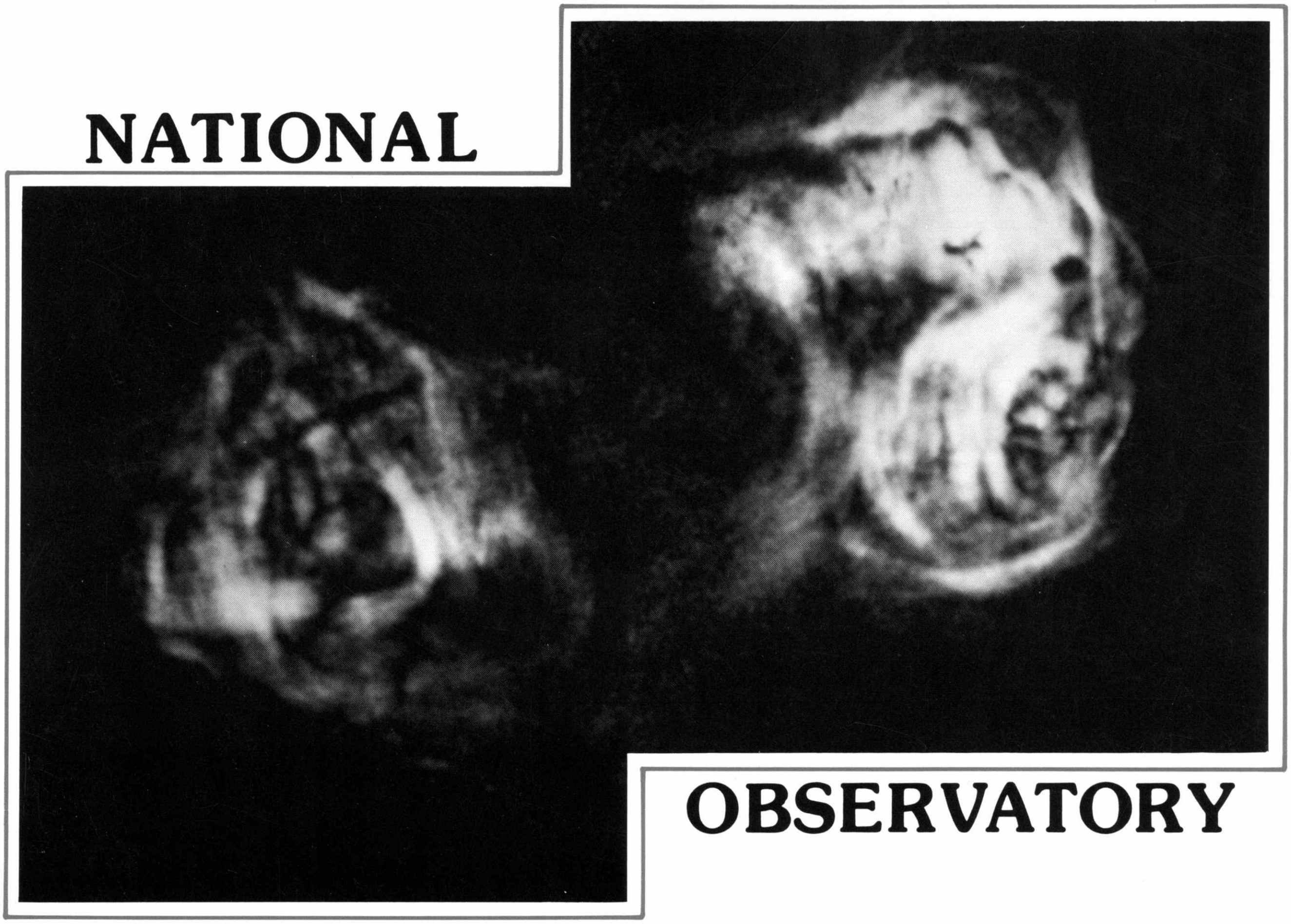
US/GB BK

RADIO

NATIONAL



OBSERVATORY

ASTRONOMY

LONG RANGE PLAN
1990–1994

Cover: The Polarized Radio Emission from Fornax A

The cover photograph is a VLA image of the linearly polarized radio emission from the radio galaxy Fornax A. The two main radio emitting lobes are produced by radiating electrons in magnetic fields which have been transported hundreds of thousands of light years from the elliptical galaxy NGC 1316 which lies between the two regions. The isolated, dark features are caused by the obscuration of the polarized emission by foreground material. The small elliptical "shadow" on the right is associated with a foreground spiral galaxy which depolarizes the radiation passing through it. But the "ant-like" feature in the center of the right lobe and the long dark features which are particularly prominent in the left lobe are not associated with luminous material.

Observation details:

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

Frequency of 1.384 GHz. Five hours of D-configuration and five hours of C-configuration

Resolution of 15"; field of view is 40' x 20'

Maximum polarized emission is 15 mJy; rms noise is 0.3 mJy

NATIONAL RADIO ASTRONOMY OBSERVATORY

LONG RANGE PLAN

1990-1994

April 1989

NATIONAL RADIO ASTRONOMY OBSERVATORY

LONG RANGE PLAN - 1990-1994

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I. INTRODUCTION

At the close of the decade of the 1980's, radio astronomy in the U.S. in general, and certainly at the NRAO in particular, is found in a state of transition. On one hand the last decade has seen unprecedented advances culminating in the construction and operation of the Very Large Array, a telescope capable of providing astronomers with the imaging resolution and fidelity needed to unravel the underlying physics of such phenomena as the jets and lobes of radio galaxies and quasars. The striking VLA images of the filaments in the center of the Milky Way, the relativistic ejecta in SS 433 and M87, and the flash of interstellar clouds detonated by the passing shockwave from the supernova Cassiopeia A, present a formidable challenge to the astronomers, physicists, and students of the next decade. The 1980's have recorded the start of the Very Long Baseline Array (VLBA), a major new facility for high-resolution imaging. VLBA construction is now half completed and the challenge of initial operations and scientific use has begun. On the other hand, the 1980's have also witnessed the collapse of the Green Bank 300-foot telescope, the premier survey instrument for the northern radio sky. Loss of this telescope leaves a large gap in the instrumental capabilities needed by astronomers to conduct their research. Recognizing both these developments, the present NRAO long range plan looks to enhance the capabilities of the imaging synthesis telescopes, the VLA and VLBA, to restore and extend the scientific capabilities lost in the collapse of the 300-foot telescope, and to use this time of transition to build the national radio observatory of the next century.

