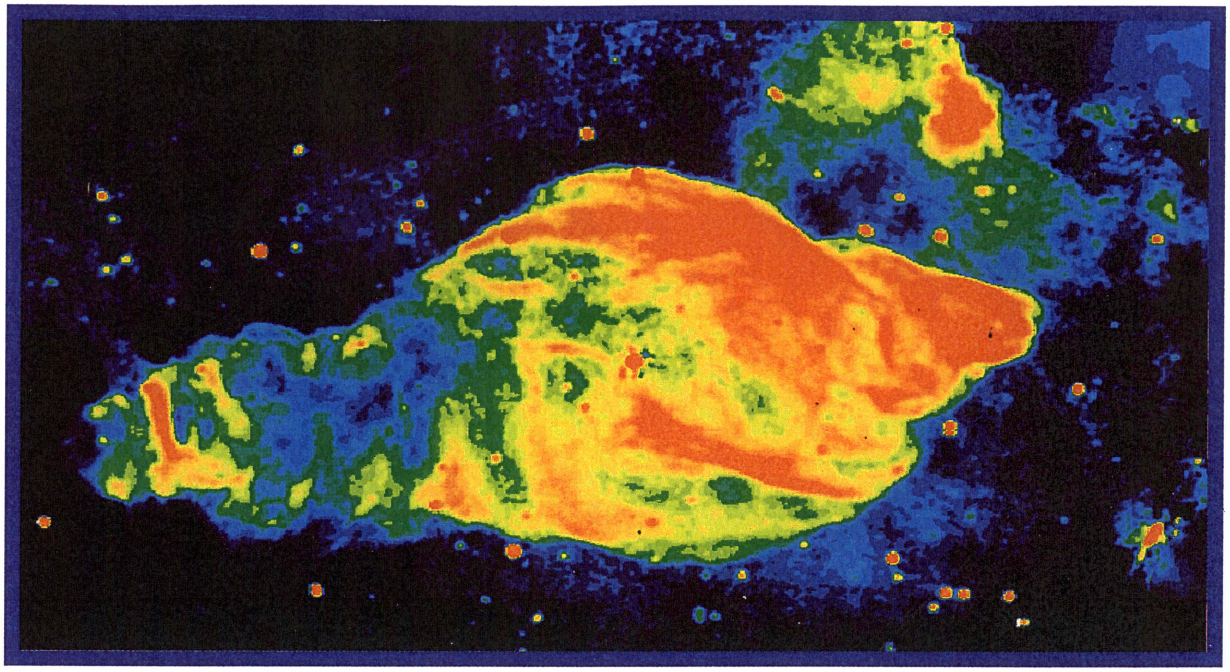

LONG RANGE PLAN
1999 - 2004

NRAO

NATIONAL RADIO ASTRONOMY OBSERVATORY

Cover: Radio image of the supernova remnant W50. The image was made with the Very Large Array at 1.4 GHz from a mosaic of 58 individual images. The regions of most intense radio emission are shown in red while regions of lower brightness are colored blue. The W50 remnant is powered by the dying star SS433 seen near the center; helical filaments of radio emission can be seen emanating from SS433. Observers: G. Dubner, F. Mirabel, M. Holdaway, M. Goss

National Radio Astronomy Observatory

Long Range Plan

1999–2004

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I. OVERVIEW

Astronomers throughout the world are preparing strategic plans for the new millennium. These plans are science driven. The scientific issues that motivate the astronomical research program in the United States for the current decade will remain top priorities for the next decade, but they will be modified by the pioneering work and unanticipated discoveries of the past few years. The current strategic vision of the U.S. scientific community for radio astronomy supported by the National Science Foundation (NSF) is outlined in the National Academy of Sciences decadal review of Astronomy and Astrophysics; a successor review will be conducted for the decade 2001–2010. In this Long Range Plan for the period 1999–2004, the National Radio Astronomy Observatory (NRAO) presents a plan for development, augmentation, and operation of facilities that provide the capabilities required by NSF researchers to address the scientific program.

What are the key scientific questions? They can be divided conceptually into three categories according to distance from us of the object or phenomenon to be studied:

- Cosmology—the origins of structure in the Universe, especially the physics of galaxy formation;
- The nature and evolution of galaxies highlighted by an understanding of the morphological differences among galaxies;
- The physical processes by which stars and planetary systems form including the role of organic, pre-biotic chemical processes.

Within these broad categories lie a host of more specific questions. For progress, all require one or a combination of the following performance specifications in the observational facilities to be used: increased sensitivity to the faint signals of distant astronomical objects; improved angular resolution for more detailed imaging; and stable, state-of-the-art instrumentation that will permit accurate calibration and precision imaging over large angular scales.

As one steward of NSF research facilities, NRAO's role in the national program of astronomical research is to design, build, and operate the major facilities required for research at radio wavelengths, in accordance with the competitively-reviewed priorities of the user community and within the boundaries of the support provided by the NSF. As we enter the new millennium, those NRAO facilities will be four telescopes unmatched by any others in the world:

- The Very Long Baseline Array (VLBA);
- The Green Bank Telescope (GBT);
- The Millimeter Array (MMA);
- The upgraded Very Large Array (VLA).

These four facilities are a major component of the NSF's program of support for radio astronomy, a program that both established the United States as the major player in radio astronomy and a program that has maintained a dominant position for the U.S. ever since. As virtually the sole source of funding support for radio astronomy in the U.S., this success and pre-eminence is a direct result of actions taken by the NSF.

The NSF suite of national radio telescopes will promote scientific innovation in astronomy exceptionally well. The VLBA provides on a routine basis images of higher angular resolution than any other telescope operating at any wavelength on Earth or in space. It is particularly well suited to the study of accretion-driven phenomena in the nuclei of galaxies, and is providing the best evidence available on the physics of extreme gravity near massive black holes. The GBT will provide a large collecting area for high sensitivity spectroscopy at all frequencies from 300 MHz to 100 GHz, enabling studies of the gas content in young and highly red-shifted galaxies. It will be invaluable for radar studies of solar system objects in conjunction with the Arecibo Telescope. The MMA will provide the sensitivity and angular resolution required at millimeter wavelengths for the study of the thermal universe: astronomers using the MMA will image the continuum emission from dust and spectral line emission from those atoms and molecules that are the signature of star formation both in our Galaxy and in the first galaxies that form in the Universe. The MMA will be the millimeter wavelength equivalent of the Hubble Space Telescope. Finally, upgrading the VLA with state-of-the-art instrumentation will increase its sensitivity and flexibility by an order of magnitude and give it the instrumental stability needed to enable new science through precision wide-field mosaicing. A comparatively modest investment in upgraded instrumentation will permit the VLA to maintain its position as the premier centimeter wavelength telescope in the world. Astronomers will exploit the enhanced VLA capabilities to image with vastly greater precision active regions on the sun, the surface features of planets, molecular maser emission from stars forming in the Milky Way, the gaseous disks of nearby galaxies, the nuclear kinematics of distant active galaxies, and a wealth of cosmic phenomena still cloaked in mystery but awaiting the attention of radio astronomers in the next millennium.

II. GREEN BANK

1. Green Bank Operations

The 140 Foot Telescope

The 140 Foot Telescope will continue to be operated as a user facility through 1998, but after that time will be closed, as its capabilities will be far exceeded by the Green Bank Telescope. During its final year of operation the 140 Foot will be involved in programs of long-term pulsar monitoring, several spectral line surveys, and support of the HALCA satellite for space VLBI experiments.

Spectrum Management and the National Radio Quiet Zone

The Green Bank Observatory is surrounded by the National Radio Quiet Zone, a unique area which provides significant protection for radio astronomy from emissions by new fixed transmitters. Transmitters continue to proliferate, however, and in the next five years significant effort will be expended on maintaining the integrity of the Quiet Zone. Among the activities will be increased attention to the propagation models which are used to predict the effect of a new transmitter on astronomical observations at Green Bank, and increased cooperation with transmitter owners to find antenna sites that provide suitable shielding for the Observatory by intervening mountains. Staff at Green Bank will also continue to work with National and International agencies to preserve as much of the spectrum as possible for radio astronomy.

Despite these protective measures, it is clear that in the future radio astronomers will have to deal more and more with operations in the presence of substantial radio frequency interference. Efforts are underway at Green Bank to develop techniques to remove interference from data, and to design devices and procedures that effectively cancel interference. An extensive program of spectrum monitoring will also be undertaken in an effort to identify, and possibly eliminate, the more aggressive sources of interference.

Education

Green Bank has been involved in public education ever since the tour program started shortly after the Observatory was founded. These activities have grown in recent years to include Observatory tours for casual visitors; local outreach to teachers, students, and the public; resident courses for college professors and students; K–12 teacher training institutes; and overnight visits by teachers and students to use the 40 Foot Telescope. In the next five years we hope to integrate these activities into a Science Learning Center, which will serve as the focus for expanded educational programs in certain areas.

The Observatory Tour Program will be expanded to include special events for families, and to operate year-round. Tour staff will offer evening programs including star parties, in-depth technical tours, and image processing sessions. Under the guidance of a new tour coordinator and with the cooperation of local and regional groups, we will work to increase the number of visitors to the Observatory and to enhance their experience while here. Support for development of exhibits and educational programs has been solicited from the NSF Education Directorate. Should these funds become available they will be used for a major expansion of the tour facilities.

The Observatory at Green Bank is ideally situated to provide science education to students in grades K–12. The rural areas of West Virginia are very deprived of educational facilities, particularly those specializing in science. The unique combination of working radio telescopes and a group of scientists, programmers, and engineers, makes the Observatory the kind of "science preserve" at which innovative educational programs can be developed and presented. We have learned that the mere experience of seeing a radio telescope up close can be a powerful motivating force for children to learn more about astronomy in particular, and science in general. Over the next five years we plan to develop programs that are aimed at regional students visiting as part of a school-sponsored day trip.

The need for innovative programs to train science teachers has received much notice in recent years. The Observatory at Green Bank has been involved with this activity for a decade; in the coming five years we will continue the Teachers Educational Institutes through a new grant from the NSF Education Directorate. The programs will provide hands-on research experience, a chance to hear and speak with working scientists and engineers, and special training in educational tools that can be used in the classroom. So far our programs have reached many hundreds of teachers and have received wide-spread recognition and praise.

We are engaged in a "bricks-and mortar" fund-raising drive to secure money for the Science Learning Center. In 1997, we were awarded a modest West Virginia State Governor's Partnership Grant, part of which will be used for architectural studies. We continue to seek funds from the State and from private foundations for the construction of the new facility.

2. The Green Bank Telescope Project

Introduction

In the first year of the present long range plan, the Green Bank Telescope (GBT) will become operational and the 140 Foot Telescope will have ceased operation as an NSF-funded facility. The

GBT will provide capabilities far in excess of what has been previously available in Green Bank or for that matter, at any centimeter wavelength single-dish telescope world-wide. An artist's conception of the completed GBT is shown in Figure II-1. Because the GBT will work with high sensitivity over an unusually broad range of frequency, spanning nearly three decades from 300 MHz to 100 GHz, it will contribute broadly to the many subdisciplines of radio astronomy.

The high gain of the GBT (approximately 2 K per Jy), its unusually error-free beam pattern, and its high efficiency represent substantial steps forward. At a frequency of 30 GHz, the GBT will be 30 times as efficient as the present workhorse instrument in Green Bank, the 140 Foot Telescope, rendering it up to one thousand times faster for many experiments which attempt to detect signals at low flux levels. At frequencies above about 30 GHz, the GBT will be more efficient at gathering photons than is the entire present VLA. Even at lower frequencies, where the physical collecting is only somewhat more than that of the Effelsburg 100 m telescope, the clean beam, relatively RFI-free site, and wide bandwidth spectrometer offer unparalleled capability.

To harness this power, the GBT will be equipped with several ancillary subsystems; state-of-the-art receivers; a spectacular new 800 MHz bandwidth, 256k-channel spectrometer; various continuum detectors; a laser-ranging measurement (metrology) system referenced to points on the ground, the vertical feed arm, and surface; and a system of actuators behind the surface panels in order to re-figure the antenna in response to unavoidable deformations due to thermal gradients and gravity (as determined from computer models and the metrology system). The metrology system is a unique aspect of the GBT. It will, for the first time, permit distortions due to gravity on thermal effects to be corrected while the telescope is used, independent of the astronomical objects which it observes.

Science Highlights

The design of the GBT and its ancillary devices was driven by considerations of the science to be done. Still new areas of inquiry are discovered continuously, and it is gratifying to realize that the power and flexibility of the GBT, both antenna and instrumentation, will allow it to contribute in even unforeseen ways to new science. Here are a few highlights of prospective scientific activities at the GBT, from both new and established research fields.

Radio Stars and Pulsars. The large bandwidths available at high frequency on the GBT will be employed in the most sensitive pulsar searches that cover the entire northern sky. These high

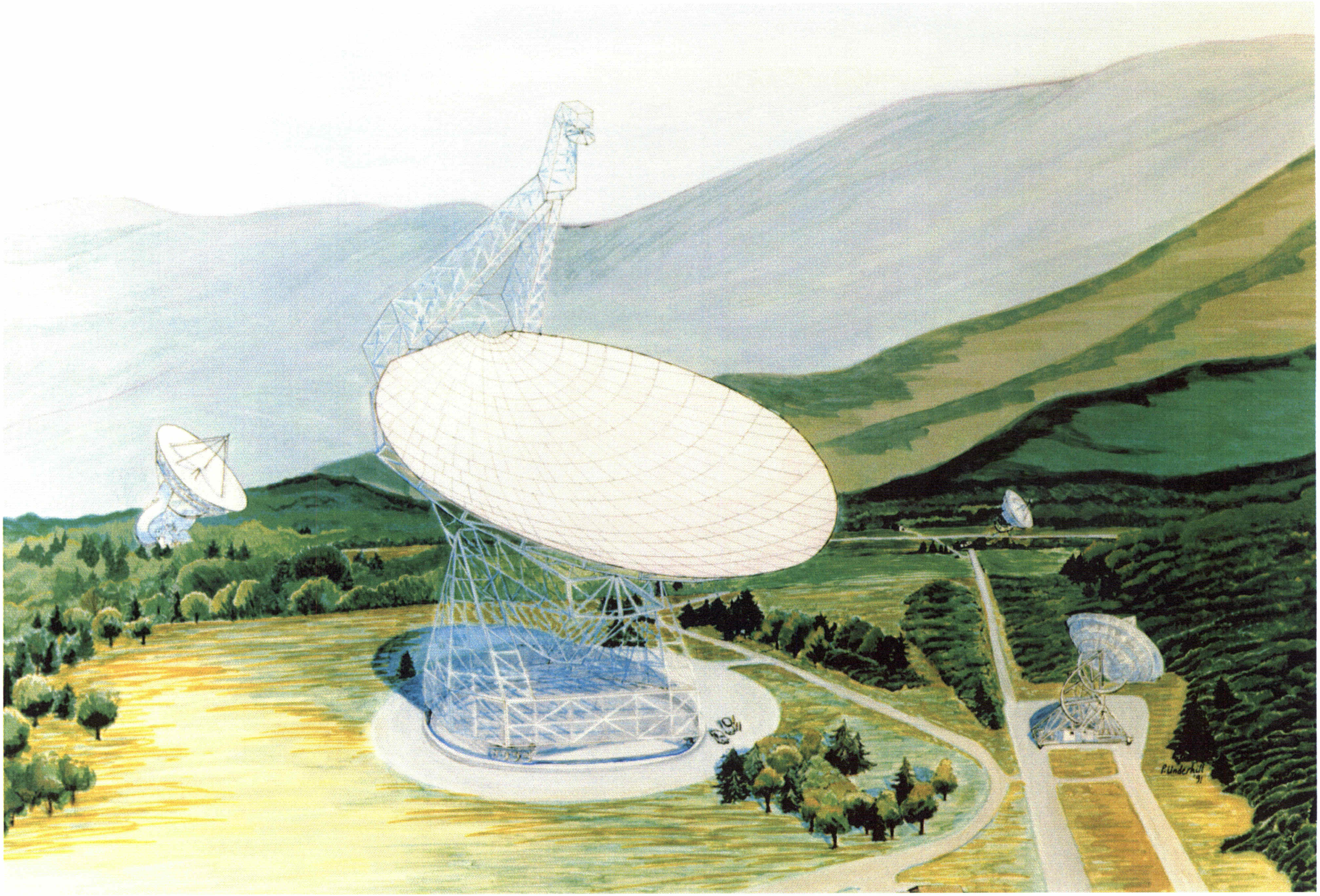


Figure II-1. Green Bank Telescope (GBT) artist's conception.

frequency searches will alleviate the constraints imposed by dispersion measure and interstellar scattering that plague low frequency observations; the GBT will undoubtedly discover many new objects, particularly in the galactic plane. Using the newly-discovered pulsars as probes of the interstellar medium, one can better constrain models of the distribution and density of free electrons in the Milky Way. Measuring the arrival times of pulses from pulsars with the GBT will provide data for testing theories of general relativity, probing the interiors of neutron stars, and studying the evolution of isolated pulsars and stars in binary systems. The high instantaneous sensitivity of the GBT will permit observations of individual pulses from pulsars, thereby allowing studies of both the radio emission mechanism and the propagation of radio waves in super strong (10^{12} gauss) magnetic fields.

Toward other kinds of stars, broadband dynamic multi-frequency polarimetric measurements will be used to study stellar winds, plasma effects in starspots, the intra-stellar magnetospheres of close binaries, and precessing radio jets fueled by accretion onto neutron stars or black holes. Multifrequency mapping of the Sun will help to define conditions in the upper chromosphere and transition regions above coronal holes.

Studies of Neutral Atomic Gas. Observations of galactic HI are required to understand the morphology and dynamics of the galactic disk; the evolution and vertical structure of the interstellar medium; the disposition of the many shells and supershells which pattern the neutral gas and trace its history; and the structure of hot x-ray emitting material in the local bubble. Knowledge of the amount of atomic gas toward extragalactic objects such as quasars, which the GBT will determine with unprecedented sensitivity and freedom from systematic errors, will be used to establish precisely the optical extinction. For gas in the galactic core, the clean and relatively narrow 8.7 arcminute beam of the GBT at 21 cm will resolve structures as small as 20 pc—typical of individual molecular clouds and HII regions. The clean beam of the GBT will be especially important for studies of the magnetic fields in interstellar clouds via the Zeeman effect.

Several tens of thousands of galaxies in the nearby universe will be easily visible to the GBT, affording study of both the local Hubble flow and the global neutral gas properties of galaxies and clusters. At higher redshifts, the unusually good sensitivity of the GBT and the availability of its extraordinarily broad-band spectrometer will make possible quick, deep surveys out to cosmological distances, tracing cosmic evolution. At its very lowest frequencies, there will be sensitive searches for HI emission from the first epoch of formation of galaxies and clusters in the early Universe.

Observations of Molecular Gas. The study of interstellar chemistry and interstellar molecular gas, however arcane, is intimately related to subjects as diverse as the formation of stars (all of which were born in the medium of molecular gas), and the origin of life on earth (which gained its water and organic molecules from a bombardment by comets whose composition was determined back when the Sun and proto-Solar nebula formed in these molecular clouds). The GBT will have a dominant role in cometary studies, making explicit the bioastronomy connection between interstellar and interplanetary phenomena in a single instrument.

The GBT will study molecular clouds and interstellar chemistry in the Galaxy across an unusually broad range of wavelength, spanning the domains of centimeter-wave (OH, H_2CO) and millimeter-wave (CO, CS, HCO^+, etc.) molecules. It will afford the use of molecular tracers of the magnetic field—like OH and C_4H—in individual clouds, similar to what is done at longer wavelengths, in more diffuse gas, with OH and HI.

Recent studies have shown that interstellar molecular chemistry occurs much more commonly than was previously supposed. In local gas in the Galaxy, even diffuse clouds with a bit of molecular hydrogen have well-developed chemistries visible in spectral absorption lines. This has an exciting analog at high redshifts $z \sim 0.5$—one where absorption against 1 Jy radio sources has been detected even using much smaller (10 m-15 m) millimeter-wave dishes. The 100 meter GBT will advance this field dramatically and should trace cosmic chemical evolution in thousands of objects ranging into the early dawn of galaxy formation.

In a few cases, ultraluminous IR objects at redshifts up to $z \sim 5$ have been detected via their CO (and other) millimeter-wave emission using 15 m and 30 m antennas. The GBT should advance this field enormously as well, owing to its large collecting area.

Continuum Patrol and Source Surveys. The confusion limit of the GBT at 21 cm wavelength will be reached after only a few milliseconds of observing! If it could be induced to move fast enough, the GBT could map the entire sky at this frequency with excellent sampling in only a couple of hours: with its available slew speed of 40 degrees/minute, the use of an array of feeds would permit such mapping at least once per day, although at probably a too-high cost to the antenna mechanisms. Conventional all-sky continuum source surveys may or may not be important for the GBT, but it could usefully map and patrol the galactic disk to find supernovae, stellar outbursts, and other transient events. The GBT would also be a sensitive way to find millimeter-wave continuum sources for use as calibrators at millimeter-wavelengths.

Very Long Baseline Interferometry (VLBI). The GBT will be an important adjunct to the Very Long Baseline Array and future orbiting VLBI missions, owing to its large collecting area. This will permit long coherent integrations on weak sources such as faint structures in distant quasars, gravitational lenses, supernovae, radio stars, and extragalactic H_2O masers. Statistical parallaxes of H_2O masers will be used to measure the distances to maser sources in our own galaxy and nearby systems, thereby establishing fundamental distance scales.

Bi-static Radar Astronomy with the Arecibo Telescope. The combination of the Arecibo Telescope as transmitter and the GBT as receiver is very powerful for radar astronomy studies of nearby asteroids and other solar system objects. For very close objects, the light travel time is too short to switch transmit/receive modes at Arecibo, and another receiving telescope is needed. For objects as distant as Saturn, the light travel time exceeds the tracking time limit of the Arecibo Telescope. Finally, it is possible to do interferometry using both telescopes in receive mode on objects of intermediate distance. For example, the Arecibo to Green Bank baseline yields information on spatial frequencies of 2 km at the distance of Venus.

Construction

Completion of the GBT construction is expected at the end of calendar year 1999. Presently, the alidade portion of the antenna (the support structure that rotates in azimuth) is complete. The elevation axle, elevation drive wheel, and box girder that supports the reflector backup structure (BUS) is also complete. This same box girder provides a sound attachment for the feed arm, the horizontal part of which is also complete and assembled on the antenna. The BUS has been pre-assembled on the ground, aligned and tested for compliance with specifications, and broken down into 22 modules for installation on the box girder. As of mid-April 1998, 16 of the 22 modules were installed on the box girder. A current photograph of the GBT construction is shown as Figure II-2.

