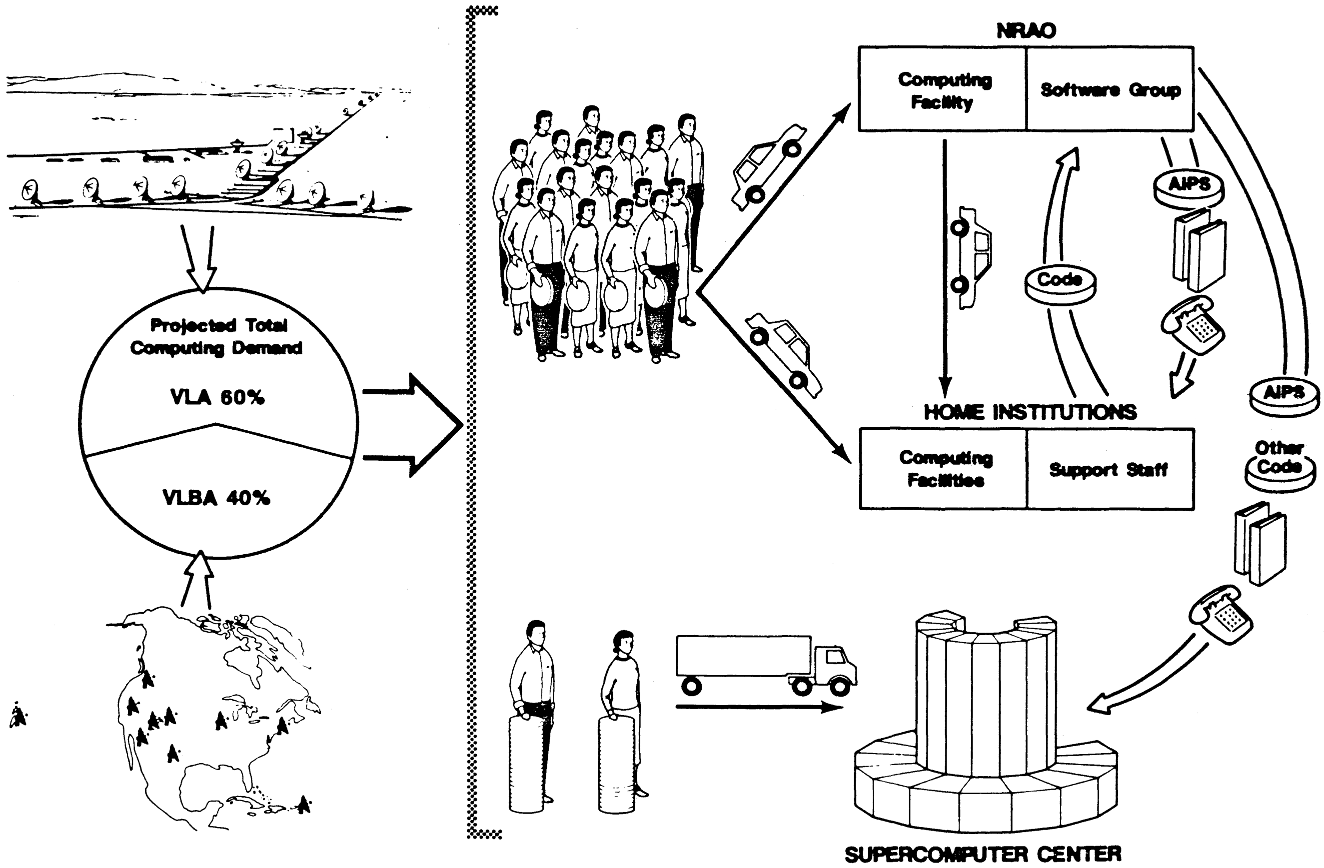


Figure 7.1. An illustration of the main features of the Array Telescope Computing Plan. The off-line computing requirements of the VLA and the VLBA will be met by computers at the NRAO, at users' home institutions, and at supercomputer centers. The data processing needs of about 90% of the users will 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.