The specific plans for each of the NRAO facilities and activities are described in the sections that follow. The highlights of the plan include:

- Completion and full operation of the VLBA;
- Construction of a high performance, fully steerable, large aperture radio telescope in Green Bank. The telescope design will offer major advances over existing instruments in every relevant area of research;
- Completion of the 327 MHz and 75 MHz capability of the VLA and first steps toward improving L-band sensitivity. In addition, it may be possible to complete a real-time link between the VLA and the VLBA antennas in Pie Town, doubling the angular resolution of the VLA;
- Expansion of the 8-beam, 230 GHz receiver of the 12-meter telescope to 32 beams so as to create a true 1 mm imaging camera. Such an instrument will incorporate low-noise SIS receivers, wide-band spectrometers and sufficient computational resources to manage the data;

- Replacement of all the Cassegrain upconverter receivers on the 140-foot telescope with wide-band, low noise High Electron Mobility Transistor (HEMT) receivers. These receivers will provide complete frequency coverage from 4.9 GHz to 32 GHz with no gaps and with a sensitivity 50 percent better than the existing receivers. The receiver design will allow it to be moved to the new telescope at a suitable time in the future.

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 recently dedicated Array Operations Center in Socorro has already demonstrated the efficiency inherent in shared facilities and flexible task scheduling in an operational environment. Over the planning period the lessons learned here will be further refined and 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 80 miles of rail track in the VLA, maintenance costs are substantial and the needs continuing.

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 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 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.

- 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 finalized and 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 Expansion and Enhancement Program (VLA/E^2) includes installation of ultra low-noise receivers, construction of a wideband fiber-optic IF and correlator, additional VLA stations to provide short interferometer spacings, and 3-4 antennas to fill the gap between the longest VLA spacings and the shortest VLBA spacings.

II. BASE PROGRAM

VERY LARGE ARRAY

The Very Large Array is the realization of the need for an imaging radio telescope that can provide radio "pictures" with a resolution similar to that obtained from optical telescopes. The initial goal of 1" resolution, comparable to ground-based telescopes, has been surpassed and the VLA is now capable of producing images with the resolution expected of the Hubble Space Telescope (0."1). Contemporary astronomical research has no wavelength boundaries but benefits from orchestrated 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, 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 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

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.

Five 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 in 1997. 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. 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 ultimate 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--precisely this approach is intended as one part of the major initiative, VLA/Expansion and Enhancement (VLA/E^2) discussed in Section IV. In the interim a substantial gain in sensitivity may be achieved using the present dewar and accepting the long, lossy waveguide runs that this entails, if the GaAsFET amplifier is replaced by an HEMT. For the present we adopt this approach.

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 commerical 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 noted in the VLA/E^2 program.

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 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.

During the summer of 1987, 5500 ties were replaced on the east and north arms by a contractor. Last year 4500 ties were replaced, mostly on the west arm by the same contractor. We determined that there was a basic inefficiency with this system in that marginal ties as well as ties that had clearly failed were replaced along the rail line. Furthermore, the contractors have worked only to replace ties; other areas such as rail ballast, junctions, and joints have not been given great attention.

Using the same level of spending this year, more work will be done in house. A 4-man rail maintenance crew has been hired, and a work vehicle (road and track capable) and a ballast carrier have been purchased for their use. A complete railway inspection has been started and work is continuing to upgrade the gauge and alignment of the spurs and intersections in the C- and D-configurations. This phase of the work should be completed by July 1989. Replacement of the worst individual ties will begin thereafter. We expect to replace 3500 ties in 1989. By October this work should be completed, and a program of splice alignment, gauging, and ballast maintenance will be initiated.

All work so far has done little more than allow repair to the rail system at a rate equal to the rate of natural deterioration. Using the full-time crew and by gradually upgrading our capabilities, an improvement in the condition of the track should be seen in the next two to three years.

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 1989, 50,000 feet of power cable has been purchased. The intent is to install approximately 27,600 feet to replace the last remaining length of cable in which a failure has previously occurred. The remaining cable will be held in reserve for future problems in 1989. At 50,000 feet of cable per year, the total system will have been replaced by the year 2000.

FUTURE PLANS - VLA/VLBA COMPUTING

Both the quality and the quantity of images produced by the VLA now greatly surpass the original goals, as the following table shows.

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 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 creates a joint VLA/VLBA computing environment suitable for the needs of both arrays. This Plan is discussed in Section IV.

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	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 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 under construction. It will be on the telescope in the fall of 1989. 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 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 our long range plans for the 12-meter.

All the developments described here are of immediate relevance to the 12-meter telescope. Most are extremely relevant to the NRAO Millimeter Array (MMA), and experience gained with the 12-meter will give the MMA project a good head-start.

(1) A 1-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 will be interfaced to the new 1536 channel hybrid spectrometer, and will be operational by 1990. At this stage the full versatility of the hybrid spectrometer will not yet be available--budget considerations have caused us to implement a reduced first-stage. We hope that funding will enable us to complete this project according to the original specifications.

During 1990, we will upgrade the 8 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 1993. 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 receiver, and ultimately will provide a 32-spectrometer system for the full radio imaging system. 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. We have started planning for a multi-workstation environment at the telescope to support data analysis of the radio imaging system. The data acquisition rate will have increased by between 1 and 2 orders of magnitude. Consequently, considerable new computer hardware and software development will be required in the next three to four years.

(2) Single-beam systems

Receivers - NRAO has traditionally provided top-performance receivers, and this is particularly true of those recently constructed for millimeter wavelengths. A new closed cycle 4.2 K system with several SIS receivers sharing the same dewar is under development. 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 NRAO MMA.

Pointing - With the new 12-meter shaped sub-reflector (a project carried out in co-operation with the University of Texas), operation at frequencies as high as 360 GHz is becoming increasingly important. This puts a more critical demand on the pointing characteristics of the telescope. In order to improve the pointing, we will implement the following: real-time monitoring of movements of the focus assembly using a laser and quadrant detector; improved focus mount offering more freedom of movement and more precise control; increased monitoring instrumentation, such as inclinometers, strain gauges, and 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 started experiments with an auxiliary optical pointing system, observing stars optically as an aid to better understanding the pointing characteristics of the telescope. We intend to expand on this theme, to give a higher level of automation, with the possibility of offset guiding on optical stars to give accurate tracking of weak radio sources.

(3) Future plans

Two future projects have been suggested. With current budget constraints it is unrealistic to devote resources to serious planning of these projects, but should the financial climate change in the coming years, the following projects deserve discussion.

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 timescales for the Millimeter Array, this disparity is likely to persist for most of the next decade, unless steps are taken quickly. One possibility for correcting this imbalance is to purchase a copy of the IRAM 15-meter telescope. 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 $5M capital expenditure. The instrumentation, frontend and backend, would be transferred from the 12-meter telescope. Operation of the 12-meter 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 sub-millimeter region.