When the 22 backup structure subassemblies are welded together on the antenna and supported on the permanent supports that hold it above the box girder, it will be possible to tilt the tipping structure and complete the assembly of the feed arm. This involves lifting into place the previously assembled sections of the vertical feed arm and welding them together. The subreflector and its supporting structure will then be installed at the top of the feed arm. This subassembly is complete and is now undergoing servo testing and refinement.

The final major task will then be to install the 2,004 reflector panels and 2,209 actuators that will be used to position the panels accurately. Approximately 1,400 panels have been fabricated and are being painted. The fabrication of the remaining panels will begin as soon as shipment of completed panels to Green Bank releases storage space. Installation of panels is expected to begin before erection of the vertical feed arm is complete. Finally, the surface panels will be aligned and the telescope made ready for acceptance testing.

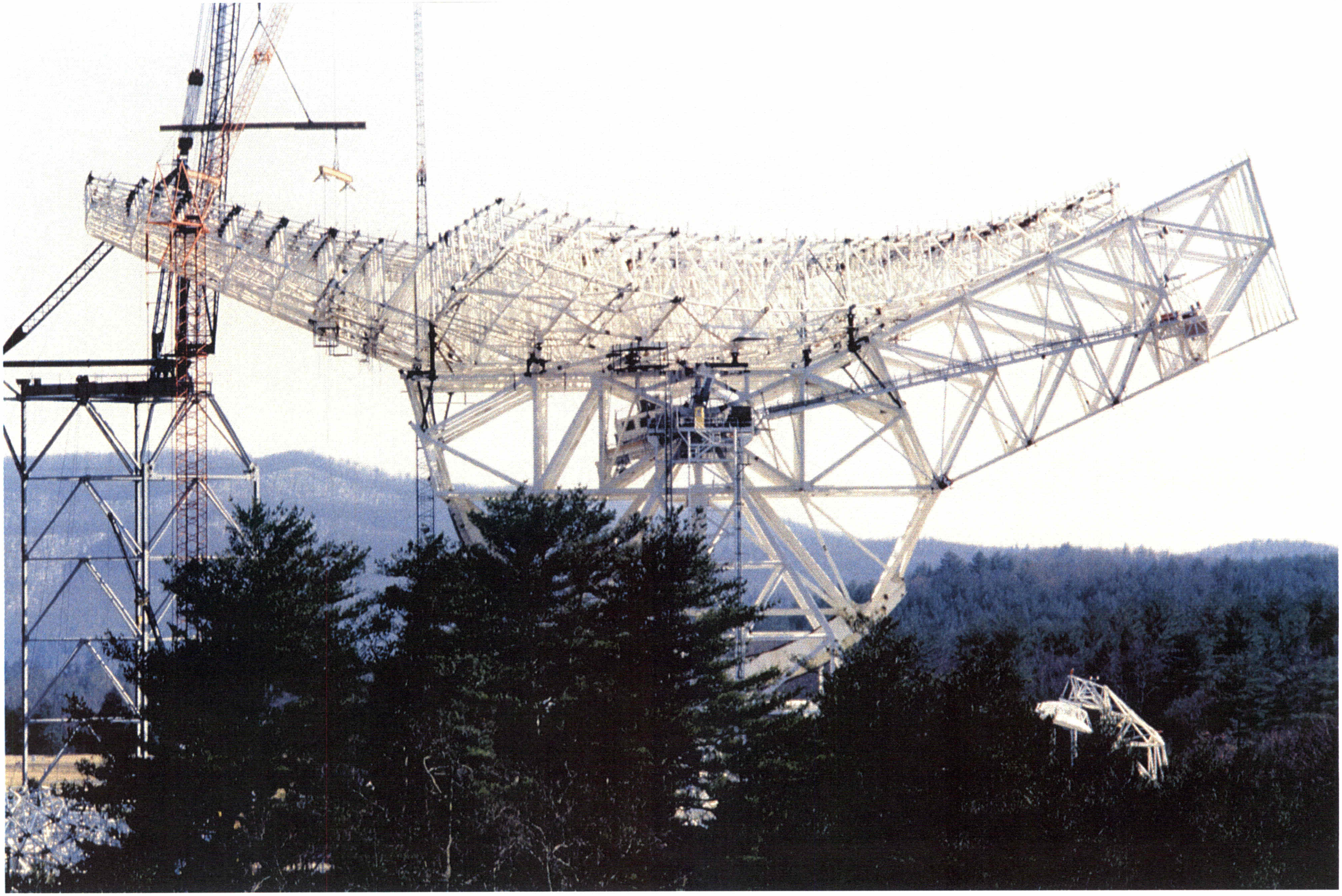


Figure II-2. Photo taken in March 1998 showing construction progress of the GreenBank Telescope (GBT).

The outline of major milestones is given in the following table:

Activity	Start Date	Completion Date
Install BUS modules on box	10-17-97	6-25-98
Inter-module welding	9-29-97	7-02-98
Install actuators	4-11-98	8-04-98
Install permanent BUS supports	3-24-98	12-23-98
Prepare vertical feed arm	12-01-97	8-27-98
Install vertical feed arm	8-27-98	2-22-99
Install permanent drive control	2-22-99	3-09-99
Install upper feed arm assembly	3-09-99	4-22-99
Align elevation gear	4-22-99	5-24-99
Electrical installation	9-10-97	1-26-99
Actuator welding, alignment, & cabling	4-09-98	7-15-99
Panel installation & alignment	4-17-99	8-11-99
Servo checkout	8-12-99	11-01-99
Surface photogrammetry & alignment	8-12-99	10-23-99
Site shutdown	3-24-98	12-31-99

Commissioning

The Green Bank Telescope construction contract provides for the delivery to the NRAO of a functioning antenna, not a radio telescope. Here the distinction is a matter of instrumentation. The research instrumentation for the GBT is being built in-house. It includes the following:

- control of all the surface panel actuators;
- a precision laser metrology system to measure the figure of the antenna reflector and accurately refer the position of each reflector panel to fixed points on the ground;
- an integrated monitor and control software system to drive and point the antenna to the precision needed for astronomical research;
- a complement of receivers at the prime focus for frequencies from 250 to 1250 GHz;
- a complement of receivers at the Gregorian focus, each remotely selectable, that will eventually cover 1.2 to 50 GHz;
- a signal transmission system for the local oscillator and intermediate frequency signals;
- cryogenics systems at the prime and Gregorian focus along with all associated interconnecting cabling;

- signal processing electronics for continuum and spectroscopic observations.

In the first several years of operation all of these NRAO-provided facilities will be brought on-line and tested by the NRAO staff and by those visiting scientists interested in participating in the commissioning phase of a major research facility. In Phase I of this process the GBT will be suitable for scientific operation up to approximately 15 GHz.

Phase II of the commissioning process will be concentrated on making the active surface setting system operational. First, it will be used in a "lookup" mode to adjust itself in response to computed gravitational loading. The laser metrology system at this point will be employed to verify the commanded positioning of the actuators. Once this is successful the GBT will be very efficient for observations at frequencies as high as 45 GHz. The final phase of the NRAO-provided effort will attempt to extend the performance of the telescope to millimeter wavelengths, frequencies higher than the atmospheric oxygen lines at 60 GHz, up to 100 GHz. To accomplish this ambitious task it will be necessary to use the laser metrology system to measure the position of each reflector panel and set that panel at the correct position thereby accounting for gravitational and thermal distortions of the antenna surface. By referring the position of each antenna to points on the ground the laser system will also provide the pointing precision needed for the GBT if it is to operate successfully for astronomical research at millimeter wavelengths. Taken as a whole, the laser metrology system will be a unique asset; it will require careful software control and thorough debugging analysis. Once operational, the NRAO-provided enhancements involving the laser metrology and precision pointing system will take the telescope to its ultimate high frequency operation.

The GBT will initially have seven receiving systems that cover much of the frequency range between 230 MHz and 26 GHz. Six of the receivers will be mounted permanently in the receiver room at the secondary focus, while the lowest frequency receiver will be installed in the prime focus boom. Additional receivers will be added at the rate of about one per year, gradually plugging gaps in the frequency coverage of the telescope. By the end of 2002 we hope to have virtually complete coverage of all frequencies between 25 MHz and 52 GHz. Higher frequency receivers are also under study, as are array receivers and multi-frequency systems. Each receiver that operates above 10 GHz will consist of at least two separate feed horns to allow rapid beam switching so as to minimize atmospheric distortions. A tertiary mirror system is now under development for the 40-52 GHz system. Once it is in successful operation, we will study the possibility of constructing additional tertiaries or other active optical components for use at lower frequencies.

Receiver Construction Schedule

Frequency (GHz)	Completion Date	Comment
0.025 - 0.075		Future prime focus receiver ?
0.295 - 0.395	12/98	Prime focus box #1
0.385 - 0.520	12/98	Prime focus box #1
0.510 - 0.690	12/98	Prime focus box #1
0.680 - 0.920	12/98	Prime focus box #1
0.910 - 1.230	11/98	Prime focus box #2
1.15 - 1.73	complete	Secondary focus - single beam
1.73 - 2.60	10/98	Secondary focus - single beam
2.60 - 3.95		Future secondary focus - single beam ?
3.95 - 5.85	complete	Secondary focus - single beam
5.85 - 8.00		Future secondary focus - single beam ?
8.0 - 10.0	complete	Secondary focus - single beam
10.0 - 12.0		Future secondary focus - dual beam ?
12.0 - 15.4	complete	Secondary focus - dual beam
15.4 - 18.0		Future secondary focus - dual beam ?
18.0 - 22.0	complete	Secondary focus - dual beam
22.0 - 26.5	complete	Secondary focus - dual beam
26.5 - 33.0	6/00	Secondary focus - dual beam
33.0 - 40.0	6/00	Secondary focus - dual beam
40.0 - 52.0	3/99	Secondary focus - dual beam

The optics systems on the GBT will present special operational challenges. The active surface alone has more than 2,200 actuators, each with a motor and transducer. The 8-meter diameter secondary reflector is controlled by a 6-actuator Stewart platform that allows considerable flexibility of motion with highly accurate positioning, but which will pose interesting problems of calibration and maintenance. There will be at least one, and more likely several, tertiary mirrors in the optical path. Moreover, all receivers at frequencies above 10 GHz will be mounted in rotating assemblies that permit tracking at a constant parallactic angle. There may eventually be eight feed rotation assemblies. The roof of the Gregorian receiver room itself contains a large rotating turret which is used to position a receiver at the secondary focal point. All of these systems will give the telescope great frequency flexibility, allow numerous short projects to be interspersed, and make it possible to consider scheduling observing projects to match daily weather conditions. But the flexibility derives from complexity, and a lot of effort will be required to take advantage of all these potentialities.

The GBT will have a large number of detector backends that can be configured very flexibly to serve a variety of scientific programs. The 2,048-channel spectral processor that is now at the 140 Foot Telescope will move to the GBT in 1998 where it will be used for pulsar measurements and for spectroscopy, especially below 1 GHz where its high dynamic range makes it resistant to interference. It has eight IF inputs and can be configured in a number of modes. A 16-channel digital continuum receiver will be the backend most often used for continuum observing, such as pointing, flux density measurements, and mapping. Very long baseline interferometry will be supported by a VLBA data acquisition system so that the GBT can be treated as an element of the VLBA for purposes of data format and correlation. To match the extended frequency coverage of the GBT and its broad-band receivers, a 256k-channel spectrometer is now under construction and will be available shortly after the GBT comes into operation. It will have a maximum bandwidth of 800 MHz, eight IF inputs for its broader bands and 32 for its narrower bands. In addition to spectroscopy, the correlator can be used for pulsar searches and other pulsar observations. Its bandwidth, large number of channels, and flexible configuration will be ideally suited to redshift searches and simultaneous studies of numerous molecular transitions. In some of its modes the data rate from the new correlator will exceed that of our existing backends by many orders of magnitude and strain the Observatory's computational and data reduction resources. The correlator is well-matched to the GBT's new fiber optic IF system, which will have a bandwidth wide enough to cover the entire sky frequency range of virtually all receivers.

There is an extensive GBT metrology program which holds the promise of being able to provide detailed information on the telescope surface and orientation in near real-time, allowing highly accurate pointing and surface adjustment. The NRAO metrology group has had to devise its own laser-ranging instruments for this task, and it is likely that this program will be in continuing development even as parts of it are put into operation. The data from the metrology system consists of measurements of the precise location and orientation of up to several thousand points, including some key structural elements of the telescope. The system can measure the location of every surface panel, fiducial points around the dish edge, the subreflector, several points on the arm and the location of the arm with respect to the surface. It will also measure the position of the surface and arm with respect to a dozen fixed points on the ground. The synthesis of these data into a beam vector on the sky (i.e., the precise antenna gain and pointing) will require considerable research and field measurements over several years by a skilled team.

The scale and complexity of the GBT structure, metrology, and electronics systems require a software control system of comparable power. The monitor and control (M&C) software now under development by Green Bank staff uses the most modern software tools and advanced programming techniques to create an environment in which every critical component on the telescope is monitored and controlled. Monitor data (e.g., voltages and physical temperature of receiver components; wind speed and humidity; motor currents; phase delay through the IF lines) are stored in the same internal data format as astronomical data, so that standard data reduction tools can be used to analyze engineering and environmental information. Observers will have access to whatever data they think relevant for their science, and the GBT staff will have the ability to create and analyze data on instrument performance with an eye to detecting potential equipment problems before they occur. The M&C system is also being built with remote observing in mind, so that astronomers using the GBT, whether they are located at the Observatory in Green Bank or connected through the Internet from elsewhere, will have access to identical, complete, real-time information. The basic concepts behind the M&C software design have been proven in tests at the 140 Foot Telescope, and parts of the software have been in routine use for pulsar observations for more than a year. Development of further M&C tools, modifications for specific observing projects, and enhancements to cover new devices or operations modes will require the continued effort of Green Bank programmers.

Integrated Testing

An integrated testbed, or Mock-up, of the GBT Electronics and Monitor and Control systems was assembled in the basement of the Jansky Laboratory in early 1997, and we are now realizing the benefits of integrated testing in the Mock-up. For example, the chief GBT RF engineer, Roger Norrod found that the electronics in the IF racks are sensitive to changes in ambient temperature. Consequently, we are modifying the temperature control scheme in the new GBT Electronics Room. Norrod also found that the noise in the detected total power from the GBT IF did not integrate down as the square root of bandwidth or time. Further investigations showed that the excess noise was due to excessive gain fluctuations in a certain type of IF amplifier. Additional tests in the Mock-up are high priority objectives in 1998 because the time required to commission the GBT can be minimized by identifying and solving problems in the Mock-up now.

Operations

The sheer size of the GBT requires new resources at Green Bank just for routine operations. The telescope will double the electric power load of the Observatory. It will have the largest emergency generators on site, which will require regular maintenance and testing. It will nearly double the number of elevators on site that have to be maintained. Its HVAC systems will add 50 percent to the site capacity. The maintenance load rises in proportion. Special equipment (e.g., a large cherry picker) will be needed just to provide access to the structure for inspection and repair. Faulty elements of the active surface will need to be identified and replaced. The large number of receivers being kept on-line at any time places extra demands on the cryogenics systems. It is estimated that one person will be needed to coordinate maintenance activities at the telescope.

Visiting scientists will require extra support to become familiar with the telescope and its new receivers, detectors, and software. The expected increase in demand for remote observing will mean that Green Bank computer staff will have to iterate development of appropriate controls, display, and feedback to observers. Telescope operators will take on greater involvement with and responsibility for the detailed execution of observing programs. Local scientific staff will have to be intimately involved with every experiment until the new modes of observing are fully developed. Observers will face unprecedented data rates when on-the-fly mapping techniques are implemented with the 256k-channel spectrometer. In sum, for efficient and successful operation of the GBT, the Observatory will have to commit significant additional resources to development of new GBT systems with consequent major enhancements of its scientific capabilities through the next five years. The budgets to support this growth are included in the NRAO long range plan summarized in Section VIII.

The GBT operations group now consists of three full-time personnel. Carl Bignell transferred from VLA/VLBA Operations to lead the Telescope Services Division in Green Bank. Jerry Lawrence, who has extensive experience in the commissioning of radar installations for the United States Air Force, was hired as the GBT Operations Supervisor. Steve Reeves transferred from his position as an operator of the 140 Foot Telescope to become our first GBT operator. A position vacated with the recent retirement of a mechanic at the 140 Foot will be filled with another GBT operator this summer.

The operations group is focusing its efforts on developing plans and procedures for operating and maintaining the GBT. The group developed a manpower transition plan which identifies the manpower needed to operate and maintain the GBT and describes how operations and maintenance manpower will shift from the 140 Foot Telescope to the GBT as 140 Foot operations come to a close. Many items needed to operate the GBT (e.g., communications hardware, safety equipment, and optical fiber between the telescope and the control room) are not provided by the GBT construction contract, and the operations group has initiated the necessary procedures to acquire essential items this year. The group is also prioritizing a list of GBT spare parts to insure that the most critical spares are purchased with our limited budget. Lawrence has specified the communication requirements for the GBT and has written the job description for GBT operators. Members of the operations group are also interacting with the software development group to insure that the operators' interface to the telescope provides the basic functionality they need.

In November of 1997, we decided to operate the GBT from the new addition to the Jansky Laboratory instead of a new local control building. The GBT operations group quickly developed a plan for occupying the space in the new addition in a way that would accommodate site-wide telescope operations.

We are actively seeking ways to improve telescope operations by soliciting input from the astronomical community. The NRAO will sponsor a workshop on science with the GBT on 27–29 July 1998. The purpose of the workshop is for potential users to discuss their planned observations and to suggest potential improvements for NRAO support. Part of the workshop will be dedicated to discussing how GBT performance can be measured and improved with astronomical observations during the commissioning phase. Additionally, a committee composed of NRAO personnel and "outside" users is being established to review the completeness and priority of the operational modes which are planned for the GBT.

Site Monitoring at 3-mm

An 86 GHz water vapor radiometer was designed and built by Mike Stennes and Lisa Wray over the summer of 1997. The radiometer was integrated into the GBT monitor and control system by John Ford, and, using software tools available in AIPS++, Joe McMullin developed a data analysis package for the radiometer data. We began collecting meaningful statistics on the atmospheric opacity due to water vapor before the onset of winter, when atmospheric conditions are expected to be most favorable for high frequency observations. We have found that the zenith opacity at 86 GHz can be less than 0.1 for extended periods of time (days).

III. MILLIMETER ASTRONOMY:
THE MILLIMETER ARRAY AND THE 12 METER TELESCOPE

1. The Millimeter Array

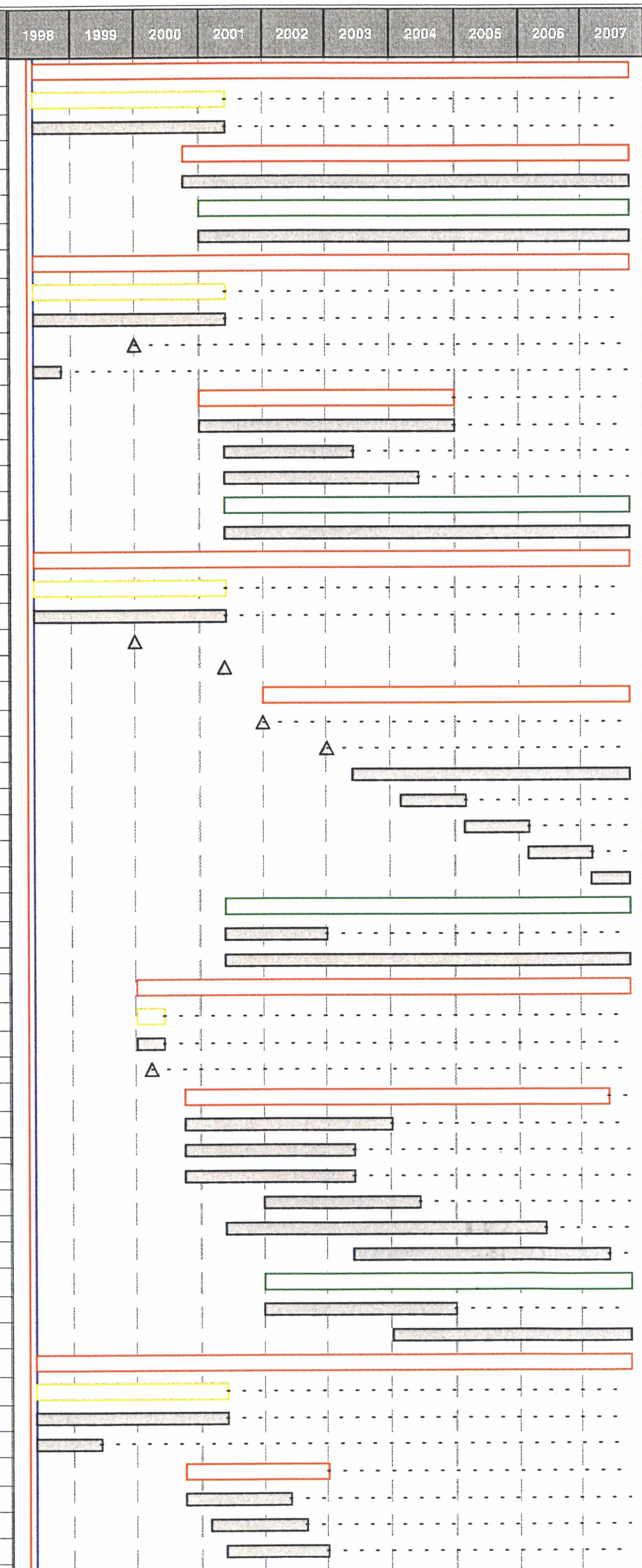
Overview

The Millimeter Array (MMA) project began in 1998. Construction of this approximately $200M synthesis array telescope is proceeding in three phases that overlap in time. The first phase is a design and development phase (D&D) in which the design of key array hardware will be done and technical decisions made where there are open options. It is also the phase in which the lead personnel will be hired to the project and the management and oversight mechanisms put in place that will be used to guide the evolution of the project. At the culmination of this phase it will be possible to evaluate with precision the construction cost of the entire MMA. The second phase of the project, extending from fiscal years 2001 through 2007, is the construction phase of the project. Here the challenge will be to fabricate, under contract, the many MMA antennas and erect them on the Chilean array site. The receivers and associated instrumentation will be fabricated by a combination of in-house efforts and commercial contracts. The third phase of the MMA project is the operational phase. For an array telescope it is possible to begin interim scientific operations as soon as the first few antennas are in place; the operations then expand as additional antennas and hardware are added to the array. There is much valuable experience to be gained from interim operations that will be used to benefit the completed instrument. Interim operations should begin as early as 2002 when the first prototype antenna is assembled on the VLA site and is available for tests.