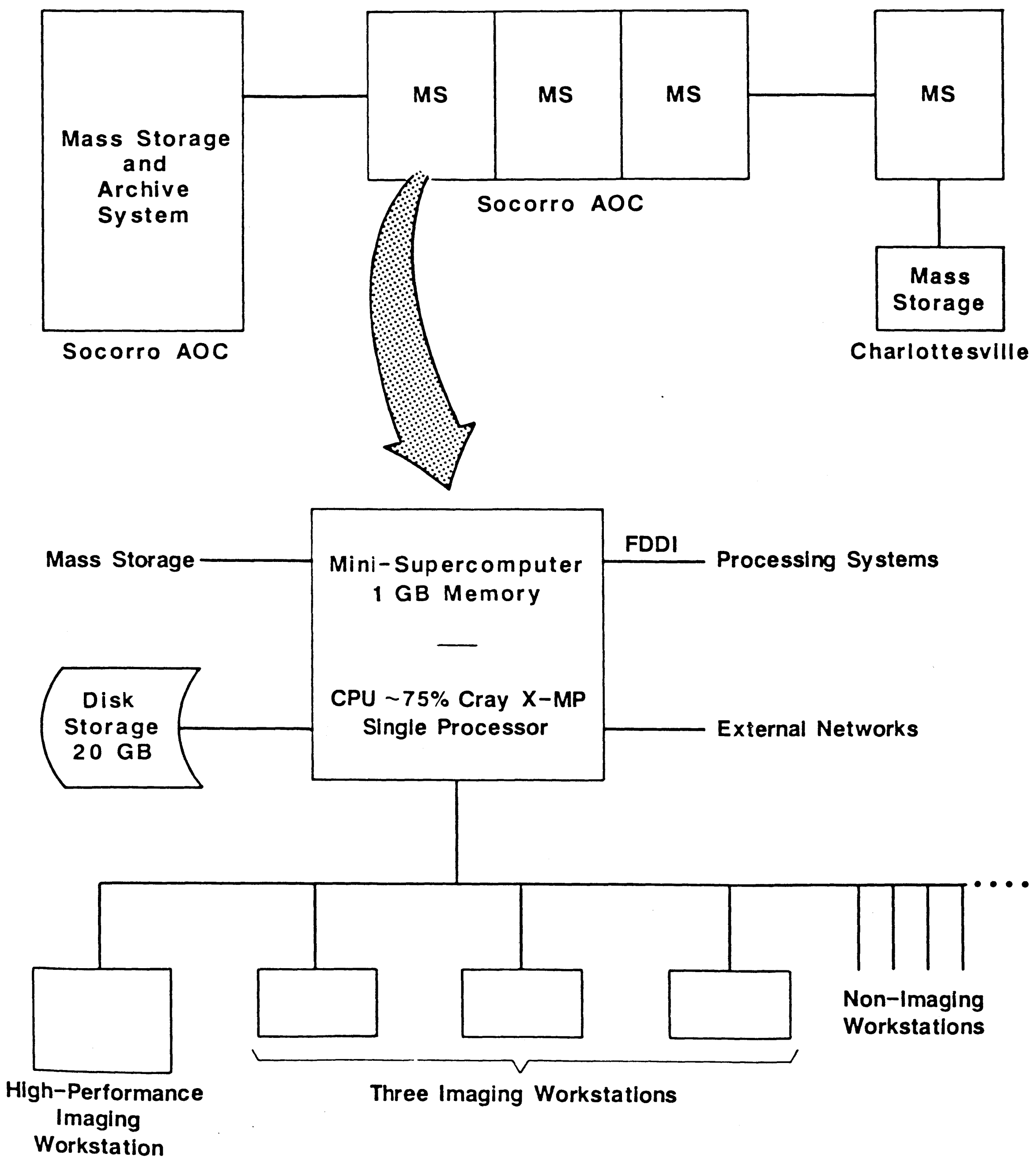


Figure 7.2. The configuration we propose for a loosely coupled network of four mini-supercomputers (MS). The lower panel shows detail of the individual elements depicted in the upper panel.

The funding required for this Plan has been included in the schedules given in Section 9, both equipment and operations, and with allowance for funds expected as part of the VLBA construction project. For purchase of equipment, the requirements are:

Total Required	\$3.450M	\$3.475M	\$3.075M
Included in VLBA Construction	1.500	1.500	1.500
Additional Required	\$3.450M	\$1.975M	\$1.575M

In addition, operations costs are expected to increase under this plan by \$700k in 1990, an additional \$425k in 1991, and a final additional amount of \$450k in 1992.