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 10 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, plus additional manpower.

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 applied 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 frequencies with sufficient sensitivity--is precisely the same capability that led to the discovery nineteen years later, in 1988, of cyanomethyl (CH_2CN), the largest known interstellar radical. 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 telescopes 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.
During the period of this Long Range Plan, that is, before completion of the new Green Bank telescope, the 140-foot telescope will serve as the only major instrument for filled aperture, centimeter-wavelength research.
The characteristics of the 140-foot telescope most distinctive and most in demand by astronomers are:

- Frequency coverage. With very few gaps, sensitive receivers are available throughout the 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, 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.

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 (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	45-85
1.0 - 1.45	Cooled GaAsFET	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 INSTRUMENTATION PLANS

Cassegrain Receiver - New receivers for the 140-foot Cassegrain system are currently under development. Cooled HEMT amplifiers are being designed by the Central Development Lab to cover the 25-35 GHz frequency range (Ka band), thus extending the capabilities of the 140-foot telescope, 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. Present and expected noise performance vs frequency is shown in Figure IV.1.

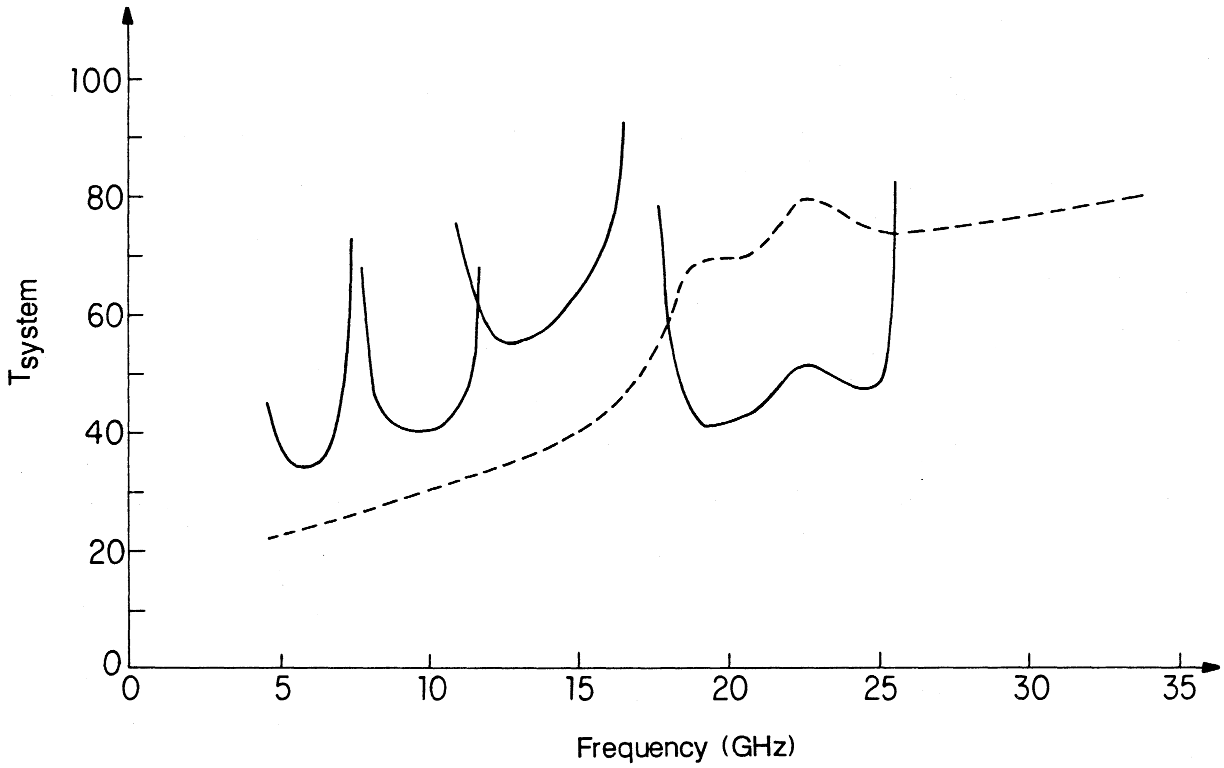

Fig. IV.1 - System temperature of one of the Cassegrain receivers on the 140-foot. The solid curves show the present performance with the upconverter/maser receiver. The dashed line is the expected system temperature with HEMT amplifiers at all frequencies.

Our plan is to build the local oscillator and IF system for the new receivers concurrent with Ka HEMT development. Ka observations would then be possible in early 1990 by cooling the Ka amplifier (temporarily) in the maser dewar. Completion of the first full band (5-35 GHz) HEMT receiver is set for the end of 1990, with both receivers ready in late 1991.

Spectral Processor - The spectral processor will go to the 140-foot telescope. Initially it will be used for pulsar measurements, but, as the demand warrants, it will be available for spectral line observations. Up to now pulsar observers had supplied their own specialized equipment for on-line data processing; the spectral processor makes this capability available to the general community. 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 chan
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

The hardware for half of the 2048 channels has been tested as a system. Cards for the second half have been built and tested and will be integrated into the system after a test run. Communications software between the MassComp and the hardware controller has passed its initial phase. Setup and data formats are defined. Maser-based timing transfer from the clock to the MassComp and the hardware controller is now being checked out.

Dual S/X Receiver - No receivers operable in the band 1.8 to 3.0 GHz exist for the 140-foot telesocpe. 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.

Multi-beam L-band Receiver - Both spectroscopic and continuum observers often conduct unbiased searches for major areas of the sky. Building upon the success of the 7-feed, 5-GHz receiver, we propose constructing a 7-feed, 10-14 GHz receiver. This new receiver could be built in such a way as to become a workhorse instrument on the new Green Bnak telescope.

Computing - During the interval 1990-1994, operation of the 140-foot telescope will become more automatic by upgrading the monitor-and-control hardware. This upgrade, as well as planned upgrades in the data analysis software, can use the 140-foot as a testbed for the new telescope. Both changes will be made within a broader NRAO context seeking to maximize uniformity of systems across the Observatory.

III. MAJOR FACILITIES CONSTRUCTION

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 image 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 arcminutes (VLA D-configuration 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; 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, 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 Array Operations Center (AOC) 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 AOC 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 well known advantages and disadvantages, it is particularly suitable for the VLBA, as there is little opportunity for scientific interaction either when observing or correlating data. 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. We, therefore, do not plan to provide sufficient internal computing resources to process all of the VLBA observations.