An outline of the expected progression of the MMA project, all three phases, is illustrated in the accompanying Gantt Chart. The presentation shows the relative timing of the major tasking for the MMA project. It is taken from the MMA Program Plan, Design and Development Volume II, as presented to the NSF in February 1998. The project planning given here presumes that either there are no partners in the MMA project or that the partners are only minor partners so that the project schedule is dictated by the authorization and availability of NSF funding. As described below, two potential international partnerships may be realized for the MMA and if this happens the latter two phases of the MMA project, construction and operations, will need to be adjusted to accommodate the participation of the others. Owing to this uncertainty, the near-term activities at the NRAO are focused on the initial phase, design and development. The budget and personnel tables in support of the MMA project are included in the Observatory Financial and Personnel projections, Section VIII, of this Long Range Plan.

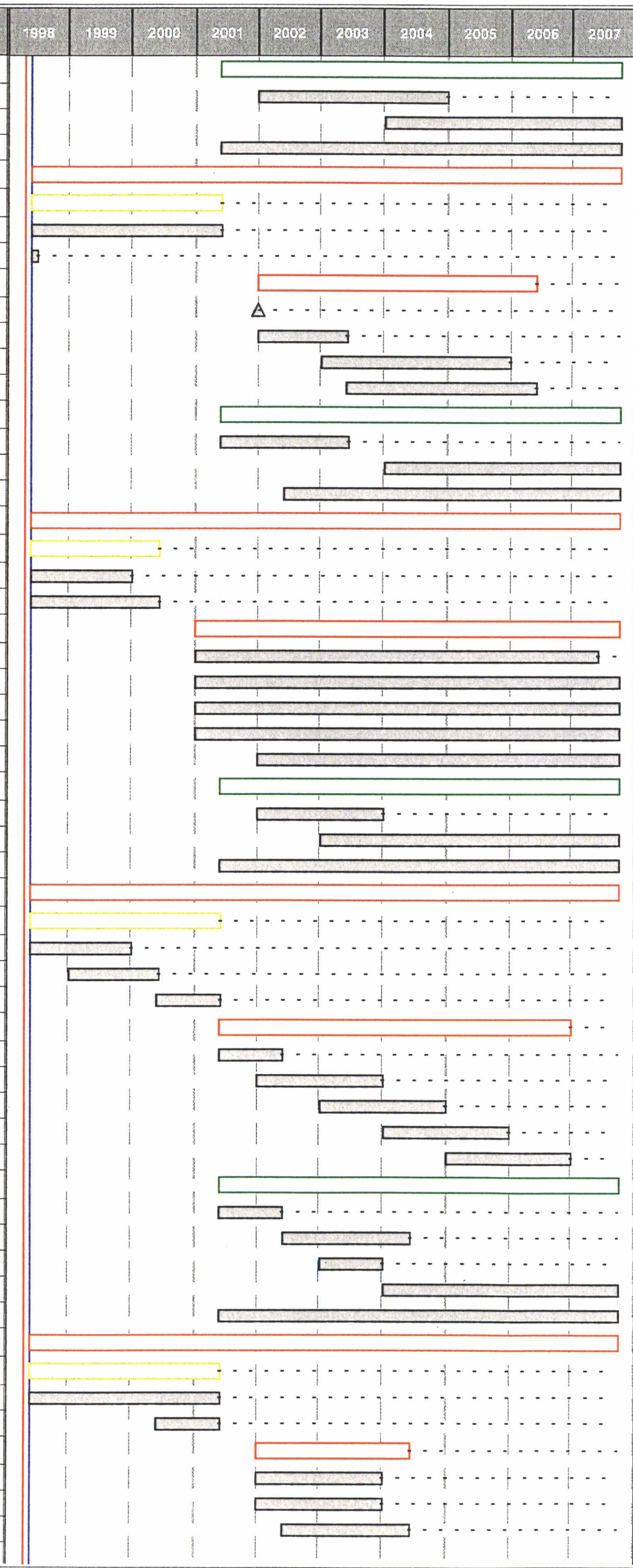
MMA Project Overview 980127.1

Task Name	Start Date	End Date
ADMINISTRATION	6/1/1998	10/1/2007
Design and Development	6/1/1998	5/31/2001
Organize Project Management	6/1/1998	5/31/2001
Construction	10/2/2000	10/1/2007
Manage Production and Procurement	10/2/2000	10/1/2007
Operations	1/2/2001	10/1/2007
Plan and Develop Site Operations	1/2/2001	10/1/2007
ARRAY SITE	6/1/1998	10/1/2007
Design and Development	6/1/1998	5/31/2001
Site Civil Engineering	6/1/1998	5/31/2001
Site Use Permission	1/1/2000	1/1/2000
Preliminary A&E Contract	6/1/1998	10/29/1998
Construction	1/2/2001	12/31/2004
A&E Contract Engineering	1/2/2001	12/31/2004
Ops Facility Construction	6/1/2001	5/30/2003
Site Construction	6/1/2001	6/1/2004
Operations	6/1/2001	10/1/2007
Hire/Train Site Ops Staff	6/1/2001	10/1/2007
ANTENNA DEVELOPMENT	6/1/1998	10/1/2007
Design and Development	6/1/1998	6/1/2001
Antenna Design	6/1/1998	6/1/2001
Sign Contract (Ant#1+option Ant#2)	1/1/2000	1/1/2000
Receive/Accept Ant#1	6/1/2001	6/1/2001
Construction	1/1/2002	10/1/2007
Receive/Accept Ant#2	1/1/2002	1/1/2002
Accept/Approve Antenna Design	1/1/2003	1/1/2003
Contract for Antenna Production	6/2/2003	10/1/2007
Receive Antennas #3-11	3/1/2004	3/1/2005
Receive Antennas #12-20	3/1/2005	3/1/2006
Receive Antennas #21-29	3/1/2006	3/1/2007
Receive Antennas #30-36	3/1/2007	10/1/2007
Operations	6/1/2001	10/1/2007
Evaluate Ant#1,2 on Test Interf	6/1/2001	12/31/2002
Train Site Antenna Ops/Maint Staff	6/1/2001	10/1/2007
SIS MIXER	1/3/2000	10/1/2007
Design and Development	1/3/2000	6/1/2000
Design MMA Bands	1/3/2000	6/1/2000
Deliver MMA 230 GHz	4/1/2000	4/1/2000
Construction	10/2/2000	6/1/2007
Design mm SIS	10/2/2000	12/31/2003
Design mm bal, Im-Sep, SIS	10/2/2000	5/30/2003
Design submm trav Wave SIS	10/2/2000	5/30/2003
Design submm bal, Im-Sep, trav Wave SI	1/2/2002	6/1/2004
Produce mm bal, Im-Sep, SIS	6/1/2001	6/1/2006
Produce submm bal, Im-Sep, trav Wave	6/2/2003	6/1/2007
Operations	1/2/2002	10/1/2007
SIS Evaluation on Test Interferometer	1/2/2002	12/31/2004
SIS Evaluation on Interim MMA	1/2/2004	10/1/2007
HFET AMPLIFIER	6/1/1998	10/1/2007
Design and Development	6/1/1998	6/1/2001
MMA Designs	6/1/1998	6/1/2001
MMA 30 and 90 GHz Prototypes	6/1/1998	6/1/1999
Construction	10/2/2000	12/31/2002
Production: 33-50 GHz	10/2/2000	5/31/2002
Production: 67-90 GHz	3/1/2001	8/30/2002
Production: 85-120 GHz	6/1/2001	12/31/2002



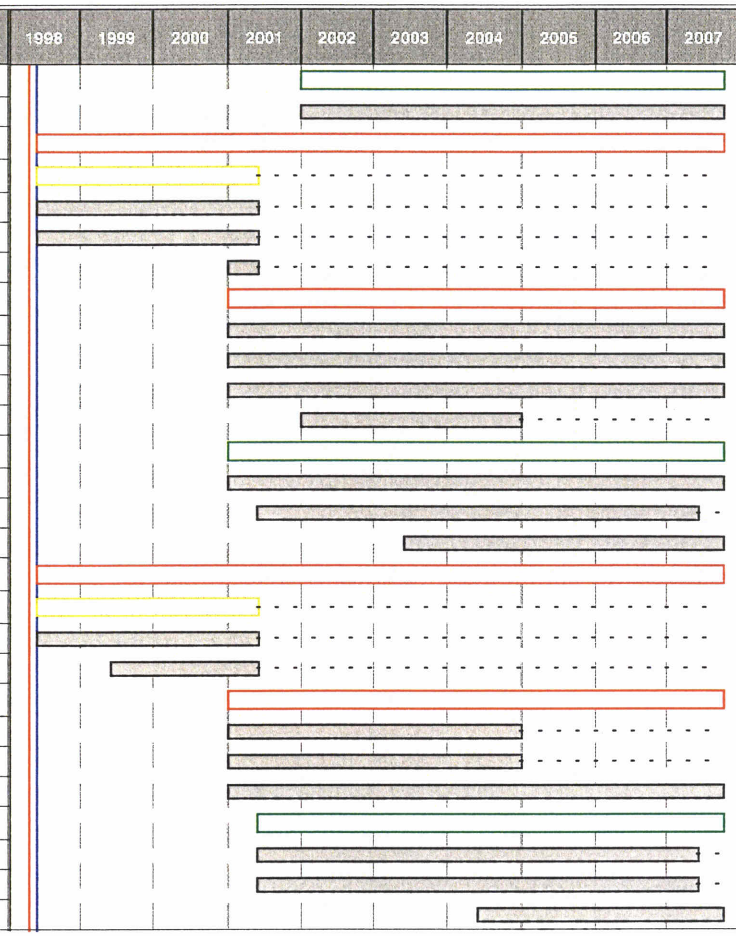
MMA Project Overview 980127.1

Task Name	Start Date	End Date
Operations	**6/1/2001**	**10/1/2007**
Evaluation on Test Interferometer	1/2/2002	12/31/2004
Evaluation on Interim MMA	1/2/2004	9/28/2007
Train Site HFET Maintenance Staff	6/1/2001	10/1/2007
LOCAL OSCILLATOR	**6/1/1998**	**10/1/2007**
Design and Development	**6/1/1998**	**6/1/2001**
Design & Prototype 230 GHz Convention	6/1/1998	6/1/2001
Design & Prototype 230 GHz Photonic	6/1/1998	6/30/1998
Construction	**1/1/2002**	**6/1/2006**
Decision: Conventional or Photonic	1/1/2002	1/1/2002
Design MMA LO System	1/2/2002	5/30/2003
Produce Millimeter Bands LO	1/2/2003	12/30/2005
Produce Submillimeter Bands LO	6/2/2003	6/1/2006
Operations	**6/1/2001**	**10/1/2007**
Evaluate mm LO on Test Interferometer	6/1/2001	6/2/2003
Evaluate submm LO on Interim MMA	1/2/2004	10/1/2007
Train MMA LO Maintenance Staff	6/3/2002	10/1/2007
RECEIVER SYSTEMS	**6/1/1998**	**10/1/2007**
Design and Development	**6/1/1998**	**6/1/2000**
Design Cryo Refrigerator and Dewar	6/1/1998	12/31/1999
Design and Prototype Receiver Package	6/1/1998	6/1/2000
Construction	**1/2/2001**	**10/1/2007**
Contract Machinjng	1/2/2001	6/1/2007
Contract Subsystem Assembly	1/2/2001	10/1/2007
Insert Assembly and Test	1/2/2001	10/1/2007
Mechanical Assembly and Test	1/2/2001	10/1/2007
Delivery of Receiver Packages	1/2/2002	10/1/2007
Operations	**6/1/2001**	**10/1/2007**
Engineering Evaluation on Test Interferom	1/2/2002	12/31/2003
Progressive Insert Installation on MMA Sit	1/2/2003	10/1/2007
Training of Site Ops/Maint Receiver Staff	6/1/2001	10/1/2007
CORRELATOR	**6/1/1998**	**10/1/2007**
Design and Development	**6/1/1998**	**6/1/2001**
Build and Deliver Test Correlator	6/1/1998	12/31/1999
MMA Design	1/4/1999	6/1/2000
Design/Assemble Proto Correlator (1/4)	6/1/2000	6/1/2001
Construction	**6/1/2001**	**12/29/2006**
Build and Deliver Proto Corr (1/4) to Test I	6/1/2001	5/31/2002
Build and Deliver first 1/4 to MMA Site	1/2/2002	12/31/2003
Build and Deliver second 1/4 to MMA Site	1/2/2003	12/31/2004
Build and Deliver third 1/4 to MMA Site	1/2/2004	12/30/2005
Build and Deliver fourth 1/4 to MMA Site	1/3/2005	12/29/2006
Operations	**6/1/2001**	**10/1/2007**
Operate/debug Test Corr at Test Interf	6/1/2001	5/31/2002
Operate/debug Proto Corr at Test Interf	6/3/2002	6/1/2004
Operate Test Corr at MMA Site	1/2/2003	12/31/2003
Operate/debug MMA Corr at MMA Site	1/2/2004	10/1/2007
Train Correlator Ops and Maint Staff	6/1/2001	10/1/2007
SIGNAL TRANSMISSION	**6/1/1998**	**10/1/2007**
Design and Development	**6/1/1998**	**6/1/2001**
System Design and Prototype	6/1/1998	6/1/2001
Assemble/debug Proto Sys at Test Interf	6/1/2000	6/1/2001
Construction	**1/2/2002**	**6/1/2004**
Contract Subsystem Assembly	1/2/2002	12/31/2003
Assembly and Test	1/2/2002	12/31/2003
Installation at MMA Site	6/3/2002	6/1/2004



MMA Project Overview 980127.1

Task Name	Start Date	End Date
Operations	**1/2/2002**	**10/1/2007**
Training of Operations and Maint Staff	1/2/2002	10/1/2007
COMPUTING	**6/1/1998**	**9/28/2007**
Design and Development	**6/1/1998**	**6/1/2001**
Design and Programming Correlator Interf	6/1/1998	6/1/2001
Real-time Array System Design	6/1/1998	6/1/2001
Operator & Astronomer Interface Spec	1/2/2001	6/1/2001
Construction	**1/2/2001**	**9/28/2007**
Program Correlator Reat-time	1/2/2001	9/28/2007
Program Array System	1/2/2001	9/28/2007
Program Interfaces	1/2/2001	9/28/2007
Evaluate Proto Systems on Existing Array	1/2/2002	12/31/2004
Operations	**1/2/2001**	**9/28/2007**
Train & Involve Site Ops Prog Staff	1/2/2001	9/28/2007
Support Test Interferometer Operations	6/1/2001	6/1/2007
Support Interim Operations at MMA Site	6/2/2003	9/28/2007
SYSTEM INTEGRATION AND TEST	**6/1/1998**	**9/28/2007**
Design and Development	**6/1/1998**	**6/1/2001**
Define System Standards	6/1/1998	6/1/2001
Prepare Test Interferometer Site	6/1/1999	6/1/2001
Construction	**1/2/2001**	**9/28/2007**
Establish MMA Site Operations Procedur	1/2/2001	12/31/2004
Establish MMA Site Engineering Standard	1/2/2001	12/31/2004
Establish Site Assembly/Integration Proce	1/2/2001	9/28/2007
Operations	**6/1/2001**	**9/28/2007**
Operations and Analysis of Test Interfero	6/1/2001	6/1/2007
Interface to Science & Engineering Staff	6/1/2001	6/1/2007
Operate Interim MMA	6/1/2004	9/28/2007



Goals and Requirements for the MMA Design and Development Phase

The scientific requirements for the MMA have been established and revised through a series of MMA science workshops held from 1985 to 1995. The proceedings of these workshops are published and have been made available in electronic form on the World Wide Web. In the MMA astronomers are seeking an instrument that will allow them to make spectroscopic images of the gas and continuum images of the dust, in normal galaxies such as the Milky Way very early in the history of the Universe. They want to observe the details of the formation of individual stars throughout the Galaxy. They want to measure the isotopic composition of the ejecta from giant stars that are progressively shedding nearly all their mass in the final throes of stellar evolution. And they want to observe energetic events on the Sun, to establish the chemical composition of comets, monitor volcanic outbursts on Io, and assess the abundance of icy asteroids beyond the orbits of Jupiter and Neptune. These representative observational programs, and many others that could be mentioned, lead to three principal requirements for the MMA:

- Precision Imaging
- Sensitivity to Detect Faint Objects
- Ease of Access for a Wide Range of Scientific Research

These requirements lead to some clear specifications for the MMA. In particular, a large number of antennas is needed to give the good Fourier (uv-plane) coverage that produces precision synthesis imaging; the antenna array must be have a physical extent of approximately 3 km to achieve $0\overset{''}{.}1$ at one its prime millimeter frequencies, 230 GHz; and the antennas must be transportable to achieve precision imaging on all spatial scales up to $0\overset{''}{.}1$. However, these same considerations lead to some practical consequences that define the work to be done in the MMA D&D phase. For example, the angular size of objects astronomers wish to image – forming groups of galaxies, interacting galaxies, regions of star formation – may be smaller than approximately 3 arcseconds or they may be as large as 3 arcminutes. If astronomers want to make an image of an object as large as 3', and they want that object to fit in the primary beam of the individual antennas, then the diameter of the antenna can be no more than about 1,000 times the wavelength at which the observations are made. For observations done at 1 mm wavelength, this means the individual antennas making up the array should have a diameter of less than one meter. An enormous number of such small antennas are needed to get enough collecting area to realize much sensitivity: 150 such antennas are needed just to achieve the same collecting area as the present NRAO 12 Meter Telescope. The cost of equipping such an array with cryogenic receivers, and of cross-correlating the data, makes such a solution impractical.

In order to preserve the scientific capability to image large objects, and satisfy the practical requirement that the antennas be of diameter large enough that a reasonable number of them will provide the needed sensitivity, means that the array must be capable of producing not just precision images, but precision *mosaic* images. Making such images requires observing with multiple, precision antenna pointings. In a seminal work Cornwell, Holdaway, and Uson showed that this can indeed be done if the deviation from perfection of the antenna figure is no more than three percent of the observing wavelength and if the pointing error of the antennas does not exceed five percent of the primary beamwidth. These severe technical requirements, deriving from a science requirement, are the engineering specifications for the antennas. Meeting such specifications in the antenna design is a major task to be accomplished in the MMA D&D program.

The need for sensitivity sufficient for the study of faint objects with the MMA implies a requirement for (1) development of broadband, quantum-limited receivers; (2) design of antennas of very low blockage so that the *warm spillover* is minimized; and (3) choice of a site for the array where the background emission and absorption from atmospheric water is minimal. The first two points are the focus of the D&D instrumentation development described below. The site issue is resolved by noting that since atmospheric water vapor is concentrated low in the Earth's atmosphere, the necessary site for the MMA is at high elevation. Two site options have been studied: Mauna Kea at 12,500 feet above sea level and Llano de Chajnantor in the Chilean Altiplano at 16,500 feet elevation.

The combination of requirements for a high-tech instrument to be located in a remote site means that great care must be taken in the design of the array. The MMA instrumentation will need to be reliable to minimize the failure rate and modular so that it can easily be removed when necessary for repair at a laboratory located at a lower altitude. Together, these considerations mean that the MMA design requires attention to maintenance issues. The three-year MMA Design and Development program is structured to make this possible.

The final astronomical requirement for the MMA to be addressed in the MMA D&D phase concerns ease of scientific access. Recognizing that the MMA will be extremely fast—images of small fields can be done in minutes—and suitable for a wide range of scientific investigation, astronomers seek to receive *images* as one of the data products from the array. This goal should not remove the ability of the sophisticated synthesis astronomer to refine his or her image through subsequent processing, but it should allow non-expert astronomers to use the instrument easily and effectively. It involves development of instrumentation and software not presently part of operating radio synthesis instruments. Fortunately, some of the ideas that will go into this task for the MMA can be tried and refined on existing instruments; that is the thrust of the MMA D&D effort in the area of data processing.

The MMA D&D project requirements outlined above result in the following goals for the initial three-year phase of the project:

- Definition and implementation of an organizational and management structure, including oversight mechanisms and review processes, that will serve the entire MMA project.
- A comprehensive proof-of-concept for the MMA instrumentation through construction of prototype hardware.
- A plan for integration of prototype hardware on a test interferometer.
- Establishment of a firm cost basis for the MMA by means of the prototyping.
- Involvement of interested MMA international partrers early in the instrumentation design and prototyping work.
- Appointment of the key instrumentation design teams and assurance that they are working effectively.
- Selection of an optimal site for the MMA and delivery of all required permits.
- Partnership arrangements with foreign countries or other non-NSF U.S. governmental agencies.
- The continuing involvement of the U.S. community in development of the MMA and fostering of the long-term vitality of U.S. university-based millimeter-wave research and development groups.

The MMA tasks will be conducted by a full-time staff assigned to the project. These people will be NRAO employees. The major tasks will be managed by *Project Division Heads* whose responsibility it is to organize the efforts of the staff assigned to the task. Each major task will have a *Working Group,* a committee of experts made up of individuals at the NRAO assigned to the MMA project, and individuals among the university groups who can advise and guide MMA work being done at the NRAO. There are four such joint NRAO-university working groups that meet at regular intervals:

- Antenna;
- Receiver;
- System;
- and Computing.

In addition, there are two others: a site testing group made up wholly of NRAO/MMA staff, and a science working group, comprised wholly of university-based astronomers whose purpose it is to advise the MMA Project Scientist. Written reports are kept for all six Working Group meetings and these reports, together with the relevant ancillary information, are posted to the Internet so as to be available to all those interested in progress of the MMA project.

An important part of the MMA project organization is the Millimeter Array Development Consortium (MDC). The MDC is a collaboration between the NRAO and the university groups that operate millimeter arrays in the U.S., namely, the Caltech Owens Valley Radio Observatory (OVRO) and the Berkeley-Illinois-Maryland Association (BIMA). By means of participation in the MDC Executive Steering Committee, OVRO and BIMA are fully involved in the decision making process for the MMA development.

From its very inception, the Millimeter Array has been a collaboration between the NRAO and the U.S. astronomical community. The ideas that form the backbone of the instrument definition are contributed by interested individuals in the form of MMA Memos. The memo series provides a forum for considered analysis of the issues facing a project of the magnitude and importance of the MMA; it provides a permanent record of the views and analyses that have gone into the definition of the MMA. More than 100 people have participated as authors of the series of MMA memos that now spans the past sixteen years of MMA development. The MMA memo series is accessible via the Internet at the URL: http://colobus.aoc.nrao.edu/memos/memolist.html. It is an important and effective means of maintaining communication about MMA planning with the community of interested U.S. astronomers.

A brief description of the principal challenges for development of the MMA instrumentation in the areas of antennas, system, receivers, correlator, and computing is given below.

The antennas are the single most costly part of the MMA, the most visible, and the most likely to have the longest life in service. The scientific requirement that the MMA have good mosaicing capability has a strong effect on the antenna design: it means that the antennas have to point exceptionally well and that the sidelobe response cannot vary appreciably with time or antenna orientation. Because the array needs to be reconfigurable, the antennas must be transportable and this in turn means that they cannot be secured in an enclosure; they must be in the open air and meet their performance specifications fully exposed to the environment (e.g., the sun and wind). Moreover, the MMA will be built at a high altitude, remote site. This implies that the antennas should be designed for low maintenance and long component life.