8. THE MILLIMETER ARRAY

In 1983, the NSF formed a subcommittee, chaired by Professor Alan Barrett, to offer guidance on the priorities for the future development of millimeter and submillimeter astronomy. Among the committee's three principal recommendations was a request for a design study for a national millimeter-wavelength synthesis array. This particular recommendation was an encouragement that the NSF build on the seminal interferometric millimeter work being done with the Owens Valley Radio Observatory's 3-element interferometer and the Berkeley Radio Astronomy Laboratory's Hat Creek interferometer. These instruments continue to demonstrate the wealth of scientific insight that can be gained from observations at high angular resolution. The Barrett Committee saw the opportunity, and pointed to the need, for an imaging synthesis array for millimeter-wavelength astronomy. The array, they noted, should have the following properties:

- 1 arcsecond resolution at 115 GHz;
- 1000-2000 m^2 total collecting area;
- good imaging capability at 1 mm.

Design of an array intended to fulfill these needs was begun at the NRAO in 1984. The resultant conceptual design was presented to a scientific workshop of approximately fifty astronomers held in Green Bank in September 1985. The workshop participants were asked to assess the scientific justification for such an array and then refine the array design in light of their scientific demands.

The strong scientific endorsement given for the millimeter-wave array (MMA) at this workshop placed particular emphasis on the array's imaging capability. The MMA should be a true imaging array, it was concluded. Frequently the objects to be observed are larger than the telescope beamwidth. In such cases many overlapping regions must be observed and the individual images merged into a single mosaic image. Many antennas are required to maximize this capability. In addition, the working groups noted that new science, not possible with any existing instruments, would follow if the MMA provided a sensitive high-frequency capability (to as high as 350 GHz) and sub-arcsecond resolution. The combination would provide a unique opportunity for astronomers to study thermal emission from the photospheres of nearby stars, to image the dust continuum emission in galaxies throughout the local universe, unconfused by Galactic "cirrus," and to detect the redshifted dust IR-luminosity from primeval galaxies.

The capabilities of the MMA given greatest emphasis by the Green Bank scientific workshop can be assembled within the following categories which are described below:

(1) Provision for rapid imaging;
(2) Sensitive imaging at 230 and 345 GHz;
(3) Wideband/multi-band facility.

Rapid Imaging Capability - An imaging millimeter array (MMA) synthesis telescope 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 GMCs through the star formation stage;
- the gas constant 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, and such questions are best addressed by appeal to 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 1 mm 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-wave 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 Design Concept - The realization of these scientific capabilities requires a refinement of the design parameters suggested by the Barrett Committee for the millimeter-wave array. Specifically:

(1) Sub-arcsecond imaging at 115 GHz (and higher) implies array baselines ≈ 3 km.
(2) Rapid imaging means that the 1000-2000 m² of collecting area be divided among many elements.
(3) Sensitive imaging at high frequency (to 350 GHz) requires that the array be located on a high site with low atmospheric opacity.

A conceptual design of a 40-element array that is tailored to these requirements is described in the 2-volume MMA design study:

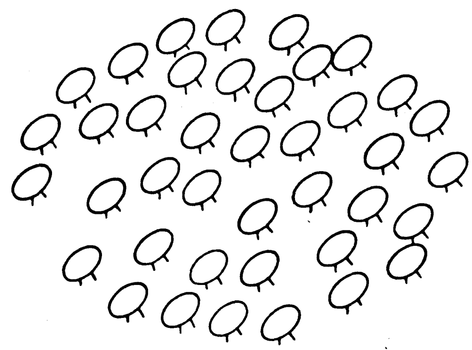
Vol. I -- Science with a Millimeter Array, edited by A. Wootten and F. R. Schwab (1988);
Vol. II -- Millimeter Array Design Concept, edited by R. L. Brown and F. R. Schwab (1988).