PROJECT STATUS - MARCH 1989

Sites - 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	antenna done; electronic outfitting 75% done
Ft. Davis TX	antenna done; electronics 50% built
North Liberty IA	antenna 90% done
Brewster WA	site construction done; antenna under manufacture
Owens Valley CA	antenna assembly started
St. Croix VI	site development begun; antenna under manufacture
Mauna Kea HI	site acquisition almost complete
Hancock NH	site acquired; site construction beginning spring 1989

Manufacture of the last two antennas was authorized in early 1989. Assembly of the last antenna on its site will begin in late 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.

Tests indicate 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.

Receivers - The following table gives the measured amplifier noise temperatures and expected system noise temperatures for the nine receiving bands along with status comments.

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

VLBA Frequency Bands and Noise Performance

Band	Tuning Range	Receiver Type	T(Phys)	$T(R_x)$	T(Sys)	Comment
330 MHz	0.132 - 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	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.

Maser Clocks - Sigma Tau Standards Corp. has delivered seven maser clocks and delivery is expected soon on two more. The masers meet specifications (root Allen variance $\leq 2\text{x}10^{15}$ at 10^{3}-10^{4} seconds, $\leq 1\text{x}10^{-13}$ at 1 second averaging time). Two masers underwent careful environmental tests at JPL to determine their long-term stability. Their test results essentially corroborated those of NRAO and the manufacturer.

Record/Playback Systems - Haystack Observatory has completed the first three recorder systems. One was integrated into the control system digital laboratory at the AOC, but is currently on loan to Owens Valley Radio Observatory for use in Network runs. Another system is installed at Pie Town. This system has been used successfully in Mk IIIA mode during Network runs in 1988. The third recorder is being held at Haystack for extensive further tests. Two "pre-production" playback systems are also close to completion at Haystack.

Five recorders and two more playbacks are scheduled for production during 1989 as part of an additional seven unit production order placed with Haystack in late 1988. The correlator requires 24 playbacks for full capacity operation. Negotiations between JPL, Haystack, and Honeywell to transfer narrow track record head production to an industrial source are at an advanced stage.

It is hoped that the VLBA recorder/playback system and recording format will eventually become the world standard. To insure a smooth transition from the present Mk III standard, which is likely to take many years, the VLBA recorders will be able to write Mk III 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 and Kitt Peak. 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. After a request for proposals and bid evaluation, a contract was 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 the end of 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.

Software - Software governing local station functions is essentially complete, but is being converted to eventually run under a new operating system. Astronomical observing routines are logically complete and the software is being written and debugged. Software to communicate between stations and the Array Controller SUN Processor running under UNIX will be written during 1989. Routinely the Pie Town and Kitt Peak antennas 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.

Construction of the Array Operations Center was completed in late 1988. This building also houses VLBA activities as well as those members of the 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.

1989:

- Completion of the Los Alamos NM and North Liberty IA stations, for a total of four 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 Playback System complete;

1990:

- Completion of Brewster, WA, Fort Davis, TX, and Owens Valley CA stations;
- Completion of subassembly of correlator, including seven stations and two data channels;

1991:

- Completion of St. Croix, VI, Mauna Kea HI, and Hancock, NH stations;
- Completion of most receiver construction;
- Installation of post-processing computers;

1992:

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

LONG RANGE PROSPECTS

As currently designed, the VLBA will vastly improve 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 be useful 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 to 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.

New Green Bank Telescope - For observations with the VLBA limited by sensitivity, the addition of the new 100-meter class Green Bank telescope will be an enormous improvement, increasing the collecting area by a factor of 2.6. This advantage is of particular importance to space VLBI.

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 excellent (u,v) coverage from antenna separations of 40 meters to 8000 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 angular 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. Two space VLBI missions are in advanced planning phases:

the Soviet RADIOASTRON mission; and
the Japanese VSOP mission.

Unfortunately, there is no comparable plan by the United States to extend to 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. Funds are expected from NASA to support this work.

Space VLBI requires an extensive ground array to provide a distribution of earth-space baselines, and it is hoped 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; these augmentations will be requested.

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 the equivalent of 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. It is expected that in the case of a serious failure at a telescope site a small group from the central location will be sent to make the repairs. The size and make-up of this group will of necessity be adjusted as experience dictates. It is critical therefore that the nucleus of this important group be formed soon so that they can achieve the requisite high degree of familiarity with the system.

A significant 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 VLBA operations center. 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.

Even in combination with the VLA, however, the VLBA will need a substantial group of computer programmers and scientific support personnel to introduce innovative techniques into the data reduction system and to provide high level scientific assistance to the users of the VLBA. It is the intention to recruit key persons in this area as soon as the budget situation permits because these people must be involved in the system at the outset. Only in this way can they learn the system and simultaneously provide the technical and scientific input during the development of the system.

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	($7.6M 1993)

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

The difference is 95 additional personnel needed to jointly operate the VLBA and 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 $7.6M in 1992 from a very modest start in 1987. Actual funds available for VLBA operations have been $0.2M (1987), $0.5M (1988), and $0.9M (1989). This means that only the Pie Town and Kitt Peak antennas will be operated for the VLBI Consortium observing runs in 1989. While the regular operation of these two antennas in VLBI Consortium runs does check out the system in actual observing by users, revealing problems early for timely correction, the delay in using the other sites as they become available is harmful to 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.

THE GREEN BANK TELESCOPE (GBT)

In early 1988, we began an investigation of the feasibility of replacing the 140-foot steerable antenna and 300-foot transit telescope in the future with a modern fully steerable instrument. The collapse of the 300-foot in November created an immediate major gap in available radio astronomy capabilities. In response to the emergency situation resulting from the loss of the 300-foot antenna and the limited capabilities of the 140-foot telescope, we have accelerated the plan to build a new radio telescope in Green Bank. The proposed new telescope will have an aperture of approximately 100-meters diameter and will work well at least to wavelengths as short as one centimeter and eventually as short as 3 millimeters.

The largest fully steerable aperture available in the United States is the 140-foot antenna in Green Bank. By using state-of the-art low noise radiometer systems developed at NRAO, the 140-foot (as well as the 300-foot prior to its collapse) has remained a powerful competitive scientific instrument for a wide variety of observational programs even though it is much smaller than the 100-meter German telescope near Effelsberg and has a considerably less precise surface than the 45-meter Japanese telescope in Nobeyama. Nevertheless, its equatorial mounting is now obsolete, its gravitational deformations excessive, its surface and pointing accuracy inadequate for work at short wavelengths, and its surface area too small for observations of weak emission.