The MMA antenna specifications are described in detail in MMA Memo 145. Table III.1 shows a concise summary of the specifications.

TABLE III.1. ANTENNA SPECIFICATIONS

Frequency Range	30 to 950 GHz
Surface Accuracy	< 25 micrometers RMS
Pointing Accuracy	< 0."8 RMS 50% of the time < 2."5 RMS 75% of the time
Phase Stability	< 10 micrometers RMS 25% of the time < 22 micrometers RMS 50% of the time < 56 micrometers RMS 75% of the time
Dynamical Performance	Switch 1.5 degrees within 1 second of time
Subreflector Nutation	3 beamwidths at 86 GHz
Close Packing	< 1.3 times the antenna diameter
Physical Design	Simple and durable.

The antennas proposed for the MMA in 1990 were conceived of as being 8 meters in diameter. The fiducial design was for a passive antenna, one with no active elements working to adjust the antenna shape or pointing. The possibility of securing partnership in the MMA with the Europeans or the Japanese has served to focus MMA antenna design studies on a larger, 10-m diameter design that would achieve the scientific goals of the MMA and the complementary goals of the Europeans and/or Japanese. Such a change provides a foundation for a partnership and yet allows a stand-alone MMA to be built of 36 such antennas, should these particular partnership initiatives fail.

The MMA antennas will be built under contract. In the MMA Design and Development plan, a contract will be let for an initial prototype antenna, with an option for a second antenna. This will be a design/build to performance contract. Although the ability of the design to meet the specifications will be the responsibility of the contractor, the MMA antenna group will engineer a concept design that they believe meets the MMA specs; that design will be given to all contractors interested in bidding on the antenna contract. At their discretion, they may use and modify that design or not. In either case, having the in-house design will give the MMA antenna engineers a tool with which to compare and assess the contractor's design. After the design is accepted, the MMA engineering team will monitor the progress of the contractor's fabrication efforts and they will be in a position to evaluate the desirability of making specific engineering refinements prior to contracting for the production suite of MMA antennas. The antenna design and all the drawings done by the contractor will become the property of AUI.

The production quantity of MMA antennas will be bid separately from the prototyping work on the initial one or two antennas. Quantity antenna procurement will be done in the construction phase of the MMA. The production procurement will be a build-to-print contract, not a build-to-spec contract. The purpose of the antenna prototyping in the D&D phase is precisely to allow us to assess the as-built design in sufficient detail that we can be confident that there is little risk associated with a build-to-print quantity antenna procurement. Such an approach will enlarge the pool of contractors interested in bidding on the MMA antenna contract and capable of performing the work satisfactorily. We anticipate a substantial cost savings will be realized by this approach and the competition it will foster.

Presently two antenna designs are being carried forward. The first, Figure III-1, is a conventional design patterned after the BIMA antenna. The second, Figure III-2, is an innovative design with a wheel and track mount. A choice will be made between these two early in the D&D phase.

The electronics system for a large synthesis array such as the MMA is complex, with the signals received by the antennas undergoing numerous frequency conversions using local oscillators with precisely controlled phases. The current concept for the MMA system design is given in MMA Memo 190. The principal parts of the electronics system are receivers, local oscillator, wide bandwidth transmission system, and correlator. Some of these sub-systems are discussed in more detail below. The detailed design of this system is an important task for the design and development phase of the project.

Some of the major technical challenges for the overall system design are the maintenance of phase stability adequate for the highest observing frequency in the various signal paths and provision of an accurate total power measurement capability. The remote location of the MMA requires that the system be designed for easy operation and maintenance, implying a monitoring system adequate for off-site fault diagnosis and the packaging of all electronics in easily replaceable modules.

The receiver plan for the MMA envisions use of transistor amplifiers, HFETs (heterostructure field effect transistor) for the frequency bands near 30 and 90 GHz, and use of SIS mixers at higher frequencies. For the 2.6 mm band that includes the CO(J=1-0) transition at 115 GHz, a choice between HFET and SIS will be made based on the performance figures demonstrated by the prototype HFET amplifier in this band.

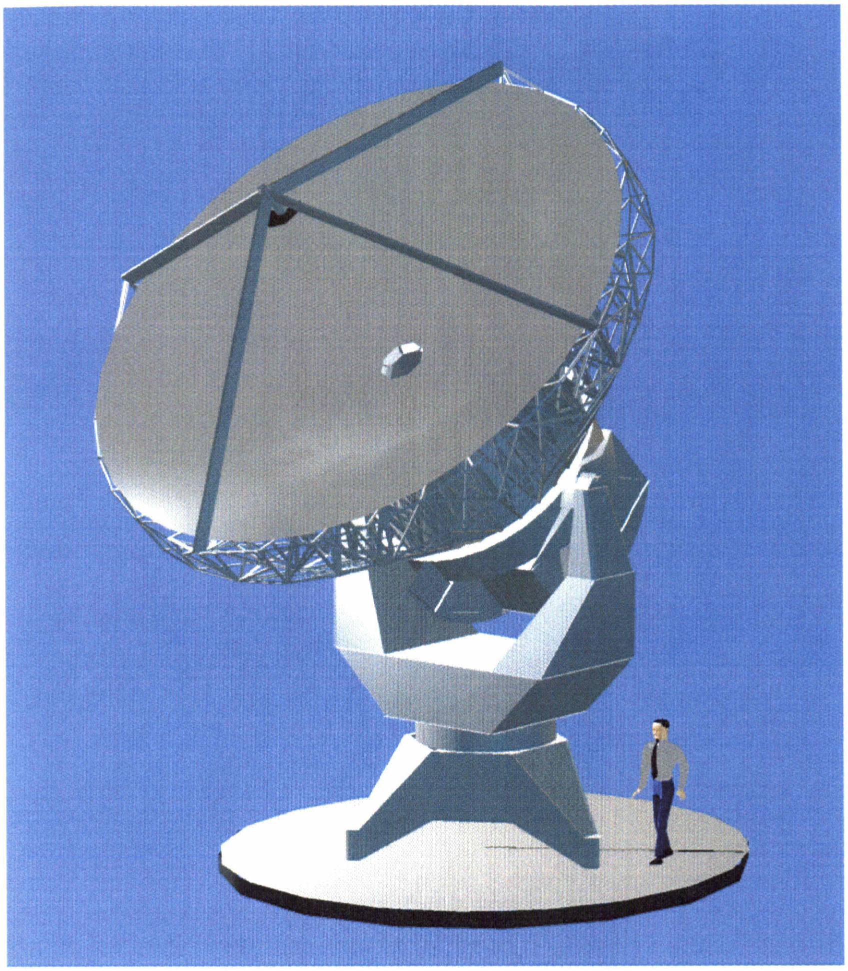


Figure III-1. MMA antenna concept derived from the BIMA design.

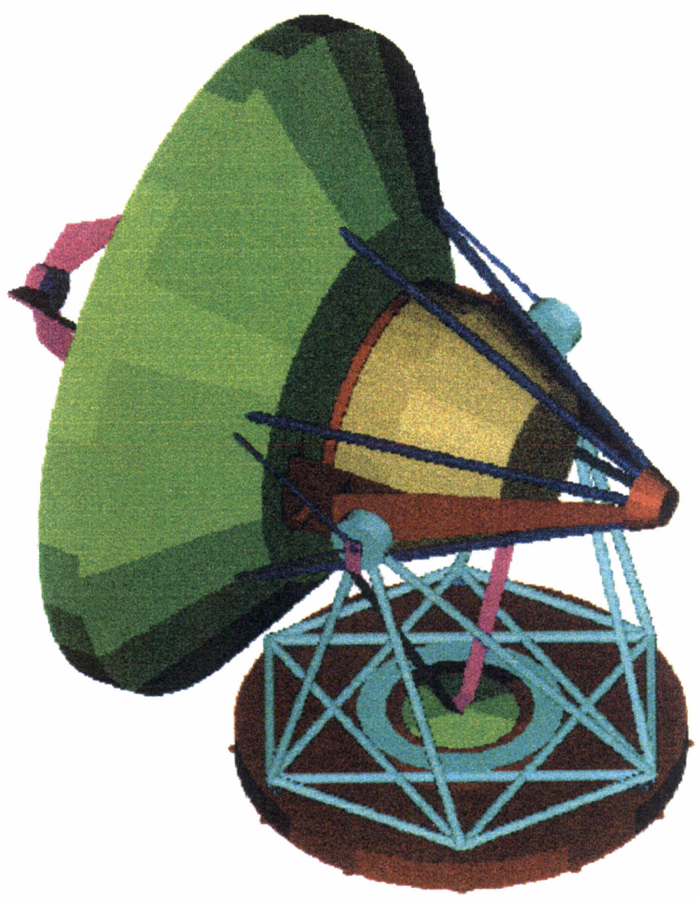


Figure III-2. MMA antenna concept utilizing an azimuth track and homologous back structure.

HFET amplifiers at 30 and 90 GHz with performance specifications similar to those of the MMA are being fabricated now at the NRAO Central Development Laboratory (CDL) for use on the VLA, the VLBA, and for the NASA Microwave Anisotropy Probe (MAP) spacecraft. Little work is necessary to refine these designs for the specific needs of the MMA.

SIS Mixers for use on the 12 Meter Telescope at frequencies from 70 to 300 GHz are also produced as needed at the CDL. However, because the sites under consideration for the MMA are so dry with such little emission from atmospheric water vapor, there are significant gains in sensitivity to be realized if it is possible to provide the MMA with truly quantum-limited SIS mixer receivers. Presently the best SIS receivers have noise temperatures in the range two to four times the photon temperature, hf/k. This receiver noise contribution can be exceeded by emission from atmospheric water vapor in the unwanted (image) sideband and it can be degraded by noise from the local oscillator. The MMA goal is to minimize both these effects through the use of balanced, image-separating SIS mixers.

While most SIS mixer receivers respond to both upper and lower sidebands, few astronomical observations require this capability; most observations seek to employ one sideband or the other. Nevertheless, for a double sideband system the unwanted response of the image sideband adds atmospheric emission to the system temperature increasing the observing time required to reach a given sensitivity. The approach to be taken in design of the MMA SIS mixers is to use micro-fabricated LO or IF quadrature hybrids to combine the signal from a pair of mixers and in and out of phase so as to separate the sidebands.

Local oscillator power is usually coupled into a SIS mixer using a directional coupler or beam splitter. If the signal path loss through the LO coupler is to be kept small, the LO loss will be large, typically 15–20 dB. In addition to wasting LO power, noise from the LO source in the signal and image bands is coupled into the mixer. A balanced mixer minimizes both these effects. It has a separate LO port for efficient coupling to a pair of mixers so that the LO power is reduced relative to the single-ended mixer. Sideband noise is also reduced by phase and amplitude balance through the mixer.

In the MMA Design and Development program a balanced, image-separating SIS mixer will be developed at 230 GHz. The device will be integrated with an HFET IF amplifier for broadband performance. The goal of the work is to demonstrate both that the design approach is sound and to produce an SIS design that can be scaled to all the MMA frequencies at which SIS mixer receivers will be used. The 230 GHz SIS mixer will be incorporated in the prototype receiver that will go on Antenna # 1 in June 2001.

The MMA Design and Development plan provides support to parallel efforts for development of the local oscillator system: a conventional microwave source multiplied by varactor diodes will be designed and built for the 230 GHz band of the prototype receiver and, simultaneously, a photonic system will be built. The photonic approach offers, potentially, greater simplicity and reliability at lower cost but it will require substantial development effort if it is to be adopted for the MMA.

The conventional LO development planned in the MMA D&D phase will be conducted in three phases. First, several 100 GHz phase-locked LO chains will be built and evaluated on the basis of available power, as well as on phase and amplitude noise. Second, the optimum design will be adapted for the specific MMA needs (capable of appropriate fringe rotation, tuning range). The third phase will involve extending the 100 GHz system to 230 GHz through the use of a fixed-tuned, planar varactor frequency multiplier. Fiducial designs for higher frequency bands will follow.

The photonic LO will involve phase-locking the difference frequency of two solid-state lasers operating near 1550 nanometers. As applied to the MMA, the pair of laser signals would be sent along a single fiber (for each antenna) from a central building to the antennas. There the signals would be put into a photomixer with the difference frequency becoming the receiver local oscillator. A contract is in place with the University of California, Los Angeles (UCLA), for development of a velocity-matched traveling-wave photodetector for the WR-10 waveguide band (75-110 GHz). When this is delivered, the complete photonic local oscillator will be assembled and compared with the conventional LO for noise and stability. One of the two approaches will be adopted for the MMA and developed further.

The plans for the MMA correlator development begin with the design and fabrication of an early-generation correlator that can be used with the test interferometer to evaluate the first antenna prototypes and to assess the performance of the initial prototype instrumentation. This is a single baseline cross-correlator, with spectroscopic capability, built around the chip developed for the spectrometer on the Green Bank Telescope.

Design of the MMA correlator itself will begin immediately but it is a much longer term effort. The plan calls for it to be built in a modular form such that it can be delivered one-quarter at a time. This staged delivery not only permits early analysis and debugging of the correlator in an operational setting but it also provides for a realistic appraisal of the controlling software and for an opportunity to use early subsets of the correlator to support interim operations of the array as it is assembled. The basic specifications for the correlator are that it will support:

- 40 antennas;
- eight IFs per antenna (maximum bandwidth per antenna of 16 GHz);
- 4 GHz maximum sampling per IF;

- 2-bit, 4-level sampling;
- 1,024 lags per baseline with a 2 GHz bandwidth, minimum;
- four product pairs (RR, RL, LR, LL) possible for polarization;
- 30 kilometer maximum baseline delay range.

The correlator planning is outlined in MMA Memo 166.

Specification of the appropriate computing environment for the MMA should combine the needs of controlling the instrumentation in real time with the needs of people and hardware to monitor the performance of those instruments and with the needs of the astronomer to interpret quickly the scientific product of the observations. Fortunately, there is an enormous amount of experience at the NRAO and in the community that may be brought to bear on the MMA computing task. The MMA planning emphasizes the need to recruit that expertise.

MMA Memo 164, is a report of the MMA Computing Working Group. It lays out the high level requirements for the computing task. Especially important among the conclusions in this report are these:

- A fundamental product of the MMA will be images, as well as visibility data.
- The astronomer will interact with the MMA by specifying scientific goals, not instrumental parameters.

Both of these requirements demand that the software supporting the MMA have more information available to it than is presently the case with operating radio synthesis arrays. This imposes a burden on the MMA hardware designs in many areas; it also means that the computing system must be capable of evolving as techniques that are useful to the astronomer/users are developed.

In the D&D program the opportunity will be taken to experiment with software tools, techniques, and interfaces on existing arrays through the Millimeter Array Development Consortium (MDC) collaboration, while at the same time sticking to the delivery schedule needed for software for support of early testing at the test interferometer. These early efforts will provide the backbone for development of the MMA computing environment.

Recommended Site for the MMA

Precision imaging at millimeter wavelengths, whether by the MMA or by existing millimeter wavelength interferometric arrays, is limited by atmospheric water vapor. There are two effects. First, emission from atmospheric water provides a *bright* background that limits the ability of astronomers to observe faint sources; absorption of the millimeter wave signals from cosmic sources by atmospheric water vapor further restricts our ability to detect astronomical objects. Second, turbulence in the atmospheric water vapor distorts the images of astronomical sources. Both of these effects can be minimized by locating the MMA where the atmosphere is extremely stable, dry, and transparent.

The MMA will achieve its goal of providing astronomical imaging with a clarity of detail comparable to that of the Hubble Space Telescope when its antennas are arranged over an area at least as large as three kilometers in extent. For the purpose of imaging a large part of the sky at low resolution, the antennas will need to be placed very close together. Thus, the site should be flat enough to allow routine reconfiguration of the forty MMA antennas to provide it with this "zoom-lens" capability. It also should be located where operational infrastructure and logistical support can easily be provided. Over the past decade, candidate MMA sites in the continental U.S., in Hawaii, and in Chile have been investigated and atmospheric tests conducted.

No site in the continental U.S. meets the MMA requirements. The frequent passage of winter storms, combined with the summer incursion of moist, Gulf air, reduces to an unacceptable level the number of days on which observations are possible.

Mauna Kea, on the island of Hawaii, and Llano de Chajnantor, in the Altiplano of northern Chile, both meet minimum requirements for the MMA. However, the extensive site-testing program clearly shows that Llano de Chajnantor is the superior location. The reasons are:

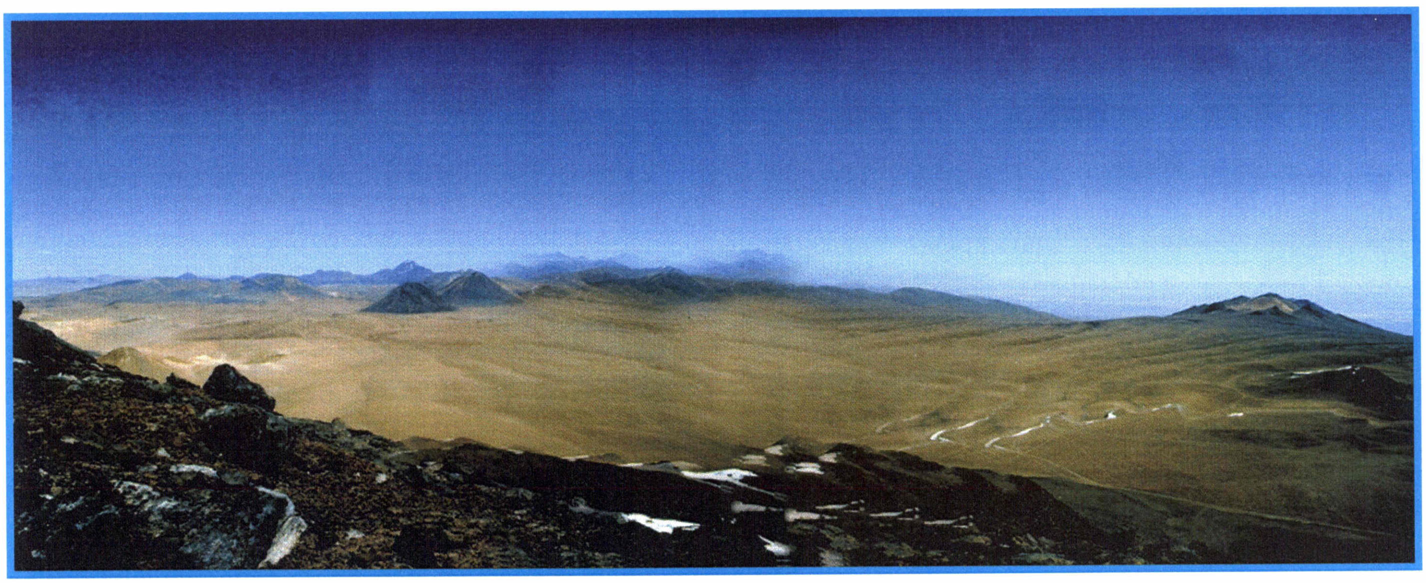
- The Chilean site's atmospheric transmission is so much better that four times as much science can be achieved there as can be accomplished in the same time at the Hawaiian site.
- The greater atmospheric stability of the Chilean site facilitates precision imaging; the combination of superior atmospheric transmission and stability allows the MMA to observe effectively at submillimeter wavelengths on this site.
- Unlike the Hawaiian site, Llano de Chajnantor provides adequate space for expansion to large MMA configurations for still higher resolution imaging in the future.
- The Chilean site can be accessed easily via a major international highway.
- The southern latitude of the Chilean site provides a full view of the entire disk of the Milky Way Galaxy, the galactic center, and the Magellanic Clouds (the galaxies nearest our own).

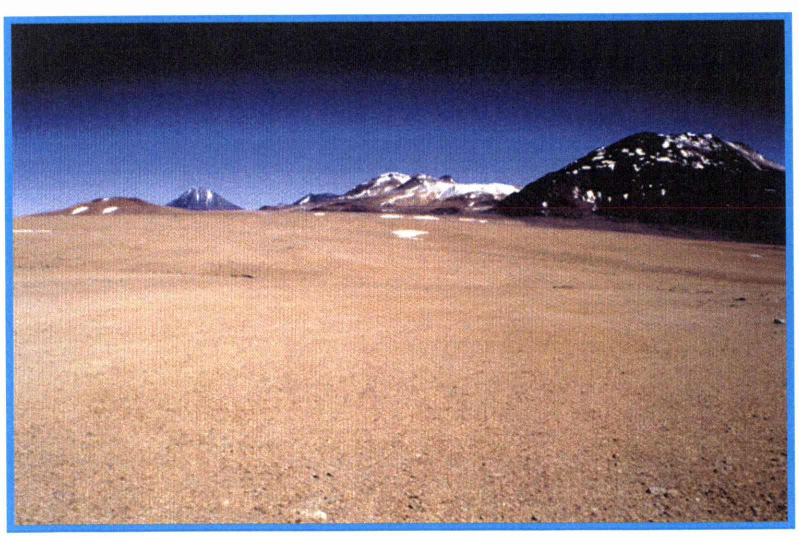
Construction and operating costs at the two sites are estimated to be comparable. Since the MMA's science may be conducted more rapidly, to higher precision, with greater possibility for future growth, and with full access to the Milky Way if the MMA is sited in Chile, Llano de Chajnantor is the superior site for the MMA.

The Llano de Chajnantor site is shown on the mosaic of images, Figure III-3. The layout of four MMA configurations on the site is illustrated in Figure III-4.

Figure III-3. Upper panel: The highway leading to the recommended MMA site. The photo is taken from the MMA site looking north toward Bolivia.

Middle panel: The MMA site; the flat area shown here has an extent of approximately seven kilometers at a mean elevation of 5,000 meters (16,400 feet) above sea level.





Bottom panel: A photograph taken on the site itself.