The properties of the array are summarized as follows:

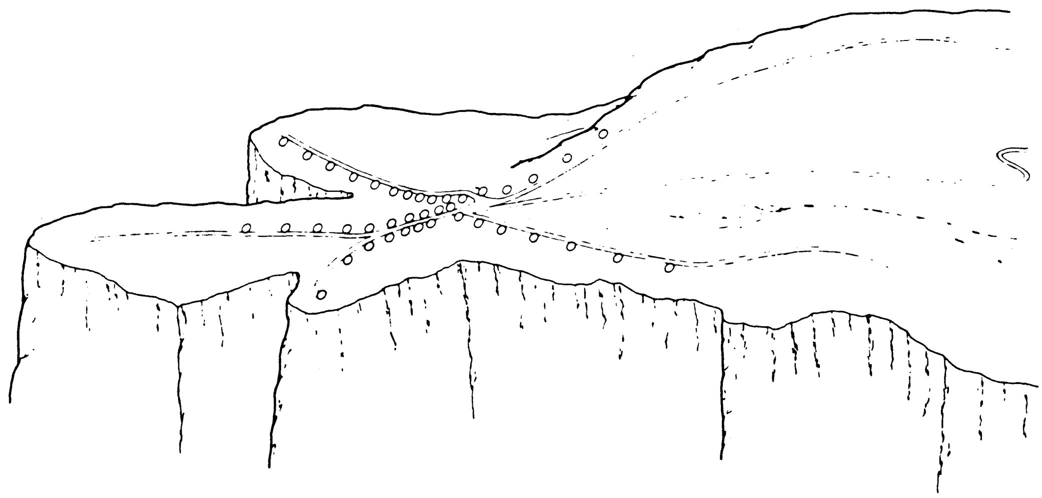
Antennas:	40 7.5 m diameter shaped reflectors Total surface error < 0.043 mm r.m.s. Transportable design Aperture efficiency > 80 percent Total collecting area 1767 m^2
Configurations:	90 m (packed circle/ellipse) 300 m (circle/ellipse, star, or other array) 1000 m (circle/ellipse, star, or other array) 3000 m (circle/ellipse, star, or other array)
Frequency Bands: (desired)	36-48 GHz 70-115 GHz 00-270 GHz 270-350 GHz
Angular Resolution:	0.1 arcsecond at 230 GHz

Located on a high altitude site so as to facilitate observations at the highest frequencies, the precise array configuration may be dictated by the local topography. Figure 8.1 illustrates both the packed (90 m) configuration and a sketch of one of the more extended configurations on a remote, high altitude, site.

Work on the MMA design both within the NRAO and together with interested astronomers in the community will continue throughout the planning period.



(a)



(b)

Figure 8.1. Examples of MMA configurations: (a) the most compact configuration for a fixed number of antennas, a packed circle/ellipse; (b) a schematic mountain-top array where topography significantly affects the larger 3 km, and possibly the 1 km, arrays.

9. BUDGET PROJECTIONS (M$)

	1988	1989	1990	1991	1992	1993
Operations						
Existing Operations	16.1	17.2	18.6	19.4	20.3	21.5
VLBA Operations	0.5	1.5	2.9	4.4	5.9	7.6
Common Cost Recovery	(0.3)	(0.2)	--	--	--	--
Major Facilities Maintenance	0.2	1.0	1.3	1.1	1.0	0.4
Array Computer Plan	--	--	0.7	1.1	1.6	1.4
Total Operations	16.5	19.5	23.5	26.0	28.8	30.9
Equipment						
Research Equipment	0.2	1.0	1.3	1.5	1.7	2.0
Operating Equipment	0.1	0.2	0.1	0.1	0.2	0.1
Array Computer Plan	--	--	3.5	2.0	1.6	--
VLA - Pie Town Link	--	--	1.0	--	--	--
Total Equipment	0.3	1.2	5.9	3.6	3.5	2.1
Total Operations and Equipment	16.8	20.7	29.4	29.6	32.3	33.0
Construction						
VLBA	11.6	12.0	12.5	13.0	2.6	--
Millimeter Array	--	--	--	1.5	10.0	15.0
Combined VLA/VLBA Imaging	--	--	--	--	6.0	6.0
Total Construction	11.6	12.0	12.5	14.5	18.6	21.0
NRAO/NSF Total	28.4	32.7	41.9	44.1	50.9	54.0

Personnel Projection (Full Time Staff)

	1988	1989	1990	1991	1992	1993
Existing Operations	277	281	285	291	296	303
VLBA Operations	10	26	53	70	87	95
VLBA Construction	67	60	56	33	4	--
Work for Others (USNO, NASA)	15	8	8	8	8	8
Array Computer	--	--	3	10	15	17
Personnel Total	369	375	405	412	410	423