The original plans for the Green Bank Observatory included the construction of a steerable radio telescope in the 300-foot class. Since the completion of the 140-foot and 300-foot transit antennas in the 1960's, NRAO has developed a number of design concepts for a large fully steerable radio telescope. Although, the Radio Astronomy Panel of the Astronomy Survey Committee noted in its 1982 report that, "All of the studies of the needs of U.S. astronomy have recommended the construction of a large general purpose radio telescope ... and an instrument in the 100-meter class is an important priority for the 1980's," no large fully steerable radio telescope has been built in the United States. Recent advances in structural analysis and design now make it possible to build large aperture antennas with performance specifications previously possible only on smaller antennas.

The proposed new Green Bank radio telescope 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. 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. It can be a positive 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, the 140-foot, or the 100-meter telescope in Germany and will be the most powerful facility of its kind in the world. For example, near the 22 GHz lines of interstellar water and ammonia, the new telescope will be an order of magnitude more sensitive than any other radio telescope in the United States and about a factor of 2 better than the 100-m German instrument. With careful adjustment of the moveable surface panels, it is anticipated that the telescope will be used even at short millimeter wavelengths where it will have more collecting area than the 45-meter radio telescope in Japan.

A major design goal of the new telescope is to reduce 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 sidelobe level will be reduced by minimizing or possibly eliminating entirely the aperture blockage from the subreflector support structure. This will also reduce multiple reflections from the support structure which limit the effective sensitivity of spectroscopic measurements.

An important consideration in the design of any new radio telescope is the tradeoff between size (sensitivity) and precision (minimum wavelength). The cost of a radio telescope increases very rapidly with size but only relatively slowly as the minimum wavelength is decreased. Recent developments in the fabrication of surface panels indicates it is possible to obtain a root mean square (rms) surface precision of 0.002 to 0.003 inches (50-75 μm) at a cost which is less than ten percent of the entire structure. The $\lambda/16$ cutoff frequency of the panels alone is 0.8-1.2 millimeters. By using active control of the individual surface panels to compensate for gravity deflections, it is straightforward to obtain an overall precision sufficient to give good efficiency at least down to one centimeter wavelength. More sophisticated corrections, which may be later introduced to compensate for thermal and wind induced errors, may give good performance even down to millimeter wavelengths.

The new radio telescope will be built in Green Bank, WV where a substantial infrastructure already exists, together with a skilled staff that has many years of experience. More important, however, is that Green Bank is in the National Radio Quiet Zone, where it enjoys unique protection from terrestrial radio interference. This protection, combined with the low side lobe level resulting from the minimumly blocked aperture will give the facility unique capabilities for a wide variety of investigations, particularly at longer wavelengths, that are subject to radio interference. Moreover, years of experience in operating the 140-foot telescope near the 22 GHz atmospheric water lines as well as analysis of nearby radiosonde measurements suggests that Green Bank is at least as good a site for possible future operation at millimeter wavelengths as existing successful millimeter observatories located in New Jersey and Massachusetts.

The planned new telescope is an important element of NRAO's plan for the radio astronomy of the next century. It complements the VLA and VLBA by serving as a discovery instrument for those radio objects needing precision images. The new telescope also completes u,v coverage, studying the largest distributions of matter and radiation. The telescope plays a pivotal role in VLBI, adding significantly to the sensitivity of the VLBA and particularly to the extension of that instrument into space. Finally, the new telescope maintains full frequency coverage over the range immediately beneath that of the Millimeter Array. With this full set of instruments--the VLA, VLBA, GBT, and MMA--radio astronomers will have the flexibility to attack problems on virtually every scale of sensitivity, angular size, and frequency.

We hope to have the Green Bank telescope operational by the end of 1994, in time for the launch of the USSR RADIOASTRON and Japanese VSOP space VLBI missions anticipated for 1995. Design concepts are now being studied with the goal of doing detailed design and engineering in 1990 and starting construction in 1991.

Budgetary estimates have been obtained by scaling the costs of other large radio telescopes and consultation with several commercial manufacturers. Overall construction costs are estimated to be $75M (1989), including the development and construction of instrumentation.

IV. PLANNED FACILITIES

ARRAY TELESCOPE COMPUTING PLAN

In September 1987, NRAO submitted an Array Telescope Computing Plan to the Foundation. This was the result of a reassessment of the projected combined computing needs of the VLA and VLBA and a study of hardware developments in the computer industry. 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 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 does not plan to operate a supercomputer center itself. The outline of the computing plan is shown schematically in Figure IV.2.

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. Figure IV.3 illustrates this system, to be located largely in Socorro NM at the Array Operations Center.

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.