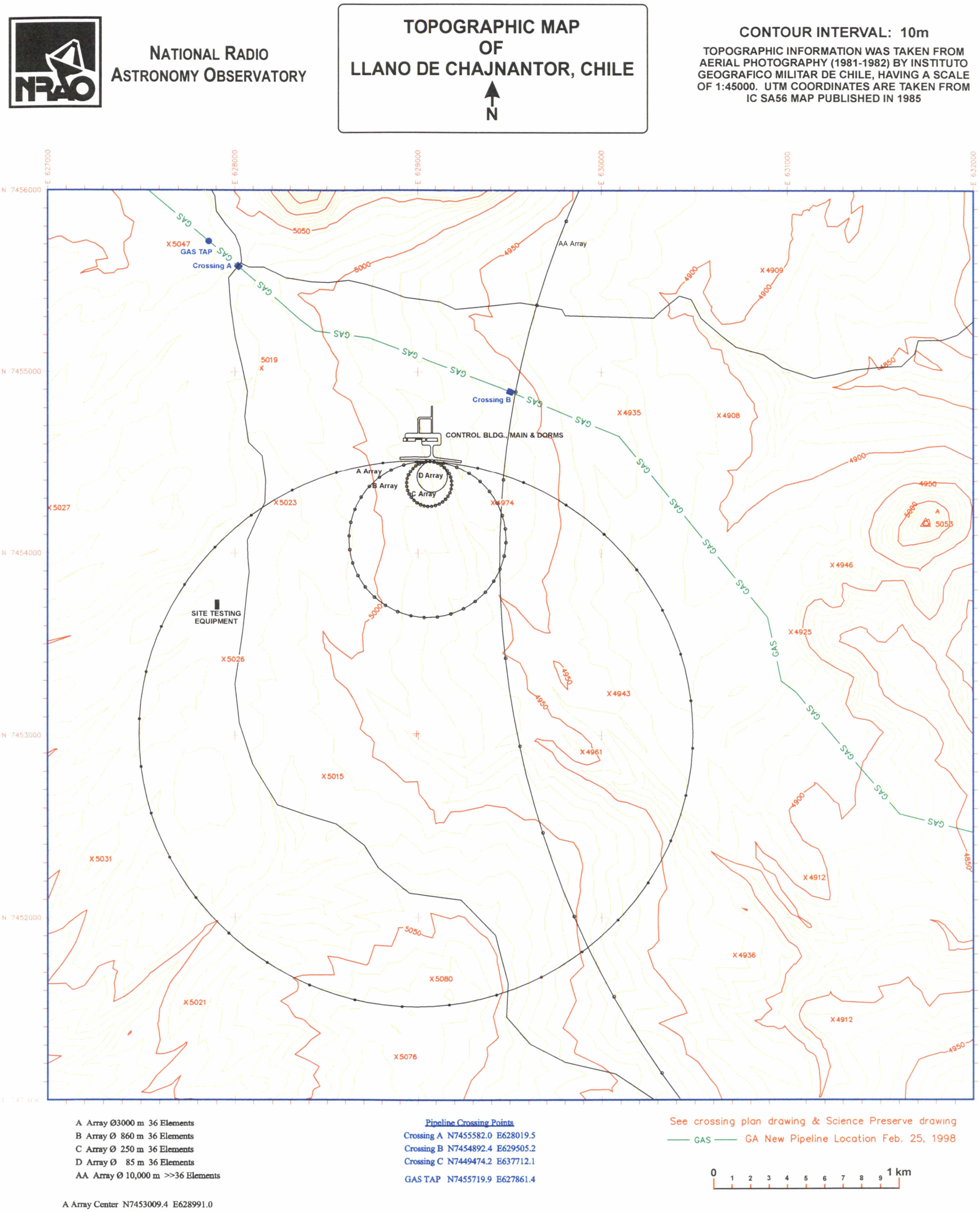


Figure III-4. Illustration of how the four MMA configurations could be arranged on the site. The four configurations are nearly circular with diameters of 85, 250, 860, and 3,000 meters, respectively. Existing roads and the possible route of a gas pipeline across the site are also shown in this figure.

Partnership Initiatives

Two partnership possibilities may have a significant effect on the MMA planning. These are the possibility of joining the MMA with the Japanese project, the Large Millimeter and Submillimeter Array (LMSA), or with the European Large Southern Array (LSA). Both of these initiatives have considerable support among their respective scientific communities and the leaders of both have expressed interest in discussing how their projects could be joined with the MMA to the benefit of all. Either combination with the MMA, or better, a combination of all three, would provide such a truly powerful imaging instrument that the U.S. community has been supportive of efforts by the MMA staff to secure such a partnership. One barrier to a joint project is the dissimilar antenna diameters considered by the three; the MMA has planned 8-m antennas, the LMSA 10-m antennas, and the LSA 15-m antennas. Recent discussions among the three groups have led to successive compromises on the diameter to the range of 10–12 meters. The MMA Design and Development antenna design efforts will therefore focus on antennas of 10-m diameter to facilitate a partnership with one or both of these groups. Should the partnership initiatives fail, the MMA construction budget estimates would allow an array of approximately 36 antennas to be built. Such an array could accomplish all the scientific goals projected for an array of forty 8-m antennas, but would do so with nearly fifty percent more collecting area. This subtle change in the baseline MMA planning is therefore an asset to be used to court partnership with the LMSA or LSA and an asset to the sensitivity of the MMA as a stand alone instrument. Progress in securing partnerships for the MMA, as indeed progress in realizing the technology to achieve the capabilities desired of the MMA itself, begins with the efforts outlined in the MMA Design and Development Plan.

2. The 12 Meter Telescope

The NRAO provides state-of-the-art receivers at the 12 Meter Telescope for all atmospheric windows from 68 to 300 GHz. As new devices and technologies become available, existing receivers have been upgraded to provide the best possible performance. All receivers use SIS junctions. The 8-beam, 1.3 mm SIS receiver system is now fully operational. Construction continues on a new 8-receiver, 4-beam system for 3 mm. This will increase observing speed on point sources by a factor of nearly four, and on extended sources by a factor of nearly eight, compared with the existing dual-polarization, single beam system.

The 12 Meter Telescope is sensitive to molecular line emission from cold interstellar clouds, star forming regions, and aging stars. Such emission can indicate the mass present, its chemical composition, its temperature, and its kinematic properties. These quantities provide essential information on the basic life-cycle of a galaxy – gas to stars, then back to gas. The 12 Meter can study this emission not only in the nearby molecular clouds and stars of our own Galaxy, but also in some of the most distant known proto-galaxies in the Universe. In addition to spectral line emission from molecular clouds, the 12 Meter also observes cold dust from star forming regions and thermal continuum emission from distant quasars and active galactic nuclei.

Studies of the molecular content of galaxies will comprise a significant portion of the 12 Meter research effort in the coming years. Although progress towards the understanding of the process by which stars are formed in molecular clouds in the Milky Way is steady, the analysis is made difficult by the great complexity of the molecular radio emission arising because of the superposition of many clouds in a typical line of sight in the Galactic plane. More and more studies of the physical processes involved in star formation are exploiting observations of the distribution of molecules in galaxies. For the next few years there will be demand on the 12 Meter Telescope to measure the general distribution of molecular gas, with emphasis on the relationship between the molecular gas and atomic hydrogen. Other studies will search for the densest clouds using molecular emission from molecules such as CS, HCO^+, and HCN. A promising approach is to study galaxies currently in the throes of an event, perhaps episodic, in which new stars are formed at a prodigious rate. The galaxies have been identified by their bright infrared emission, and the 12 Meter will be used to make an inventory of the molecular gas from which it is believed the new stars are forming. It is of interest as well, to explore the possible reasons for the onset of this period of rapid formation of stars and a number of avenues will be explored. For example, one theory postulates that star bursts are triggered by the merging of two galaxies, and observations will be made of the strength of the emission of CO as a function of the separation of galaxies in carefully selected pairs.

The field of astrochemistry was pioneered with the 12 Meter (at that time the 36 Foot) Telescope and that area continues as one of the Observatory's most active and fruitful. The detection and study of interstellar and circumstellar molecules provides tests for theories of molecule formation and destruction and new diagnostic tools for the full spectrum of millimeter-wave astronomy. A promising new area of astrochemistry research at the 12 Meter Telescope is the study of refractory and metal-bearing molecules. Chemical models based on cosmic abundances suggest that numerous metal-bearing molecules should be present in detectable amounts in both the interstellar and circumstellar media. Yet, very few such compounds have been found so far. It is hypothesized that most of these molecules may have condensed onto dust grains, but a few refractory species, namely silicon compounds, are found in abundance in the gas phase. The whereabouts of gas phase, metal-bearing molecules is one of the outstanding mysteries of astrochemistry.

One of the most active areas of research at the 12 Meter in the coming years will be wide-field, rapid imaging of both continuum and spectral line sources. New techniques and instruments will facilitate such research. Specifically, the on-the-fly observing mode is available both for continuum and spectral line observations, for single-beam and for multi-beam systems. In this mode, data are taken continuously while the telescope is scanned across a source, which is a much more efficient mapping mode than the traditional step and integrate technique. The on-the-fly technique is currently the primary observing mode for the 8-beam receiver, and will probably become the main observing mode for the 8-receiver, 4-beam, 3 mm system currently under construction.

The existing 12 Meter Telescope hybrid correlator spectrometer is now more than ten years old. It supports 8-beam multi-feed operation, operating then as eight independent spectrometers. Unfortunately in this mode, each IF is limited to a total instantaneous bandwidth of 300 MHz, which at 1.3 millimeters is inadequate for most extragalactic observations. Further, the specific hybrid design can cause defects in spectral baselines related to the segmentation of wide bandwidth observations into 37.5 MHz sections. This is particularly true under poor weather conditions, NRAO owns sufficient spare VLSI chips from the GBT correlator design, that a new, higher performance correlator has been built as a replacement. This gives the 12 Meter the capability of several thousand channels per IF for an 8-receiver system, with an instantaneous bandwidth of up to ~1 GHz per IF.

Finally, a real-time link now exists between the 12 Meter Telescope and the Kitt Peak VLBA antenna. The link allows the 12 Meter to receive the maser local oscillator signal from the VLBA control room, and allows it to transmit an IF signal back to the VLBA tape recorder. This link greatly reduces the work involved in configuring the 12 Meter for millimeter wavelength VLBI observations. Routinely scheduled VLBI sessions now take place.

Future Plans

In the period of this Long Range Plan, the 12 Meter Telescope and the Tucson staff will play a growing role in the development of the Millimeter Array. As the MMA project develops, there will be the necessity for real hardware design, prototyping, and testing, including multi-band, millimeter, and submillimeter-wave receivers, digital spectrometers, and continuum backends. The 12 Meter Telescope will serve as a testbed for these developments, and the prototype MMA instrumentation will be used by visiting observers as one important step in the evaluation process.

Specific instrumentation plans for development of MMA hardware include the following:

- evaluation of the prospects and penalties of a high frequency IF on the performance of SIS receivers;
- assessment of the practical utility of MMIC devices as a LO source at frequencies at and below 115 GHz;
- design and prototype of a phase-locked laser local oscillator system;
- experimentation with a wideband HFET as a fundamental amplifier at 3 mm wavelength for continuum observations;
- design of a wideband digital autocorrelator for use with multi-beam receivers.

IV. VERY LONG BASELINE ARRAY

Status

The Very Long Baseline Array (VLBA) is operational in all its major observing modes. It is routinely scheduled in response to observing requests that are received at three proposal deadlines annually (1 February, 1 June, and 1 October). The VLBA supports Global VLBI Network sessions interspersed during the year among the scheduled VLBA-alone observing, and it supports observations with the Japanese orbiting radio telescope HALCA. The VLBA is oversubscribed by a factor of two to three each year.

Among the principal reasons the VLBA was built was to provide high fidelity imaging on milliarcsecond angular scales. Prior to the VLBA the *ad hoc* arrays of existing radio astronomical antennas involved in VLBI observations were so heterogeneous in their instrumentation that the astronomer's ability to produce a reliable image was limited by items such as mismatched IF filters, polarization performance, and calibration quality from one antenna to another. The VLBA designed these problems out of the system by constructing an entire system of identical receivers and antennas. That was the theory and that now is the reality.

Space Program

Figure IV-1 is a composite image of the central engine of the active galactic nucleus of NGC 4258. The VLBA was used to image a Keplerian disc of H_2O masers rotating around a super-massive object of 25 x 10^6 $M_\odot$, presumably a black hole. The same data was also used to generate an image of the continuum jet which is seen to lie along the axis of rotation of the disc. This is the most direct evidence to date for the standard model of active galaxies proposed by theorists in its original form nearly 20 years ago.

Monitoring of the H_2O maser emission will enable astronomers to measure the proper motions of the maser spots and hence determine a very precise geometric distance. Monitoring of the continuum emission will enable an examination of the physical processes occurring very close to a super-massive black hole (see Figure IV-1a).

For objects still closer to us, such as stars in the Milky Way, the angular resolution of the VLBA corresponds to astronomical-unit length scales. Figure IV-2 illustrates the ability of such incredibly high resolution for explorations of stellar physics. This figure shows VLBA spectral images of SiO emission from the AGB star TX Cam.

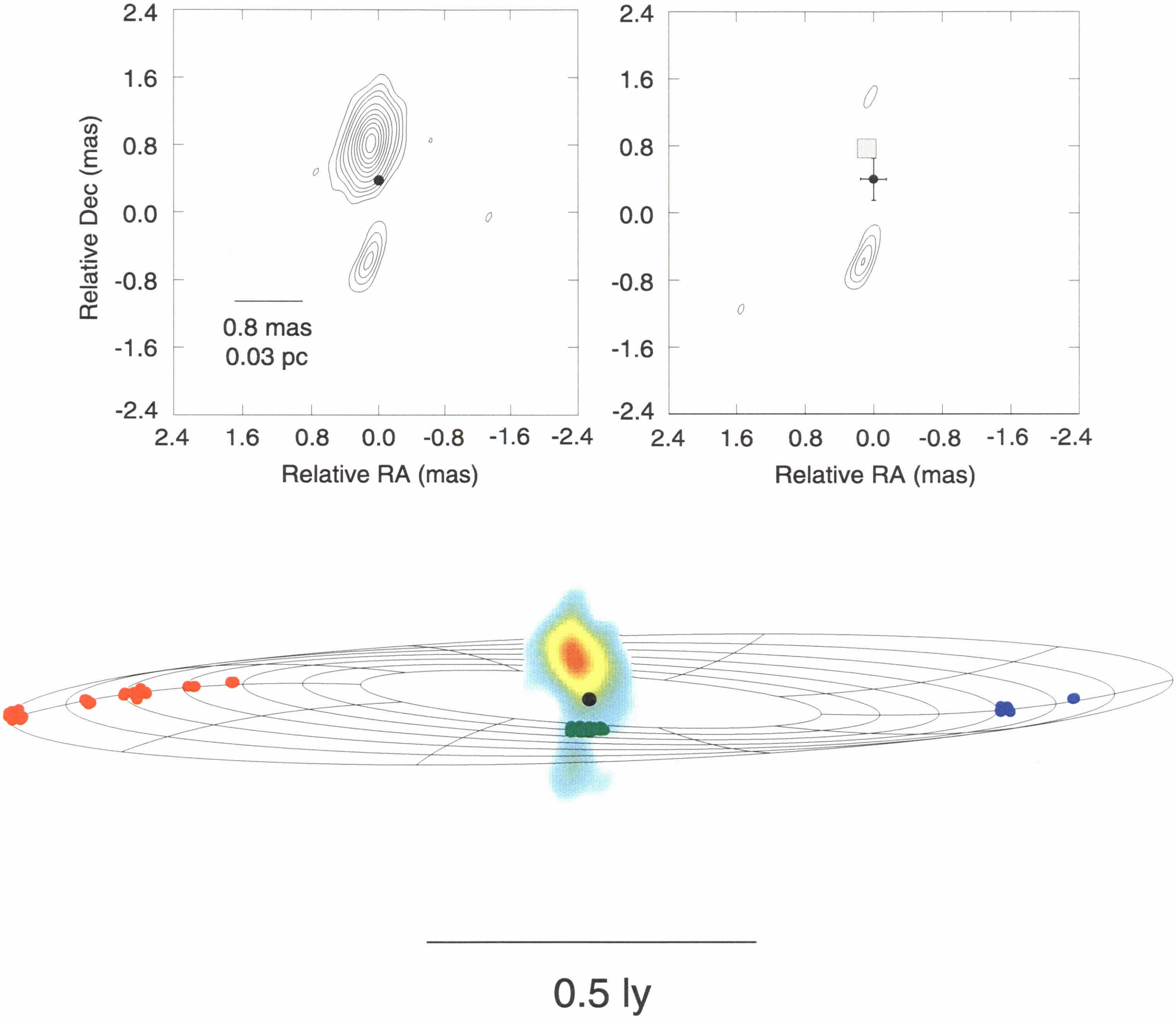
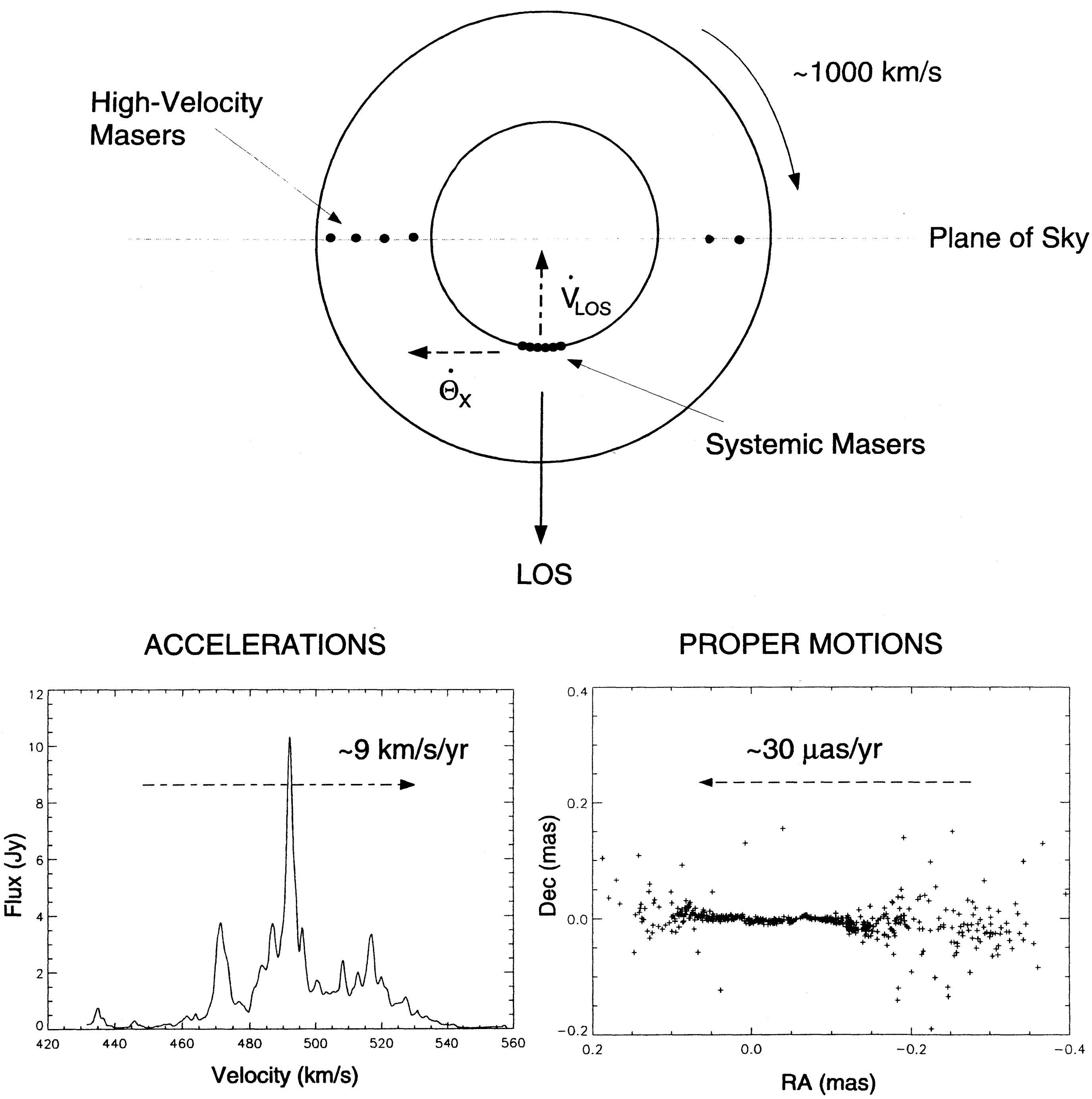


Figure IV-1. VLBA images of the maser emission from the nucleus of NGC 4258 reveal a subparsec-scale, thin, warped disk around a 25 million solar mass black hole. The masers are shown superposed on the best-fitting disk model in the bottom panel. VLBA continuum observations also reveal subparsec-scale jet emission along the rotation axis of the disk (upper left and bottom panels). There is no continuum emission at the location of the black hole (upper right panel - this is the same image as the left panel but with the northern source subtracted), and this has important consequences on models of AGN accretion.



$$(\dot{V}_{LOS}) \cong \frac{[V_{ROT}]^2}{[\Theta_R]D} \qquad (\dot{\Theta}_X) \cong \frac{[V_{ROT}]}{D}$$

( ) : OBSERVABLE

[ ] : MODEL DEPENDENT

Figure IV-1a. Schematic description of the manner in which multi-epoch VLBA observations of the rotating disk in NGC 4258 can be transformed into a highly accurate geometric distance to the galaxy.

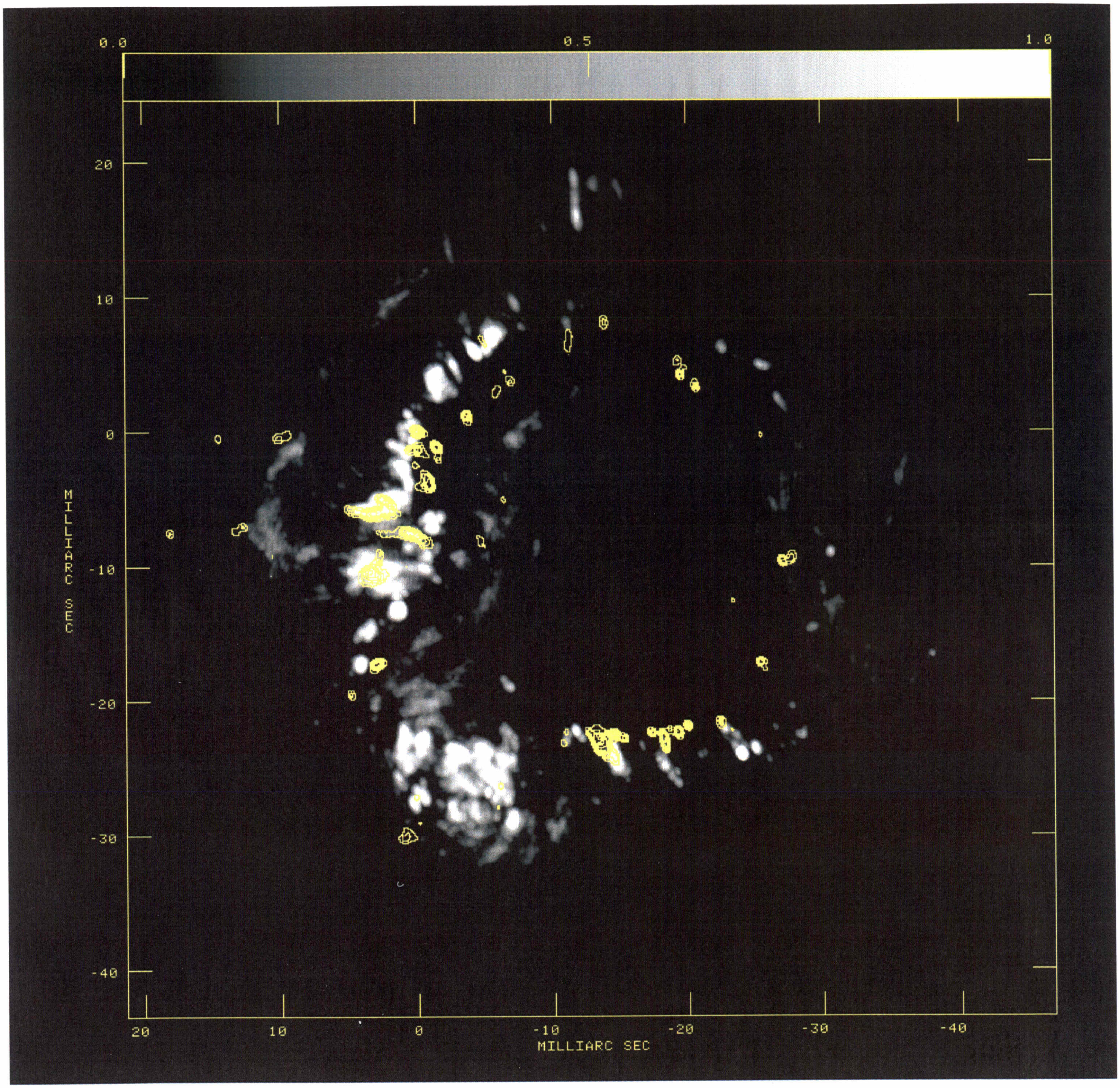


Figure IV-2. VLBA spectral images of SiO emission from the AGB star TX Cam.

These images were obtained as part of a monitoring program of the SiO masers aimed at the study of the maser proper motions and variations in the magnetic field structure. The contours show the emission as it was on 24 May 1997, the grayscale shows the emission six months later, on 21 November 1997.

As can be clearly seen, the ring of masers has expanded dramatically, the ring diameter increasing by about 0.6 astronomical units. The structure of the maser emission has also become much more complex with clear indications of more than one ring of masers. Observations intermediate to the two images shown here reveal that many of the maser spots are moving outwards with a velocity of approximately 3.6 km/s. This is consistent with the hypothesis that the mass-loss is initiated by shock waves originating inside the star. The monitoring observations are continuing and will follow the maser emission through the full 557 day cycle of TX Cam.

After many years of searching, the radio afterglow from a gamma ray burst (GRB) was detected from GRB 970508 by Frail and his colleagues with the VLA on 13 May 1997. Besides confirming a prediction of the fireball model—GRBs come from the collision of two neutron stars—the fluctuations of the source strength in the radio (twinkling due to interstellar scintillation) allowed Frail et al., to measure the size and expansion velocity of the fireball. The small size was confirmed by VLBI observations on 16 May 1998 (see Figure IV-3). A series of VLBI observations allowed Taylor et al., to demonstrate (via parallax) that the distance to GRB 970508 is greater than 1 kiloparsec, fully consistent with the cosmological distance of the source.

Present Instrumentation

The VLBA is a dedicated instrument for very long baseline interferometry. The ten antennas are distributed about the United States in a configuration designed to optimize the distribution of baseline lengths and orientations (u-v coverage). Baselines between 200 and 8,000 km are covered, which provides resolutions up to 0.2 milliarcsecond at 43 GHz. The shorter baselines, and hence the highest concentration of antennas, are near the VLA for optimal joint observations and to allow for a future project to fill the gap in the range of baselines covered by the two instruments. The antennas are 25 meters in diameter and of an advanced design that allows good performance at 43 GHz and useful performance at 86 GHz. The antennas are designed for remote operation from the Array Operations Center (AOC) in Socorro. Local intervention is only required for changing tapes, for maintenance, and for fixing problems.

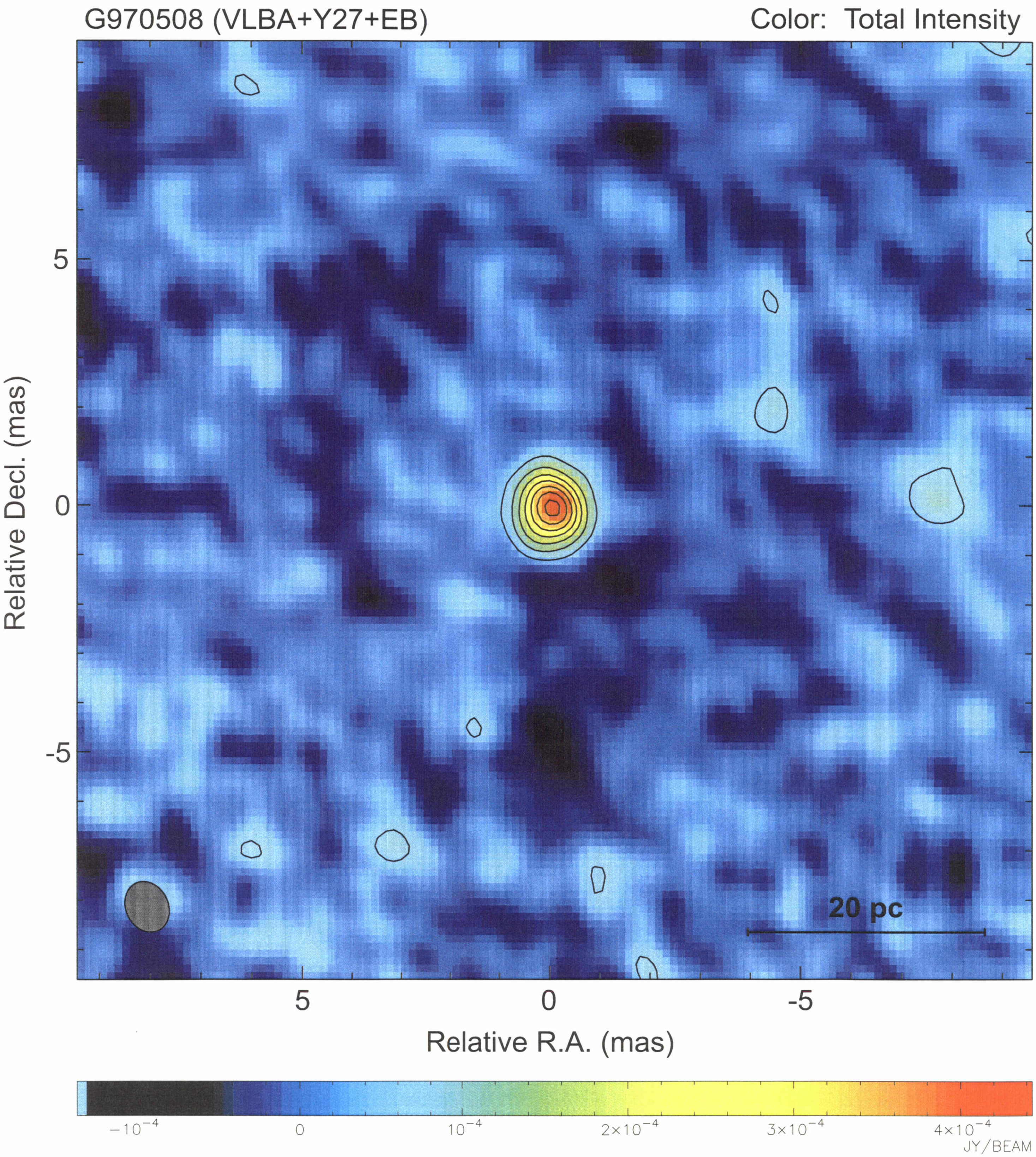


Figure IV-3. First VLBI observations of the radio afterglow from a gamma ray burst. This image of GRB 970508 was obtained a few days after its discovery with the VLA and shows the afterglow to be very compact (size less than 1 milliarcsecond).

Table IV-1. VLBA Receiving Systems

Wavelength (cm)	Frequency Range (GHz)			Aperture Efficiency (Note 1)	System Temp [K] (Note 2)
90	0.312	-	0.342	0.45	195
50	0.580	-	0.640	0.40	200
20	1.35	-	1.75	0.57	32
13	2.15	-	2.35	0.50	34
6	4.6	-	5.1	0.72	40
4	8.0	-	8.8	0.70	35
2	12.0	-	15.4	0.50	73
1	21.7	-	24.1	0.60	100
0.7	41.0	-	45.0	0.45	100
0.3	86	-	91	0.1	150

Notes:
1. Overall aperture efficiency and total system noise temperature at zenith. Values are representative of those measured on several VLBA antennas.
2. Single-frequency performance (without dichroic) shown.

The VLBA is outfitted for observations in ten frequency bands as shown in Table IV-1. All receivers are dual polarization. The receivers at 1.4 GHz and above contain cooled HFET amplifiers from the Central Development Lab (CDL). The low-frequency receiver is a room temperature GaAsFET. The cooled receiver for each band is in a separate dewar mounted directly on the feed to minimize noise contributions from waveguides, etc. All receivers cover both right and left circular polarization. The VLBA requires highly accurate frequency standards and a wide-bandwidth recording system at each site. The VLBA sites use a hydrogen maser manufactured by Sigma Tau Corporation for the frequency standard. The recording system is based on a Metrum (formerly Honeywell) longitudinal instrumentation tape recorder that has been extensively modified by the Haystack Observatory. The recorder is similar to the one used in the Mark III and Mark IV VLBI systems. There are two drives at each VLBA station to allow more than 20 hours of recording at 128 Mbits/second between required visits to the station for tape changes. The tapes are 16 microns thick, with about 3.4 miles of tape on a 14-inch reel.

The VLBA correlator is located at the AOC in Socorro. It is able to correlate as many as eight input data channels from each of up to twenty sites. For most modes, 1,024 spectral channels can be provided for each input channel. The correlator is of a novel design, pioneered by the Nobeyama Radio Observatory in Japan, in which each bit stream is Fourier transformed to a spectrum before cross correlation (the *FX* architecture). Output data is archived on DAT tapes, while the input tapes are recycled for more observing shortly after correlation. Users receive their correlated data in FITS format on any of several media, including DAT and EXABYTE tapes.

VLBA postprocessing is done in the astronomical image processing system (AIPS). Software development for VLBI in AIPS is essentially complete, apart from support for some advanced capabilities of the array such as polarization calibration, utilization of the pulse calibration system, and Space VLBI. Astrometric/geodetic processing will be done primarily in the system developed by the Crustal Dynamics Project, now Dynamics of Solid Earth (DOSE), at NASA. Over the next few years, the post-processing will shift to the AIPS++ system as that system acquires the necessary capabilities. The in-house computing for the VLBA is done mainly on workstations of the SUN Ultra class.

Space VLBI

The NRAO provides support for the joint NASA-NSF initiative in space VLBI. Specifically, the VLBA is used as one ground radio telescope array to provide co-observations with the HALCA spacecraft; as much as 30 percent of the time that the VLBA is scheduled for scientific observations may be devoted to support of the peer-reviewed HALCA general observing program. HALCA is an 8-meter diameter radio telescope that is pioneering the concept of space VLBI; it is a mission of the Japanese Institute of Space and Astronautical Science (ISAS). All of the data taken by the VLBA in conjunction with HALCA are correlated at the VLBA correlator in Socorro and scientists using HALCA/VLBA data have access to NRAO support personnel and computational facilities at the AOC established for this purpose with NASA funding.

The HALCA science data are telemetered in real-time to the Earth at one of five tracking stations. Three of the tracking stations are at the DSN sites (Goldstone, CA; Canberra, Australia; Madrid, Spain), the fourth is the Japanese tracking station at Usuda, and the fifth is operated by the NRAO with NASA funding in Green Bank. The mission of the tracking station is not only to record the science data but also to transmit to the spacecraft a precise frequency standard and to measure the time-delay of the signal from the spacecraft to the ground. The latter is used by the mission orbit determination group to reconstruct the satellite orbit and by the correlator to center the astronomical fringes in the correlator delay window.

HALCA was launched in the spring of 1997 and is now in routine science operations. Scheduling of all mission elements, including the VLBA programs on HALCA, is done by the mission operations group at ISAS in Tokyo. Optimum scheduling of the science observations is complicated not only by the usual constraints that accompany a space mission—the need to avoid pointing the telescope near the sun, the need to keep the sun on the solar panels—but in addition, for an interferometry mission one would like the plane of the orbit to be nearly perpendicular to the Earth-source direction so that one achieves the longest projected baselines. These requirements not only restrict the sources visible at any time but they also mean that the imaging, the uv-coverage on any particular source, changes continuously. It is not possible to repeat an observation in detail on timescales separated by weeks or months. Nevertheless, HALCA is producing very interesting VLBI images, an example of which is shown in Figures IV-4 and IV-5.

Figure IV-4 shows the uv-coverage of a HALCA plus VLBA observation of the quasar 1156+295. The inner points, those less than 50 million wavelengths, are the tracks of the interferometer pairs on the ground; the outer tracks are the correlations with the spacecraft. The image made from these data is shown in Figure IV-5. The left panel of this figure is the image made with the ground (VLBA) antennas only; the right panel is the image made by including the ground-to-space baselines. One can see clearly the expected gain in angular resolution realized by having baselines twice as long as the ground-only array provides. Scientific analysis of this and other HALCA images is in progress.

Within the timespan of this Long Range Plan we can expect to see considerable progress and interest in HALCA observations and we expect that the next generation space VLBI spacecraft, the Russian RadioAstron spacecraft, will also contribute to this new realm of VLBI radio astronomy.

Future Plans

For the immediate future, much of the available effort will be focused on obtaining the full potential efficiency of the correlator and improving the antenna performance. The VLBA is capable of correlating data from the 10-element VLBA at four times faster than real-time in certain cases. Attaining this level of efficiency requires fine-scale debugging of the correlator real-time software and streamlining of correlator operations. All major modes of the correlator are now supported by the software; they have been tested and they are being used in science observations. The newest function, pulsar gating, was implemented in March 1998. Correlation of space VLBI data has now been routinely demonstrated. In the longer term, over the period of this Long Range Plan, emphasis will be given to improving our knowledge of the array geometry, to enhancements in high frequency observing capabilities, and on routine production of Space VLBI data from the VSOP/HALCA mission.

The performance of the VLBA as a geodetic/astrometric instrument is being tested and improved as the geodesy community works toward their goal of station motion measurements accurate to one millimeter per year. Most of these projects will not involve significant funding. Some hardware may be needed; for example, tilt meters may be needed on the antennas to improve pointing.

A vital continuing project is to make the VLBA phase stable. With a connected element array such as the VLA, the phase of the array elements is found by observations of phase-calibration sources of known structure. This allows images to be made without using the self-calibration techniques upon which VLBI normally depends. Weak sources, which require coherent integrations over the whole time of an experiment and over all baselines, can thus be observed, and imaging of complex sources is simplified. Accurate relative positions can be measured which allows for proper motion and parallax studies and for alignment of images made at different frequencies or different times. If phase calibration using nearby calibrators can be used on the VLBA, it will have a major impact on the science that can be done. The success of phase-calibration for the VLBA depends critically upon the accuracy of the geometric model for the array, the earth, and the celestial sources. A simple geometric model can be used to extend the phase-coherence time from tens of minutes up to several hours. Recently we achieved full phase coherence by using a more complete and accurate geometric model based upon extensive geodetic and astrometric observations, and the task now is to make this capability a routine function for VLBA users.

One of the major advantages of the VLBA over the older VLBI Networks is its ability to work at high frequencies. The antennas were designed for good performance at 43 GHz, and receivers for that frequency have been installed and are working well. The antenna structures were designed to work to 86 GHz, and the surfaces were configured as well as possible within the technologies used, to permit observations at this frequency. Present measurements gave an efficiency near ten percent at 86 GHz. We installed one 86 GHz receiver at Pie Town in the last quarter of 1996, and a second will be installed at Los Alamos in April 1998. Fringes were found between Pie Town and Haystack at 86 GHz early in 1997. The completion of this project will double the maximum angular resolution of the instrument and make the VLBA the instrument of choice for high-resolution observations at the longer millimeter wavelengths.

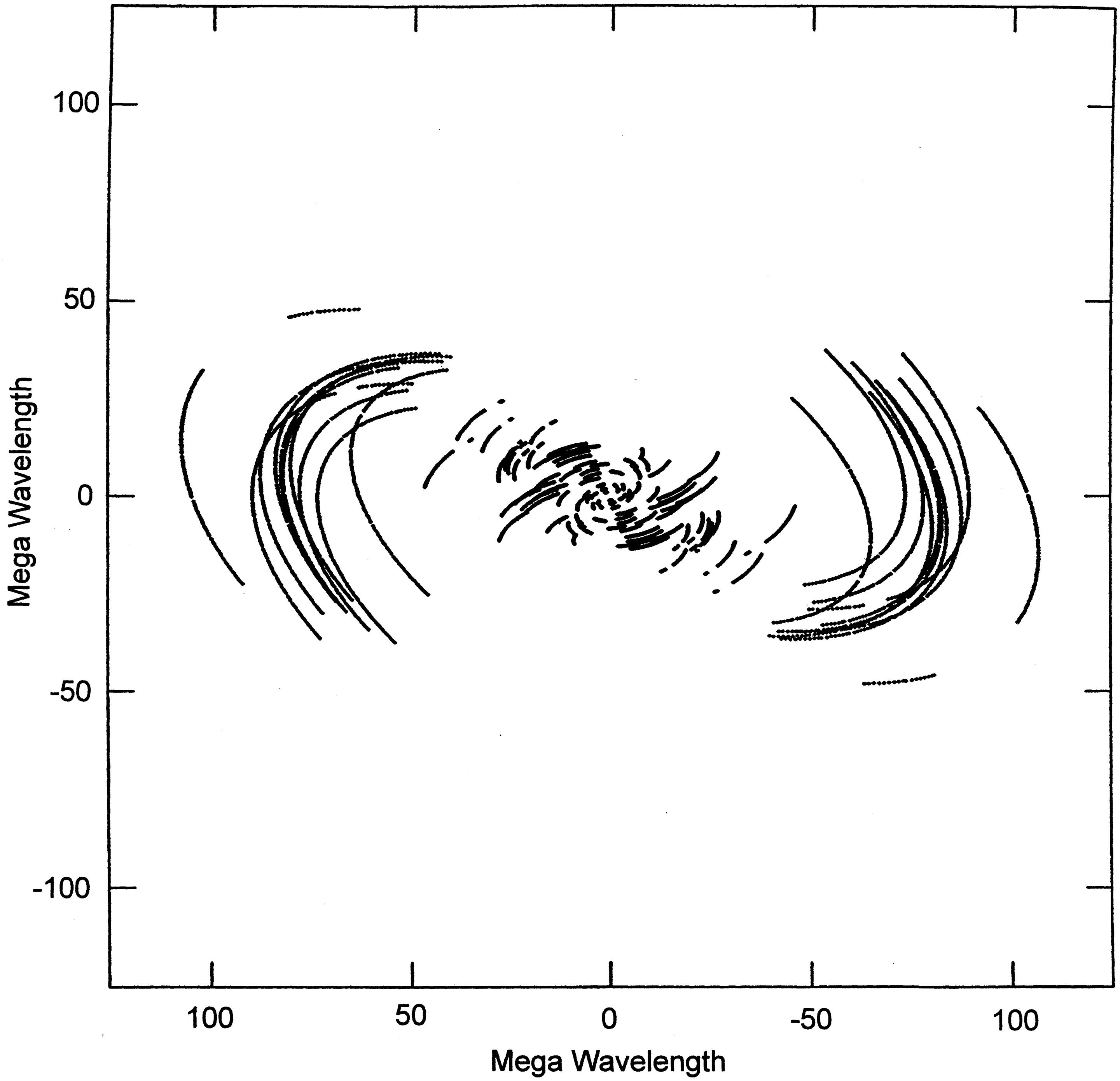


Figure IV-4. The uv-coverage of the HALCA+VLBA observation of the quasar 1156+295.

1156+295: First VSOP Image with Structure In-Orbit Test Observation

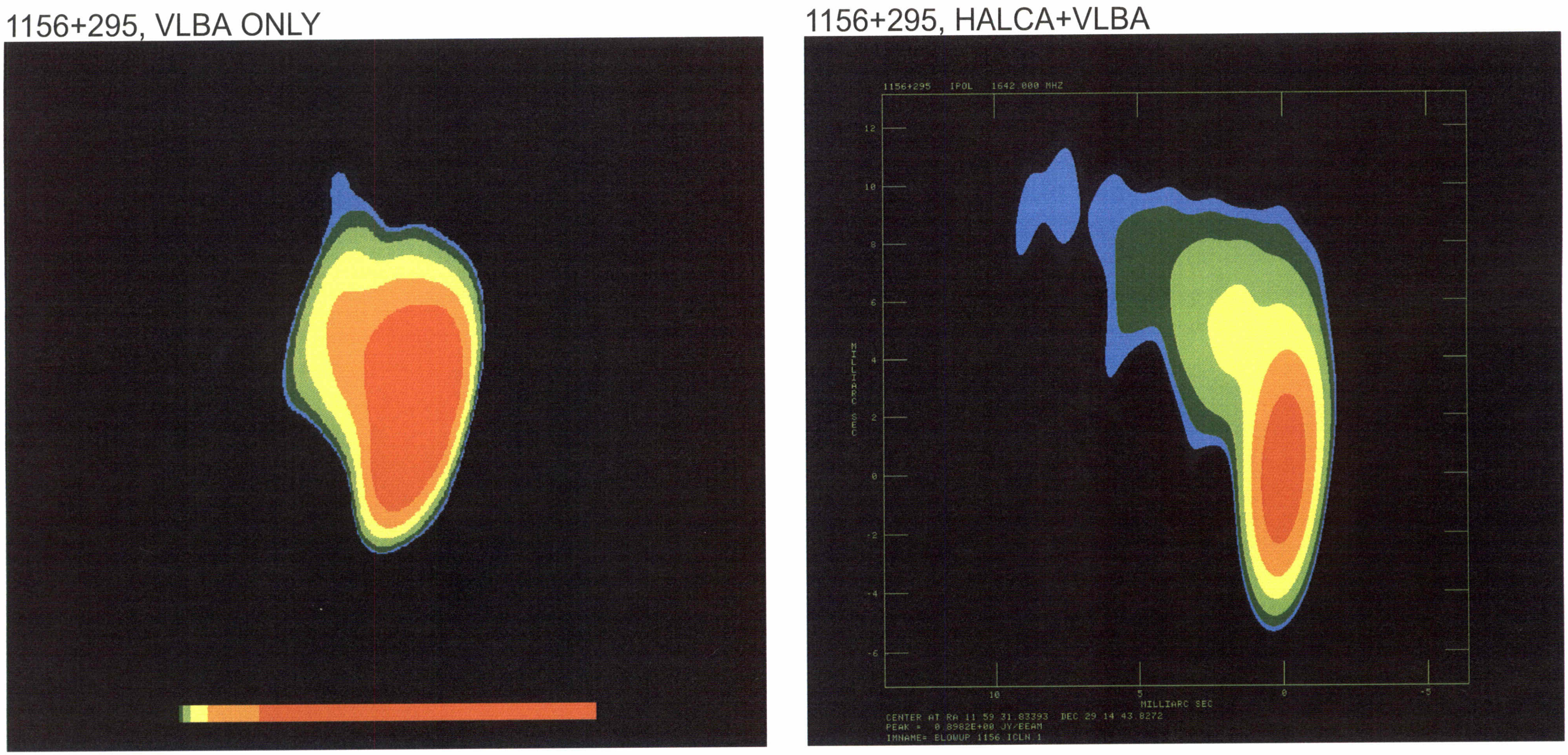


Figure IV-5. Left panel: image of the quasar 1156+295 made at 1665 MHz with the VLBA. Right panel: same image as on the left except that interferometer baselines between the VLBA antennas and the spacecraft have been included; these longer baselines provide the higher angular resolution apparent here.