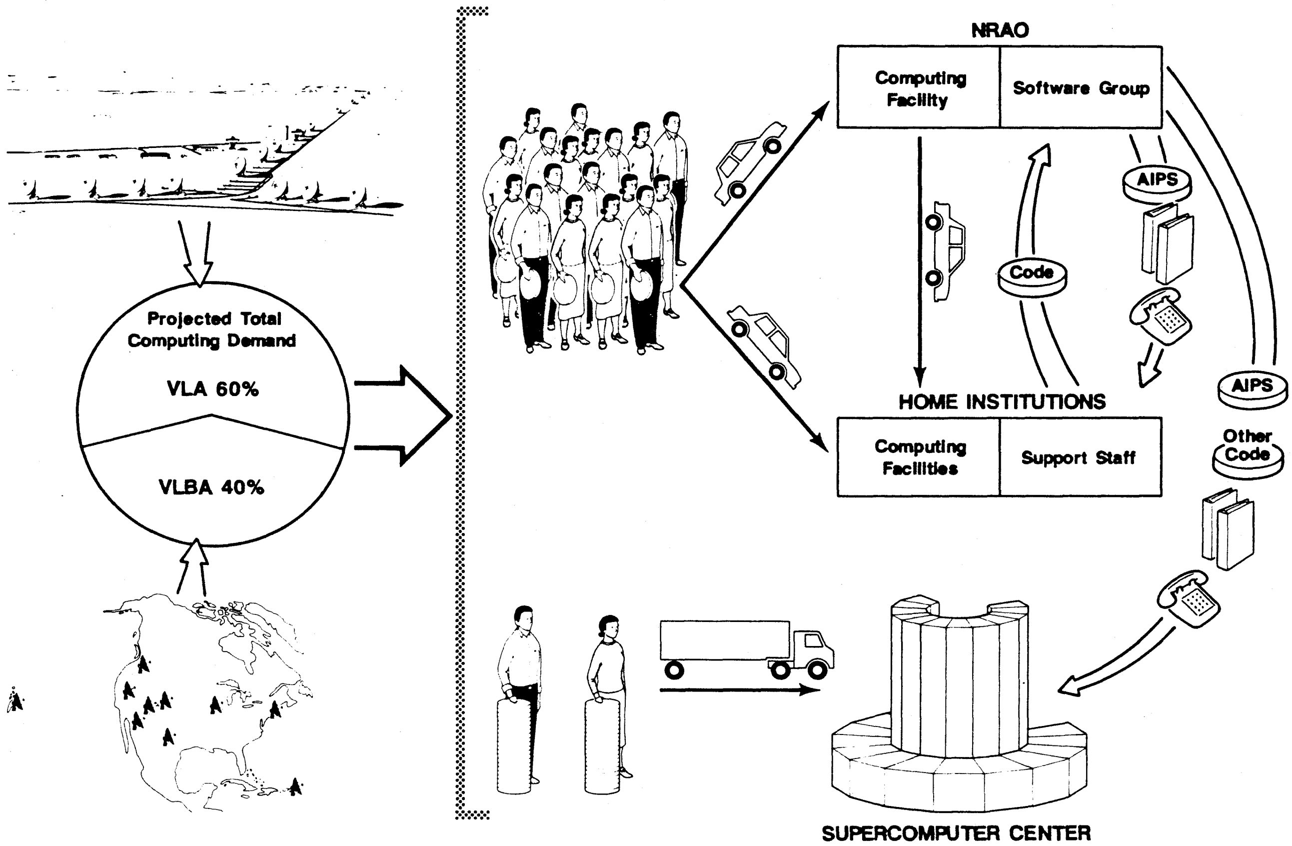

Fig. IV.2 - An illustration of the main features of the Array Telescope Computing Plan. The off-line computing requirements of the VLA and the VLBA will be met by computers at the NRAO, at users' home institutions, and at supercomputer centers. The data processing needs of about 90% of the users will 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.

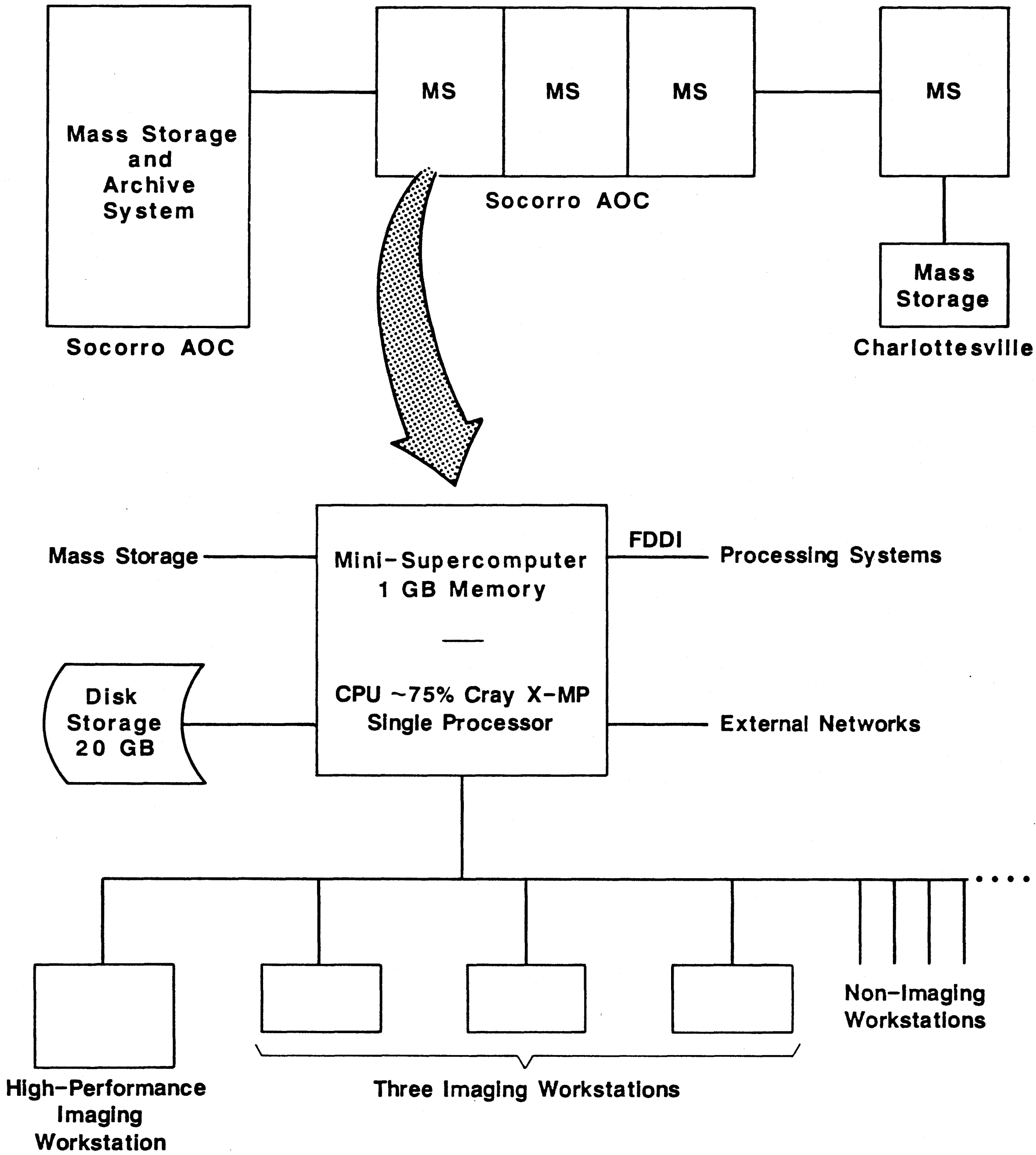

Fig. IV.3 - The configuration we propose for a loosely coupled network of four mini-supercomputers (MS). The lower panel shows detail of the individual elements depicted in the upper panel.

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

	1991	1992	1993
Total Equipment Required	$3.5M	$3.5M	$3.0M
Included in VLBA Construction	3.3	-	-
Additional Required	$0.2M	$3.5M	$3.0M

The operations costs associated with implementation of the computing plan are included in the budget schedules of the Long Range Plan.

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-sixth 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 will update and resubmit the Array Telescope Computing Plan to the NSF in the Fall of 1989; three groups are being set up to work on this. One will re-examine the scientific needs; another will review the hardware implementation; a third will reassess the plan for software and algorithm development. The composition and workload of these groups is currently being defined, and the reviewer's comments on the previous version of the plan are being carefully considered.

THE MILLIMETER ARRAY

The Millimeter Array (MMA) design concept, summarized in Volume II of the MMA Design Study, describes 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.