A number of other technical developments are scheduled for the period of this Long Range Plan. For sensitivity-limited observations, the instantaneous recording rate of the VLBA can be doubled for a short period of time by recording simultaneously on both tape drives. This will be accomplished by means of an enhancement to the correlator software, and is expected mid-1998. All developments will involve substantial testing before they can be made available for routine observations.

At its shortest operating wavelength of 7 mm, the VLBA operates at resolutions as low as 0.0002 arcsecond (0.2 milliarcsec), and is by far the highest resolution imaging instrument in the world making astronomical observations in any wavelength band.

Through the NSF MRI program we have proposed to equip the VLBA and other radio telescopes with receivers to cover the 3.6 mm wavelength band. This will improve the angular resolution to 0.0001 arcsecond for the investigation of compact continuum emission from quasars, active galactic nuclei (AGN), gravitational lenses, and a variety of radio stars, as well as allow the imaging of highly excited silicon monoxide (SiO) and methanol (CH_3OH) masers which are found around late type stars and in HII regions. At typical galactic distances (1 kpc), the corresponding linear resolution is about 0.1 AU; while for nearby galaxies it is a few light days and even at cosmological distances (z=1) only about one light year. At short millimeter wavelengths, the compact cores of quasars and AGN become optically thin, so it is possible to probe much closer to the central engine where relativistic plasma is accelerated and focused into twin narrow beams or jets. The SiO and CH_3OH masers are linearly polarized so high resolution observations are able to probe the magnetic field close to the photosphere where the dynamics and mass loss mechanisms are poorly understood.

A single 3.6 mm receiver, operating in the band 81-91 GHz, has been constructed and installed on the VLBA antenna near Pie Town, New Mexico. Preliminary measurements indicate a zenith system temperature of about 100 degrees and antenna efficiency of 10 to 15 percent. Very long baseline interferometer observations made in conjunction with other millimeter antennas gave encouraging results with coherence times up to 30 seconds. In 1998, we will construct and install 3.6 mm receivers on three additional VLBA antennas.

We will later a) construct and install six additional 3 mm receivers on the remaining six VLBA antennas; b) fabricate and install a 3 mm receiver on a single antenna of the VLA to enlarge the field of view of the VLBA at this wavelength by a factor of ten in area; c) fabricate and install a 3 mm receiver on the 100 m radio telescope located near Bonn, Germany, to enhance the resolution, sensitivity, and image quality of VLBA images; d) fabricate and install a 3 mm receiver on the Green Bank Telescope (GBT) now under construction to further enhance the sensitivity and image quality; e) fabricate a spare receiver to use when one of the other VLBA receivers has been sent to Socorro for repair or adjustment; and f) measure and adjust the surface of the VLBA antennas to obtain optimum performance at short millimeter wavelengths.

This program is being pursued in collaboration with the MPIfR.

Scheduling and Observing

Astronomical observing on the VLBA consists of Global Network projects during the Network sessions and VLBA projects at other times. Global Network observing amounts to about three weeks every three months and is expected to continue into the future. Projects that need more baselines than the VLBA can provide, or that need to use large antennas for sensitivity, will continue to use the Network. Most Network projects use the VLBA, the 140 Foot Telescope, the VLA, and antennas of the European VLBI Network (EVN). Arecibo, NASA's Deep Space Network, and antennas in places such as South Africa, Brazil, Japan, Australia, and China are occasionally used. NRAO, along with the EVN, administers the proposal submission and, along with the Europeans, assesses the Network projects, thus allowing a uniformity with VLA and VLBA projects.

The observing efficiency of the VLBA can be further improved by implementing software that allows the recording of data from multiple projects on a single data tape. Currently, a change in observing programs requires a change of tapes, a function that requires the presence of one of the only two technicians that comprise the entire staff at each VLBA antenna. This software improvement is a high priority and should be completed in 1998.

V. VERY LARGE ARRAY: UPGRADE PROJECT

1. Overview of the Project

The Very Large Array (VLA) is approaching the twentieth anniversary of its dedication. Conceived in the 1960s, constructed during the 1970s, and dedicated in 1980, the VLA is a successful and extraordinarily productive radio telescope. It is used by more than 600 investigators from more than 150 institutions every year. There is every indication that demand for the VLA will continue, owing both to its unique capabilities and to the fact that it provides the radio observations at arcsecond angular resolution needed for the interpretation of observations made at optical, IR, and x-ray wavelengths. Modern technology can vastly increase the capabilities of the VLA and the time has come for us to upgrade the VLA with modern electronics to open up new, exciting avenues of research which cannot be pursued with the current instrument.

Over the years, various upgrades have been made to the VLA. Some of these were designed into the instrument at the outset (the expansion from two to four IFs in 1983 and the expanded support of spectral line modes in 1988). Others arose as an extension of the original design (the 90 cm, 3.6 cm bands, and 7 mm). Still others came from advances in available technology (the 20 cm receiver upgrade).

Even so, the VLA is an aging instrument. Its basic design is based on technology available in the 1970s. Since that time, major technical advancements have been made in receiver components, correlator design, and the transmission of broadband signals, which if implemented on the VLA, would make it many times more powerful.

Despite the fact that the VLA is and will remain for a long time the pre-eminent centimeter-wave radio telescope in the world, it is important to improve its capabilities continuously, both to increase the science the instrument can address, and to ensure that staffing and funding of the instrument remain at the high level needed to support the science potential of the instrument. As summarized below, the capabilities of the VLA can be improved by an order of magnitude or more in resolution, sensitivity, spectral performance, speed, and flexibility, by implementation of new technologies at a capital cost of less than half the construction cost of the array.

2. Technical Summary of the Upgrade

The VLA Upgrade will lead to significant gains in four broad areas: sensitivity, frequency coverage, spectral line capability, and angular resolution. As presently conceived, the following key elements are being considered for the VLA Upgrade:

- Replace most of the VLA receivers to achieve lower noise temperatures with much wider bandwidth (up to 8 GHz/polarization), and add two new observing bands, with a primary goal of obtaining continuous frequency coverage from 1–50 GHz.
- To design a mounting which will permit removal of the subreflector, and installation of up to four prime-focus UHF feeds to cover to 200–1000 MHz range.
- Replace the buried waveguide with a fiber-optics data transmission system to transmit the broadband signals.
- Design and construct a new correlator to process both broadband continuum signals (up to 8 GHz/polarization) and to provide improved spectral resolution and flexibility for spectral line work with up to 2000 channels per polarization product. The new correlator will support a larger number of antennas (≥ 36).
- Add antenna pads in support of a super-compact array, the E configuration, for improved sensitivity to low surface brightness emission.
- Establish a fiber optics link between the VLA and nearby VLBA antennas and add four or more new antennas in order to establish baselines intermediate in length to those in the VLA and VLBA, also linked to the VLA by optical fiber, to give an extended configuration providing about eight times better resolution than the A configuration.

The impact of these improvements on the VLA's scientific capabilities will be enormous. The continuum sensitivity of the instrument will improve by more than an order of magnitude in some bands. New and powerful spectral observations will be possible and new areas of the frequency domain will be opened for exploration. Furthermore, with the addition of new antenna elements, the angular resolution of the VLA can be greatly improved. These improvements will allow the VLA to retain its status as the premier aperture synthesis telescope well into the next century.

Improved Low Noise Receivers

A gradual upgrade to the VLA receiver systems has been going on since the early 1980s. For several years this involved installing better low noise amplifiers in the existing receivers. More recently, a new style receiver was introduced using the VLBA design in which the receiver is attached directly to the feed and the polarizer is cooled in the cryogenic dewar. This reduced the noise contribution from the polarizer and eliminated long, ambient temperature waveguide runs that added to the system temperature.

The VLBA style receivers are now used at 1.4 GHz, 8.5 GHz, 45 GHz, and for the two new 23 GHz receivers on the VLA. These receivers will remain with perhaps only minor modification. The greatest improvement in system temperature can be made in the 5 GHz, 15 GHz, and 22 GHz bands using the VLBA style receivers and modern HFET amplifiers. Completely new receivers will be built for these bands. Implementation of such receivers should reduce the system temperatures at these bands by up to a factor of three.

The new receivers will provide > 1 GHz bandwidth per polarization needed for continuum sensitivity. They also will tune a wider frequency range to permit the study of new spectral lines whose astrophysical significance was unknown when the VLA was first built. The frequency range in the 5 GHz, 15 GHz, and 22 GHz bands will be extended. A redesign of the 1.5 GHz feed will likely be done to permit high sensitivity observations at frequencies below the current limit of ~ 1280 MHz, as this feed's illumination and spillover characteristics are very poor at the low end of L-band.

At present, only thirteen VLA antennas are outfitted for 45 GHz operation; this band would be made available on all antennas as part of the upgrade.

New Observing Bands

Two new receiver systems would be added at the Cassegrain focus 2.5 GHz (S-band) and 33 GHz (Ka-band). These will open new molecular line observations to the VLA, improve rotation measure studies, and permit the VLA to participate in bistatic planetary radar observations with the Arecibo Observatory. The S-band system should be the most sensitive system for study of steep spectrum, nonthermal sources while the Ka-band system will be the most sensitive system for studying sources with spectra typical of optically thick thermal sources. Table V-1 summarizes the proposed frequency tuning range of new and upgraded VLA observing bands at the Cassegrain focus.

Less well defined are prime focus receiver systems. At present, the 300–340 MHz and 73–74.6 MHz systems are located at the prime focus. The current plan is to build a rotating turret at the prime focus, on which would be mounted the current subreflector and four low-frequency UHF feeds, covering approximately the 200-1000 MHz band.

Table V-1. VLA Upgrade Proposed Observing Bands

Band	Range (GHz)	Bandwidth (GHz)	BW Ratio	
L	1.1 – 2.0	1.0	1.8	Upgrade
S	2.0 – 4.0	2.0	2.0	New
C	4.0 – 8.0	4.0	2.0	Upgrade
X	8.0 – 12.0	4.0	1.50	Upgrade
Ku	12.0 – 18.0	6.0	1.50	Upgrade
K	18.0 – 26.5	8.5	1.47	Upgrade
Ka	26.5 – 40.0	13.5	1.50	New
Q	40.0 – 50.0	10.0	1.25	Complete

Table V-2 presents a comparison of the continuum sensitivity of the current instrument to that achievable through the upgrade. Fairly realistic assumptions about usable bandwidth have been made and an atmospheric contribution has been added where relevant. The number under ΔS refers to the continuum sensitivity in μJy/beam achieved in twelve hours integration, summing over two orthogonal polarizations with the bandwidths listed. The current VLA bandwidth is limited to ~ 90 MHz per polarization.

The new observing bands, particularly the continuous frequency coverage shortward of 30 cm wavelength with better than μJy sensitivity will open up the capability of the VLA to study objects emitting much of their energy by thermal processes.

Table V-2. VLA Sensitivity

	Upgraded VLA			Current VLA	
Band (cm)	T_{sys} (K)	B (GHz)	ΔS (μJy)	T_{sys} (K)	$\Delta S_{current}$ (μJy)
90	80–135	0.05	20–35	150	120
50	45–90	0.10	9–18	-	-
30	25–32	0.2	2.7	-	-
20	30	0.5	2.0	33	6.0
11	31	1.5	1.0	-	-
6	29	3.0	0.7	45	6.7
3.6	31	3.0	0.7	31	4.4
2	37	4.0	0.6	110	20
1.3	50–70	8.0	0.9	160	37
0.9	38	8.0	0.7	-	-
0.7	55	5.0	1.7	80	165
0.6	170	3.0	6.0	-	-

The new IF/LO system will allow the transmission of wideband signals, and the wider IF bandwidth will bring with it increased sensitivity.

A New Correlator

The current VLA correlator is limited to a bandwidth of 4 x 50 MHz. A new correlator is needed to process the ≥ 2 GHz of bandwidth and to achieve the increase in continuum sensitivity and instantaneous spectral coverage. Moreover, the current correlator limits the type of science which can be done due to its limited spectral resolution at wide bandwidths. With a 50 MHz bandwidth, the VLA can only produce eight spectral channels in total. With so few channels, wide-field imaging at low frequencies, spectroscopy at high frequencies, and searches for redshifted spectral lines are extremely inefficient. Further, having only two tunable IFs excludes many components of those molecular lines which are split into multiple transitions.

Current specifications for the correlator call for up to 8,000 channels distributed over all Stokes' parameters in up to eight independently tunable sub-bands. This combination should permit avoidance of, and identification and excision of, radio frequency interference. The bandwidth of each channel would be adjustable by factors of two over a wide range, allowing widely variable spectral resolution. The spectral resolution should, at least, be comparable to that of the Millimeter Array, of order 0.05 km/s. This represents a factor of three improvement in the spectral resolution on the smallest bandwidth now available, and an order of magnitude improvement in the largest spectrometer bandwidth now available. The demands of planetary radar may require even finer spectral resolution, as small as 8 Hz.

The new correlator will be capable of processing data from up to 36 antennas and have sufficient delay to accommodate baselines up to 500 km. The correlator could then process some combination of the 27 VLA antennas, two or three of the innermost VLBA antennas (those at Pie Town, Los Alamos, and Fort Davis), and four or more new antennas on baselines between those contained in the VLA and those contained in the VLBA.

Increased Surface Brightness Sensitivity

While the VLA provides four array configurations which cover a wide range of angular scales, the instrument is less than optimum for imaging objects of low surface brightness, often on angular scales comparable to or greater than the size of the primary beam. For resolution corresponding to baselines less than 100 meters, existing or soon to exist single dishes such as the GBT are well-suited to such work. But for resolution intermediate between the VLA D array (1 km) and 100 meters, there is a gap where imaging is difficult and surface brightness sensitivity is a problem. One proposal would move the outermost VLA antennas from the D array closer to the array center and create a new, more compact array, the E array, with a characteristic maximum baseline of 300 meters. At least nine new stations would be necessary.

Such an E array would more than double the number of baselines less than 300 meters. This would not only halve the time needed to reach a given surface brightness but also dramatically improve the uv coverage on such baselines and would make mosaicing practical with beams of four to nine times larger in area than the current D array. The increased brightness sensitivity of the E array will benefit all studies of the galactic interstellar medium as well as studies of extended regions of nonthermal emission such as halos of nearby galaxies.

Increased Angular Resolution

Recognizing that there is a gap in the uv coverage between the maximum baseline lengths sampled by the VLA and the minimum baseline lengths sampled by the VLBA, the addition of antennas to the VLA is an important second phase to the VLA upgrade project. This neglected part of the uv domain—that which is intermediate to the VLA and the VLBA—is currently accessible only to the MERLIN array in Great Britain. With the addition of four or more new antennas, plus the innermost VLBA antennas (at Pie Town and Los Alamos), the angular resolution of the VLA could be improved by an order of magnitude. Its flexibility, sensitivity, and uv coverage would be far superior to MERLIN's.

The new correlator should accommodate up to 36 antenna stations, in anticipation of including the Pie Town and Los Alamos VLBA antennas for some experiments via fiber optics links and with the plan of eventually adding up to seven new antennas.

The increased angular resolution provided to the VLA will principally benefit studies of stellar emission (thermal and non-thermal) and studies of the details of extragalactic radio sources. In the latter case, not only is the resolution needed but so is good imaging capability on the scale of a few to several tens of milliarcseconds. This capability will be provided by the new antennas and complementary observations with the existing VLA and VLBA.

Antenna Improvements

To increase the VLA sensitivity at the highest frequencies, the surface figure of all the antennas will be reset using holographic maps made at the highest (40–50 GHz) frequencies. An example of one VLA antenna which has been so reset is shown in Figure V-1. One panel of this figure shows the holographic surface irregularities before adjustment was attempted; its rms error is 0.42 millimeters. The other panel is the same antenna after adjustment, where the surface rms has

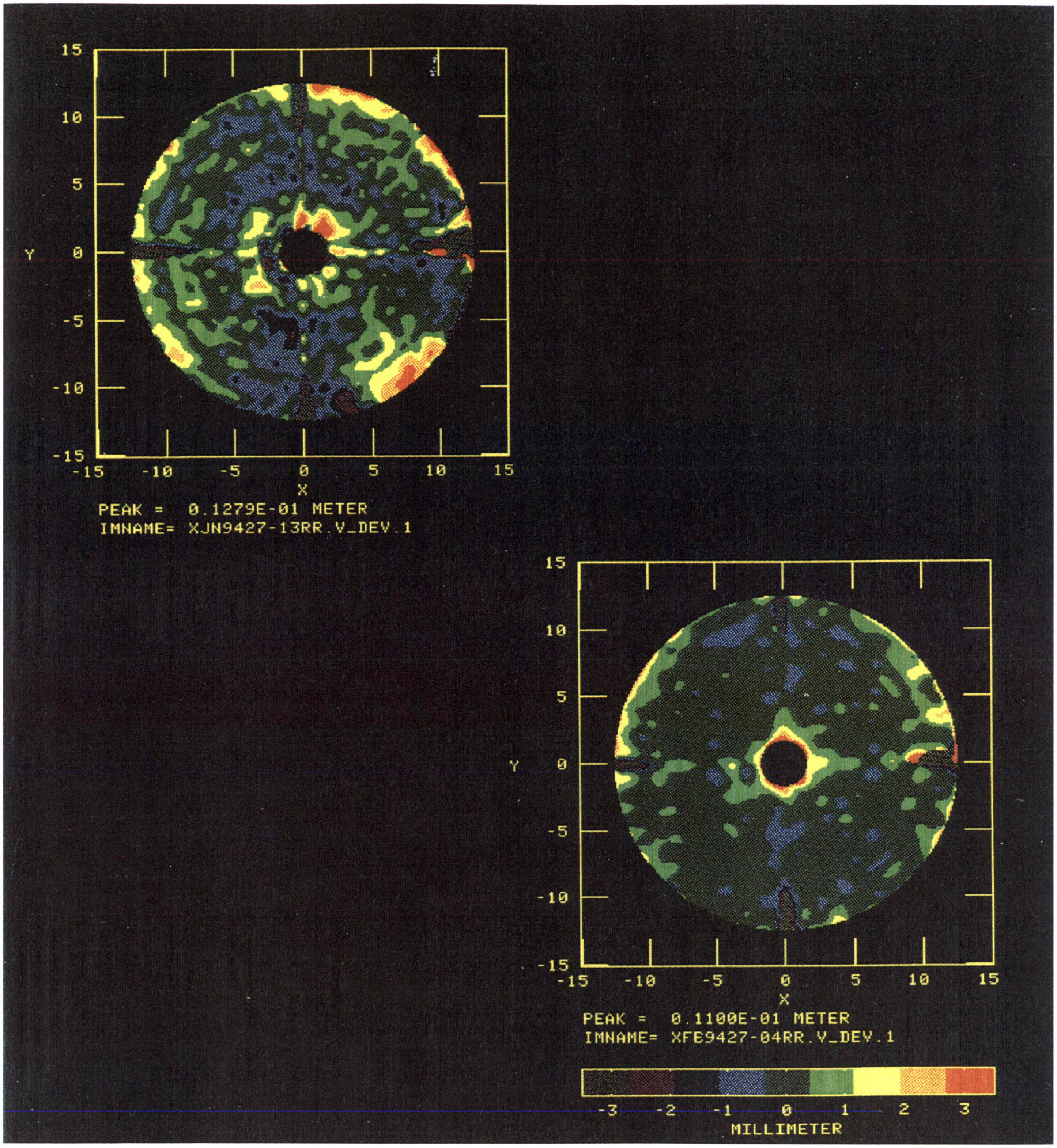


Figure V-1. Holographic maps of the surface of a VLA antenna before and after the surface shape has been adjusted.

been reduced to 0.17 millimeters. If improvements of this magnitude can be achieved on all the VLA antennas, the array sensitivity will be improved by a factor of two and a half and the observing speed of the array will increase by a factor of six at high frequencies. Thirteen antennas (all outfitted at 43 GHz) have now had their surfaces adjusted. The resulting efficiency is 35 to 40 percent.

3. Major Research Instrumentation Program

The NSF has a program whose goal is to permit grants in the $100,000 to $2,000,000 range for improvements to the nation's major research instrumentation. The NRAO is eligible to compete for these grants and has submitted two proposals to this program. The program requires 30 percent of the funding come from a non-federal source.

The first proposal is for $883K to fund completion of the Q-band (43 GHz) receiving system on the VLA. The external partner is the Max Planck Institute for Radio Astronomy in Bonn, Germany. This proposal was not successful in the 1997 application and we have reviewed and re-submitted it this year. The second proposal for $666K is to fund instrumentation to add the VLBA Pie Town antenna to the VLA, using an optical fiber link already in place between the VLA control room and the Pie Town antenna. This proposal was successful and the project is now well underway. The funding partner for this proposal was the State of New Mexico, but a comprehensive bill including the $200K along with many other funding proposals was vetoed by the governor in March 1998. AUI has promised to provide the needed matching funds.

The scientific potential inherent in the Q-band addition to the VLA is illustrated by the image of the star forming in the core of the molecular cloud L1551 (Figure V-2). This image, made with the initial 11 Q-band receivers on the VLA that were provided by the Autonomous University of Mexico, reveals the physical nature of a binary pair of stars still shedding the molecular gas from which they formed.

4. Cost and Schedule

A detailed plan for the VLA upgrade is being prepared in consultation with interested members of the U.S. scientific community. A VLA Upgrade Science Workshop was held in Socorro in January 1995, in order to establish a sound science case for the upgrade. Since then, the VLA Upgrade Project has been formally organized with a Project Scientist and Project Engineering Director. Nine working groups are being appointed and a memo series has begun. The goal is to produce a design study by mid-1998, in time for consideration by the next decadal survey committee. A detailed project review will be held in Socorro in June 1998.