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."1 at 230 GHz, for example, requires an array of maximum extent 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 drive the design of the MMA; they are described in some detail in Volume II of the MMA Design Study. 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 GMCs 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, 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 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. Through consultations with the Millimeter Array Advisory Committee and suggestions from the community, the MMA design parameters continue to be refined. A summary of the MMA is given below:

Array --

Number of Antennas:	30-40
Total Collecting Area:	1750 m^2
Total Resolution:	0."07 λ (mm)

Antennas --

Diameter:	7.5-8.5 m
Precision:	λ/40 at 1 mm
Pointing:	1/20 beamwidth
Transportable	

Configurations --

Compact	< 100 m
Intermediate:	300-1000 m
High Resolution:	3 km

Frequencies --

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

Site --

High Altitude--suitable for precision imaging at 1 mm

In 1990 we will circulate a draft MMA proposal to the community and begin to prototype equipment important to the success of the MMA. Detailed engineering design will be done in 1993 and construction started in 1994.

THE VLA EXPANSION AND ENHANCEMENT PROGRAM

The VLA has demonstrated such a substantial advance in virtually all capabilities sought by radio astronomers--angular resolution, frequency range, sensitivity and image fidelity--that the array is asked to provide even more facilities for a still larger range of scientific investigation. Here the motivators are many, but they begin with the fact that since the VLA incorporates so much of the "infrastructure" needed for any radio astronomical investigation one can, in principal, optimize the VLA capabilities to suit any study at a cost that is very modest compared to the cost of building a special purpose instrument. In addition, the skills of the resident VLA staff and the ease with which the VLA can be used by non-experts, further argues for an augmentation of the VLA rather than an independent program--if the goal is to carry out research expeditiously and in a manner which may be exploited by other members of the community. For these reasons, as well as because the breadth of radio astronomical science, the need, still exceeds the capabilities of the VLA, we plan a comprehensive program to *expand* and *enhance* the VLA. This we refer to as the VLA/E^2 program.

The expansion component of the VLA/E^2 program involves a substantial increase in the VLA's capability to measure the following:

- spatial frequencies;
- frequency range;
- frequency/time domain.

Thinking of "expansion" simply in terms of a growth in the physical dimension of the VLA, a lengthening of the arms of the array, we include 3-4 new, fixed, antennas in the VLA/E^2 program located at distances of a few tens to several hundreds of kilometers from the VLA itself. These antennas, linked in real-time to the VLA, will bridge the gap between VLA resolution and VLBA resolution. Expansion of the VLA's capability to measure low spatial frequencies, extended, low brightness emission, involves not new antennas but new VLA stations clustered near the array center. The VLA needs to be able to expand *inward*.

Expansion of the VLA frequency range can be achieved both to higher frequency, 43 GHz, and to lower frequency, 75 MHz. The former requires new amplifiers and feeds in addition to an improvement of the pointing and improvement to the figure of the primary antenna mirrors through holographic measurement and resetting. The latter depends on the installation of effective RFI shielding. Of equal importance to an increase in the frequency range of the VLA is an expansion of the bandwidth at each of the VLA's primary observing frequencies. This involves wider band receivers and feeds, in principle a straightforward retrofit made possible by technology developed in the Central Development Laboratory.

Finally, expansion in the frequency/time domain refers to the need for an increase in the VLA capability to observe simultaneously at two or more widely separated frequencies, or to switch rapidly, and to sample at millisecond rates.

The enhancement component of the VLA/E^2 program involves an improvement to the VLA sensitivity, at all frequencies, angular resolutions, and time resolutions, by means of a wider band IF and correlator system. A significant increase in the observing bandwidth can be achieved once the correlator is replaced by one with faster digital logic and/or by a hybrid analog/digital correlator such as the VLBA or Berkeley-Illinois-Maryland Array correlator. In either case, the IF waveguide transmission system would also need to be replaced by a fiber optic system with greater bandwidth capability.

Significant enhancements are also needed in the VLA capabilities for solar observations and for imaging extended objects. In the former case, special hardware is needed to permit reliable calibration, while in the latter a provision for total power observing at each of the VLA antennas is required.

Several of the salient aspects of the VLA/E^2 program are described in more detail below.

Increased Angular Resolution - The size of the VLA was determined by the desire to achieve 1" angular resolution at the HI 21 cm line--1" being the resolution of a ground-based optical telescope. However, we now know that 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. To increase the angular resolution of the VLA and maintain excellent image fidelity requires the addition of new antennas at greater distances from the center of the array than are presently available, viz. fixed outrigger antennas more than 20 km from the VLA. These, of course, must have LO and IF links to the VLA.

Ideally, the new antennas would provide interferometric baselines out to and including the shortest VLBA baselines. 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 fixed angular resolution. For example, wideband spectral studies at fixed resolution 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. This can be achieved by adding 3-4 additional VLBA antennas in New Mexico and Arizona for use with either the VLA or the VLBA as appropriate for individual experiments. Once in place, we will have created an array of at least 40 elements (27 VLA antennas, 10 VLBA antennas plus 3 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 1990s.

Finally, it is interesting to note that the sun is rarely observed at high angular resolution because it is in the near field of long baseline arrays. The 40-element array described above could circumvent this difficulty by application of a single point, antenna-based phase correction made to the data on-line: this would bring a small patch of the solar atmosphere into focus. The scientific payoff would be handsome. The solar atmosphere is believed to be highly structured on sub-arcsecond scales. It appears likely that coronal heating occurs on these scales via dynamical dissipation of magnetic fields ("nano-flares") or by resonant heating in thin sheaths surrounding magnetic flux tubes. Only microwaves and X-rays have access to layers of the solar atmosphere where these processes are believed to occur (transition region, corona). Large arrays are needed to provide the necessary degree of angular resolution required to observe these processes. The VLA/E^2 array is ideal.

The E-Configuration: An Expansion for Increased Brightness Sensitivity - Unexpected when the VLA was designed were the enormous HI envelopes around, and between, nearby galaxies. Surely, the implications from the kinematics of these HI "haloes," that the mass of a galaxy is principally non-luminous and the size greater than the visible extent, is one of the most far-reaching results of twentieth century astronomy. Although much of the observational work which led to this conclusion was done on the VLA, the VLA configurations are poorly suited to such research. The difficulty is that not enough of the total VLA collecting area can be concentrated at short interferometer spacings. The most compact VLA configuration, the D-configuration, still provides baselines as great at 1000 meter. For studies of low brightness structures--galactic HI haloes being the best example--one would like all the collecting area compressed to a dimension much smaller than D-configuration

A plan to configure the VLA antennas densely at the array center has been discussed. This requires a departure from the VLA "wye" at the array center, some additional rail track and antenna stations. Such an E-configuration would provide a needed complement to the more extended VLA configurations at all wavelengths.

Frequency Expansion - The VLA antennas were designed to permit useful operation at 43 GHz under benign conditions. Installation of receivers for this "Q-band" will nearly double the maximum resolution of the VLA; permit still higher resolution joint VLA/VLBA observations at 43 GHz; and allow astronomers to image the SiO and methanol masers at 43 and 44 GHz, respectively. To achieve this end will require more precise characterization of the pointing of VLA antennas, holographic maps of the antenna surfaces which can guide a readjustment of the surface panels, and construction of the cryogenic Q-band HEMT receivers and feeds.

An S-band capability, 2.2-2.4 GHz, has been long sought by astronomers seeking to understand the evolution of bursting, stellar, radio sources and magneto-ionic effects on the polarization of non-thermal radio sources. In addition, an S-band capability would again facilitate joint observations with the VLBA, and it would permit the VLA to participate in a wide range of geodetic experiments run at a standard Deep Space Network frequency.

Frequency Bandwidth Expansion - The limitation of narrow band receivers is nowhere so telling as in atomic and molecular spectroscopic observations. Entire astrophysical investigations are excluded from the VLA simply because the requisite frequencies are not supported--studies of methanol masers is an example. The wider the receiving bands can be made, the wider the range of science that will benefit from the VLA.

With expansion of the receiver/feed bandwidth at every frequency as a goal, the first specific task is to broaden the L-band capability. Atomic hydrogen in galaxies is seen in emission at redshifts right out to the lower limit of the VLA L-band receivers. Surely the science doesn't stop at this redshift. Expansion of the L-band receiving system on the VLA is of the highest priority. There are two tasks. First, to obtain a low system temperature as possible the L-band HEMT receiver should be mounted in its own dewar, as is done in the VLBA, with the length of waveguide runs removed. Second, the L-band feed must be redesigned and replaced so that useful performance can be achieved to frequencies as low as 1000 MHz. HI imaging at redshifts approaching 0.5 is an exciting development that is yet unexplored.

Expansion in the Frequency/Time Domain - Radio astronomical objects such as the sun or flare stars, which vary rapidly in time, could be observed more effectively if the VLA could observe with two different frequencies at the same time. Observations to verify the General Theory of Relativity by measuring the bending of radio waves by the sun's gravitational field also require a dual frequency capability. The VLA design included provision for a dichroic reflector system which would allow dual frequency observations in the 6 cm and 2 cm wavelength bands. As built, the VLA did not incorporate this feature. It can be added now at modest cost.

Enhancement of the VLA Correlator - To observe wide fields of view with high spatial resolution and high sensitivity it is necessary to break the wide continuum bandwidth into several narrower frequency channels to avoid bandwidth smearing at the edge of the field. For wide field continuum mapping, this will provide an increase in sensitivity of almost a factor of three. Some line projects requiring large bandwidth would also be enhanced by this modification. Examples are the simultaneous observation of multiple transitions, observations of extragalactic lines, water-vapor masers or OH masers and the simultaneous observation of individual galaxies in clusters.

To synthesize out to the first null of the primary beam at 21 cm wavelength in the A-configuration, it is necessary to break the 50 MHz bandwidth into 64 channels. The current VLA correlator provides only four channels in 50 MHz when polarization data is required. Although the technique of pre-analog filtering is in principle a feasible way of increasing the spectral resolution in the wide VLA bandwidths, the technique makes no provision for bandwidths greater than 50 MHz. An alternative would be to use the FX correlator design. Considerable investigation and prototyping is needed to achieve an optimum design for the enhanced VLA correlator.

A Total Power System for Enhanced Imaging - Observers using the VLA have traditionally been restricted to observing sources smaller than the primary beam of the array antennas. However, recent design work motivated by the Millimeter Array project has led to the realization that the complete range of spatial frequencies needed to properly image objects which extend over many primary beams can potentially be extracted from a single array of equal diameter dishes, rather than requiring a combination of data observed with a variety of dish diameters. This is accomplished by fully sampling the primary beam of the interferometer array over the object of interest (while in a compact configuration) leading to all but the shortest spacings, and additionally (or simultaneously) obtaining total power measurements with one or more of the same dishes. The current VLA receiver configuration is incapable of providing total power measurements of sufficient quality to be useful in such a mode. If switching circuitry were to be provided, the VLA could produce high fidelity images of objects of arbitrarily large angular size.

Enhanced Solar Capabilities - A needed enhancement to the current VLA solar hardware is high temperature calibration sources on all antennas. Presently calibration relies on a measurement of system temperature which is only done for a few antennas. It is assumed that all antennas are identical and that therefore one can apply an identical calibration to the whole array. Experience, however, shows that the antennas can differ substantially from each other. We need a proper solution.

At frequencies greater than 5 GHz it is possible to saturate receiver elements when observing more intense solar bursts. A means of inserting additional attenuation for such observations is the best way of overcoming the problem.

V. BUDGET PROJECTIONS

	1989	1990	1991	1992	1993	1994
Operations						
Base Operations	16.4	17.4	18.6	19.4	20.5	31.9
VLBA Operations	0.9	1.5	3.7	5.9	7.6	
Major Maintenance	0.2	0.7	1.0	1.0	0.5	
Array Computing Plan	-	-	0.5	1.0	1.5	
Total Operations	17.5	19.6	23.8	27.3	30.1	31.9
Equipment						
Research & Operating	0.3	0.7	0.9	1.1	1.2	2.1
Array Computing Plan	-	-	0.2	3.5	3.0	-
Total Equipment	0.3	0.7	1.1	4.6	4.2	2.1
Total Operations & Equipment	17.8	20.3	24.9	31.9	34.3	34.0
Construction						
VLBA	11.8	12.2	12.6	3.9	-	-
GB Telescope	5.0*	70.0*	-	-	-	-
Millimeter Array	-	0.2	0.4	1.0	2.5	10.0
VLA/E[2]	-	-	-	1.0	3.0	6.0

PERSONNEL PROJECTION (Full Time Staff)

	1989	1990	1991	1992	1993	1994
Base Operations	285	290	296	300	303	417
VLBA Operations	22	50	66	84	95	
VLBA Construction	57	54	36	3	-	
Array Computing Plan	-	-	3	10	15	
GB Telescope Const.	5	to be determined				
Work for Others: (USNO, SSTI, NASA)	9	8	11	13	14	14
Personnel Total	378	402	412	410	427	431

*NSF supplemental appropriation