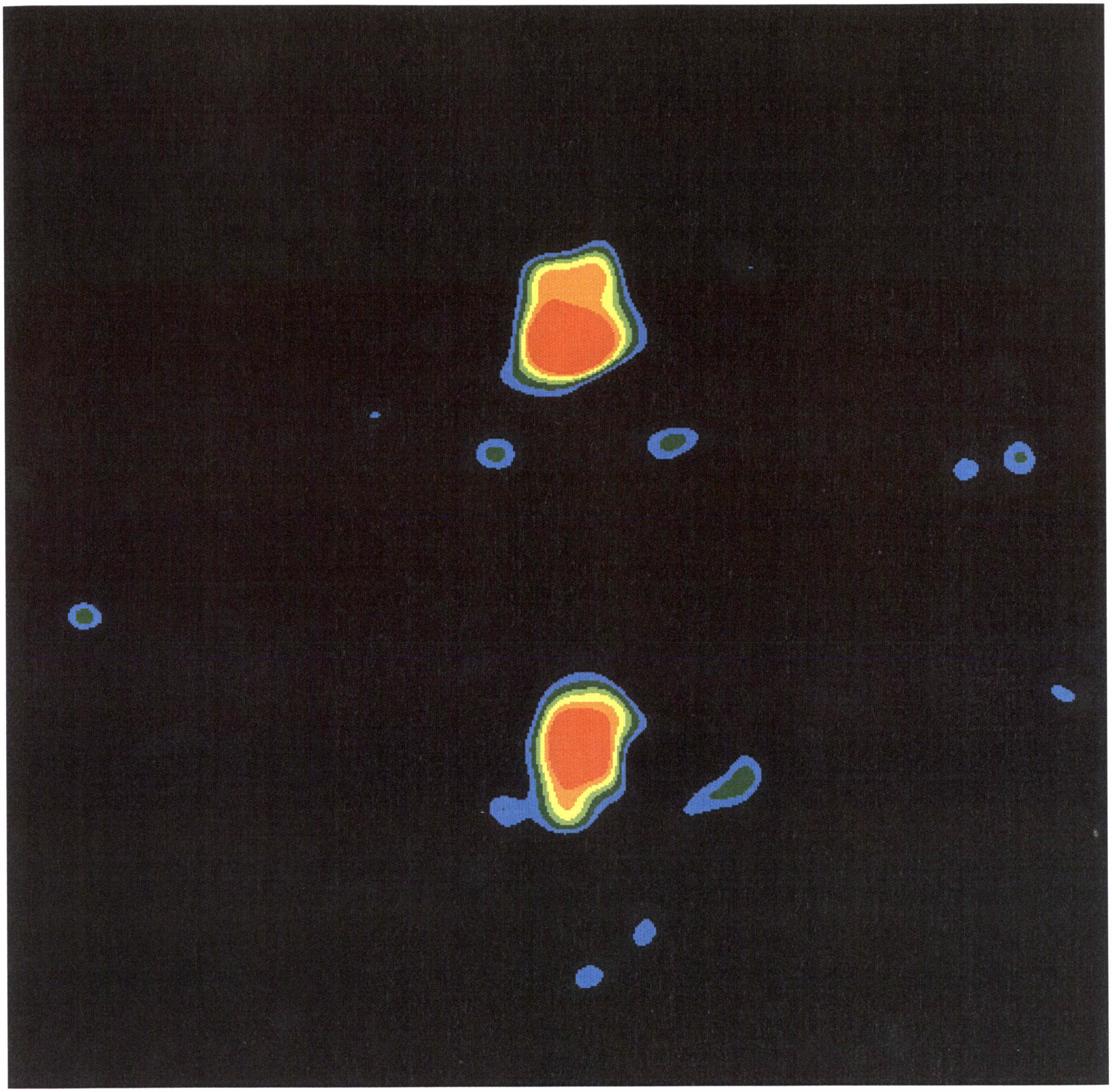


Figure V-2. A VLA image at 7 mm of the core of the L1551 star-forming region. This image, made with an unprecedented angular resolution of 50 milliarcseconds (7 au), reveals the presence of two compact protoplanetary disks around the stars in a binary system. These disks are truncated by tidal forces between the two stars and have radii of only 10 au. This is in contrast with disks around single stars, where radii of 100 au are believed to exist. Although these disks do not appear capable of forming outer planets like Uranus, they have the mass to produce inner planets similar to the Earth.

VI. SOFTWARE DEVELOPMENT AND COMPUTING

1. Overview

Computing lays a vital foundation for scientific research by NRAO users and visitors. Besides the obvious necessity for computer control of the systems that comprise a radio telescope, the use of computers and data reduction systems are essential to translate most of the raw data from radio telescopes into the imagery and other products which lead to scientific results. Significant processing is required before scientific analysis can even begin. In radio astronomy, computer analysis is fundamental to the process, rather than merely being a useful adjunct to scientific analysis. Moreover, owing to the unique application to radio astronomy, the software required for astronomical research must, as a necessity, be written in-house. There are no commercial vendors of radio astronomy research software.

Maintaining observational and scientific capability is the fundamental goal of computing at the NRAO. Staff and visitors at NRAO facilities need access to adequate computing resources, including hardware, software, and personnel support. Constant striving to keep ahead of computing demands at NRAO is essential to meet NRAO's overall goals for supporting astronomical research. Computing systems and software should not be the limiting factor in the science which users are able to accomplish with NRAO facilities. As observational requirements on computing increase (driven by improved observational methods, new technological capabilities, and deepening scientific understanding and knowledge), the Observatory must respond appropriately.

2. Requirements

There are three principal components to computing support at the NRAO. Highest priority must be given to the first area, namely, computing support for instrument control and operations, including personnel, software development, and operations. Of nearly equal importance are the other two components (1) software development and (2) support for the research activities of visitors and users of the NRAO.

Over the next five years, a number of exciting developments at the NRAO will place new demands on NRAO's computing facilities and personnel. Planned instrumental developments and improvements will result in important new scientific capabilities, and will certainly demand improvements in several areas in computing at the Observatory for maximum scientific return.

- The demands of the VLBA will continue to grow in the next five years. Typical data sets are up to several gigabytes in size, resulting in many hundreds of images. There will be hundreds of such data sets produced per year. We will continually work on improvements to the computing facilities to avoid limiting the scientific productivity of the VLBA over the next five years.

- The GBT will become operational. Computer control of the telescope, the actuators, and the receivers is an enormous task. Efforts are underway to insure that software will be in place to handle GBT data reduction.
- Advanced experiments with the VLA are producing one to two orders of magnitude more data than typical experiments during the 1980s. These sorts of experiments strain the processing facilities (both hardware and software) at NRAO sites or at the user's home institutions. In some areas, the NRAO user community is, in effect, self-limiting its use of NRAO facilities and not tackling scientifically important problems because of limited computing resources in the community.
- Array receivers and rapid imaging techniques, combined with high resolution spectroscopy, are revolutionizing single-dish radio astronomy, with data rates two to three orders of magnitude greater than in the past. Careful attention to the software and hardware needs for processing large volumes of single-dish data is needed to prevent limitations on the scientific return.
- Improved scientific visualization techniques needed for dealing with the large data volumes from new instruments and receivers. Personnel limitations have slowed work in this area. Two important problems in visualization are already known: the visualization of three dimensional spectral images, and the visualization of large raw data sets for calibration and editing purposes.
- By the end of the period of this Long Range Plan, the MMA will have begun initial operations. Investments in computing (hardware, software, and algorithms) will be necessary if the MMA is to maximize its science return. Real-time imaging with the MMA is a scientific necessity which requires improvements in hardware and development of new software and algorithms. During the design phase of the MMA, significant development of advanced computing algorithms for imaging is needed to optimize the design of the MMA.
- Plans to upgrade the VLA will result in a dramatic increase in the VLA's scientific capabilities and place heavy demands on computing to handle the increased data rates. Significant software development will be required to take full advantage of the VLA upgrade, especially in the area of wide bandwidth imaging and large field imaging. Some of these areas could benefit the community today; others are needed to optimize the upgrade plans.

Ultimately, scientific computing is driven by the demands of new instruments and new techniques. The developments above are all placing demands on the data reduction facilities at the NRAO and on the personnel involved with software development.

3. Strategy

Computing Hardware

The maximum return from the investment in advanced instruments and facilities at the NRAO will be achieved if adequate investment in computing hardware is maintained. Scientific computers have a useful life of three to five years, due to the rapidly increasing demands placed on computing and the rapid improvements in available computing capability. At NRAO we will need to continue the current process of gradually replacing obsolete computing equipment, resolving problems which developed during the mid 90's due to budget restrictions. The most efficient strategy is one of continual upgrades and improvements. This strategy will allow us to support the current instruments (VLA, VLBA, 12 Meter, and 140 Foot) and also to be prepared for the future instruments: the GBT, the MMA, and the upgraded VLA.

Software Development

The emphasis in software development at the NRAO has been in two areas: operationally supporting NRAO instruments, and developing and supporting software systems for users of the instruments in analysis of their radio astronomical data.

An important focus of the imaging and analysis efforts at the NRAO has been aimed at bringing the AIPS++ software into operation (see below), and building on that to provide advanced capabilities needed in all areas of radio astronomy: connected element interferometers, very long baseline interferometry, single-dish spectroscopy, and single-dish mapping. The Observatory also maintains and distributes packages for data analysis, AIPS, and UniPOPS. Ongoing effort will be directed towards improving algorithms, especially in areas related to advanced interferometric imaging (in support of instruments such as the VLA and the VLBA) and on-the-fly single-dish imaging.

Single-Dish Computing

Developments in single-dish computing over the coming five years will be driven by the needs of the GBT and the 12 Meter Telescope. Both instruments will require the capabilities being developed in AIPS++ to fully support various advanced observing techniques. The long term strategy for single-dish data analysis is clear: single-dish data analysis will be an integral part of the AIPS++

package. The benefit of this strategy is that a synergy between the techniques needed for single-dish and interferometric analysis will develop. For example, both techniques can produce large three-dimensional spectral image cubes, there will be a large similarity in the analysis and visualization methods needed for such images.

VLA Computing

The most urgent need faced by the VLA is for upgrade and replacement of its on-line control system. The current system is almost fifteen years old and is starting to show its age in terms of reliability and high maintenance costs. The replacement, to be implemented over the next few years, will be the minimum to keep the VLA operational, but will also provide the foundation needed for VLA upgrade project in the future.

VLBA Computing

Computing support for the VLBA is focused in two main areas. First, continued development is required in the systems used for the support and operations of the VLBA. The VLBA is frequently used as one part of large, complex experiments involving foreign antennas and for the next few years, the orbiting radio telescope HALCA. Support and processing of these experiments is challenging, and significant software development of the online systems used with the VLBA (especially the VLBA correlator) will increase efficiency and maximize scientific return. Second, as experience with the VLBA continues to mature, advanced imaging techniques with the VLBA will yield important scientific results, algorithm development will be important to securing the best results.

Advanced Projects

The rapid development of computing technology over the past few decades has proven essential to research capabilities in radio astronomy. The pace of development within the computing industry has not slowed in recent years, offering many opportunities for enhanced scientific capabilities. Over the next five years, several emerging technologies promise great benefit to radio astronomy and will prove essential for operation of the MMA and the VLA Upgrade in the next decade:

- Advanced data storage technologies: The growing size of radio astronomy data sets, driven by the spectral line capabilities of both single-dish instruments and interferometers, often swamps current data reduction facilities. Several options exist to ameliorate problems NRAO users face when dealing with large data sets, ranging from improved backup tape systems to advanced multi-terabyte mass storage facilities combined with high speed networking. Over the next five years, given sufficient resources, NRAO will plan and implement storage technologies which both relieve current bottlenecks and also prepare a foundation for handling the volume of data expected from future instruments.

- Multi-processor computing: A significant part of future increases in computing performance will come from computers which implement some sort of multi-processor technology. The upper levels of computing performance are becoming dominated by machines which implement multiple processors, from 4 to 32 or more. This trend is likely to continue, driven by the economic advantages of using highly capable mass-produced processors in a parallel architecture. Software development at NRAO will be required to take full advantage of these machines; this effort should move forward over the next five years, in combination with gradual implementation of multiprocessor machines where needed at NRAO. By 2003, the standard machine that users are likely to need will be a four to eight processor machine with 128 to 256 MBytes of memory, 10 to 20 GBytes of local disk space, and connected through a high speed network to a 10 terabyte mass storage facility, running AIPS++. That class of machine will be part of the way towards what will be needed only a few years later, for dealing with data from the completed MMA.

The AIPS++ Project

The AIPS++ project has the goal of creating an advanced astronomical information processing system for radio astronomy. It is a collaboration between a number of radio observatories, the major partners being the Australia Telescope National Facility (ATNF), the Berkeley-Illinois-Maryland Association (BIMA), the Netherlands Foundation for Research in Astronomy (NFRA), and the NRAO. The project center is at the NRAO Array Operations Center in Socorro.

AIPS++ is now in use at a number of consortium sites for critical purposes: at ATNF for analyzing data from the Parkes Multi-Beam survey, at NFRA as the off-line partner of the new WSRT Telescope Management System, and at Green Bank for engineering support for the construction of the Green Bank Telescope. In addition, AIPS++ is now moving from development into distribution to the astronomical community. This will occur via a series of major releases, starting in late 1998 and followed by one major release per year. As part of this planned release process, beta releases were made in February 1997 and September 1997 to the member sites of the AIPS++ consortium and to a number of external sites. Another two releases are planned for May 1998 and fall 1998. We plan to use these beta releases as testbeds before the first major release. This first public release will be targeted towards astronomical use of the system. To aid and encourage use of the system by code developers, in late 1998 we plan to hold a workshop on how to program inside AIPS++.

The initial capabilities of the released code are targeted mainly towards synthesis processing, but AIPS++ is also in development for use as the prime data reduction facility at the NRAO Green Bank Telescope and the next beta release will contain a package for processing of single-dish spectral data.

Quarterly reports for the AIPS++ Project may be found at the following URL: http://aips2.nrao.edu/aips++/docs/project/quarterlyreports.html. More general information may be obtained from the AIPS++ home page at: http://aips2.nrao.edu/aips++/docs/html/aips++.html.

VII. ELECTRONICS DEVELOPMENT

Instrumentation and electronics development is carried out at all NRAO sites to a certain extent, but the design and evaluation of devices and new instruments that are of potential benefit to the operation or performance of NRAO telescopes are performed primarily at the Central Development Laboratory (CDL). The CDL works collaboratively with the engineering staff at all the observing sites. Much of the electronics development that will be accomplished in the next five years is covered elsewhere in this report in association with the discussion of the long range plans for the individual NRAO telescopes. Specific development work at the CDL will include the following:

- Design and construction of HFET amplifiers;
- Design and fabrication of SIS mixers;
- Development of planar diode frequency multipliers for use in LO sources;
- Development of advanced electromagnetic structures;
- MMA technology development and demonstration tasks;
- Correlators and spectrometers;
- Continued work on new concepts in feed arrays and interference canceling receivers.

HFET Amplifiers

HFET amplifier work has continued with successful development of all InP HFET amplifiers between frequencies of 18 and 110 GHz, and balanced amplifiers using GaAs devices below 1 GHz. Figure VII-1 shows the performance of the space-qualified high-frequency amplifiers developed for the Microwave Anisotropy Probe (MAP) project, compared with the theoretical performance and with the performance of SIS receivers. The highest frequency amplifier developed so far covers the band 75–110 GHz with a noise temperature of 60 K, making it competitive with SIS receivers for narrow-band spectroscopy and surpassing the instantaneous performance of present NRAO SIS receivers for wideband continuum work. This performance has been achieved with InP devices specially fabricated for the NRAO by Hughes Research Laboratories; more than 6,000 such devices are available from the two wafers thus far built for the NRAO and another 40,000 were made for the MAP project. The MAP devices have a surface passivation layer which makes them unusable above about 90 GHz, but they will suffice to provide gain below that frequency. Since many NRAO 50 μm devices were used in the highest frequency MAP amplifiers, it will be necessary in the future to obtain another unpassivated wafer.

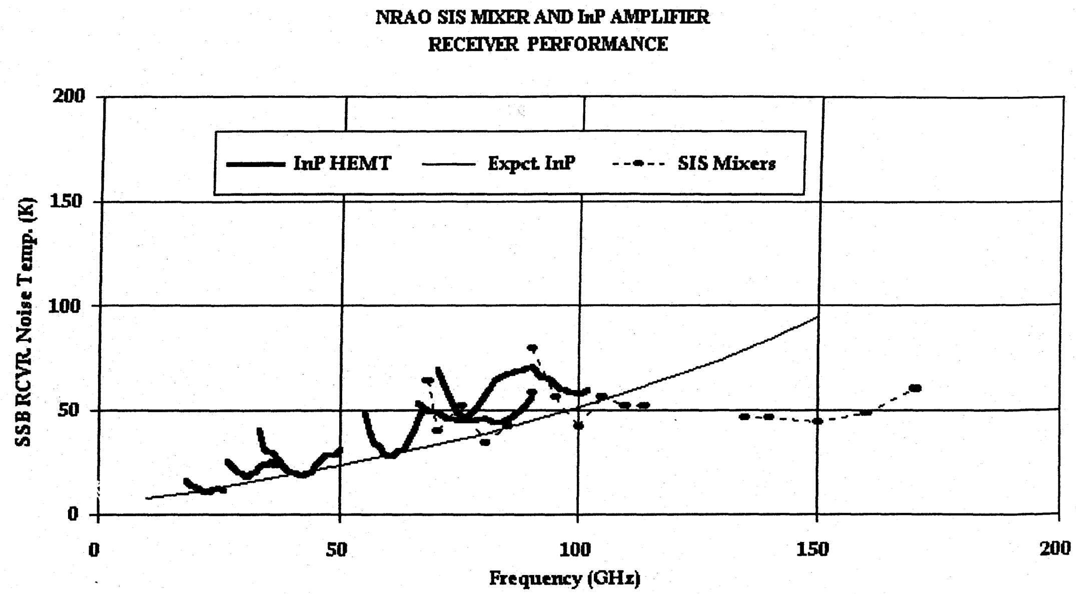


Figure VII-1. MAP HFET amplifier receivers and NRAO SIS mixer receivers

An amplifier covering 65–90 GHz with a noise temperature of 45 K has been built and two of these have been incorporated into a prototype receiver for the VLBA, which has been installed and tested, yielding good performance; another is nearing completion. It is planned that the VLBA will be fully equipped for 86 GHz operation within the next few years.

For use with the MMA, we expect to develop an amplifier which extends the highest frequency to 115 GHz so that the CO emission line will be covered. We anticipate this amplifier will have a noise temperature of less than 70 K. If the noise temperature can be made competitive with SIS mixers, then the simplicity and economy of a receiver using amplifiers (physical temperature of 15 K required instead of 4 K) for the CO line may dictate use of such devices for the MMA and for the GBT, if the GBT can be made to work at that frequency. At the least, the MMA will use amplifier receivers for phase calibration and scientific observations at frequencies between 30 and 90 GHz. HFET amplifiers also have the advantage of a larger dynamic range than SIS mixers and thus reduced susceptibility to the effects of interference.

The CDL has nearly completed the 100 amplifiers for the NASA Microwave Anisotropy Probe (MAP) satellite. New amplifiers for the VLA and VLBA upgrades and other NRAO projects will begin when the last of the MAP flight amplifiers have been delivered in the summer of 1998.

In addition to the MAP project, the NRAO will continue to make amplifiers, mixers, and electromagnetic devices available to the scientific community on a cost-reimbursable basis. This vital function of the CDL has resulted in advances in receiver capability on radio telescopes throughout the world and we intend to continue this important service in addition to making components for NRAO use.

We expect over the next few years to phase out the use of GaAs devices except perhaps at the very lowest frequencies and to convert almost entirely to InP devices. These in some sense will be the ultimate amplifiers for use in radio astronomy, since there do not appear to be any new materials on the horizon which could give lower noise. However, we note that in the centimeter wavelength region the quantum limit is much less than 1 K and we will keep abreast of current developments.

At the low frequency end of the spectrum, we have developed balanced amplifiers using Lange couplers fabricated on printed circuit boards. These amplifiers have a noise temperature of 2–3 K and will be used initially in the low-frequency GBT receivers. This technology can certainly be used above 1 GHz, perhaps as high as 2 GHz with the present technique and even higher in the future. The advantage of a balanced amplifier over a single-ended design is twofold: first, the input match can be made very good so that generation of circular polarization from linear polarization can be achieved in the RF; and second, the third-order intercept point is higher and thus intermodulation distortion caused by in-band interference is reduced. Current designs work very well up to 1 GHz and this work will be extended to as high a frequency as we find to be useful in amplifiers over the next few years.

The performance of HFET amplifiers in wideband radiometric systems is affected by the random gain fluctuations usually called "1/*f* noise." We have acquired an advanced capability for characterizing the phenomenon and will continue actively to investigate it.

SIS Mixers

Superconductor-Insulator-Superconductor (SIS) mixers fabricated of niobium are made for the CDL by the University of Virginia (UVA) Semiconductor Devices Laboratory on a regular basis. For some new developments, we have contracted with JPL for some designs which cannot yet be fabricated by UVA.

The most recent devices produced and tested are of a new tunerless design which so far has been shown to work well from 210-280 GHz with less than 60 K receiver noise temperature (double sideband). Experiments will continue with this building block which is being incorporated into other designs. Using this fundamental mixer design, we have designed a single-chip sideband separating mixer which has been fabricated at JPL. The layout of this mixer is shown in Figure VII-2, and its performance is shown in Figure VII-3. The first such wafer manufactured experienced a small problem with the fabrication of the terminating resistors for the hybrids, and there was some LO leakage under the chip; both these issues have been addressed with a new wafer and mixer block design. Even with the problems, the performance of the prototype nearly meets the goals of the project.

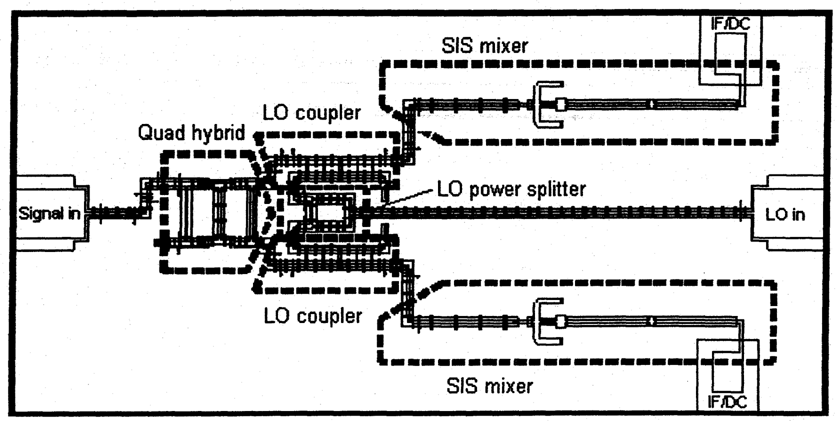


Figure VII-2. Layout of sideband-separating mixer chip

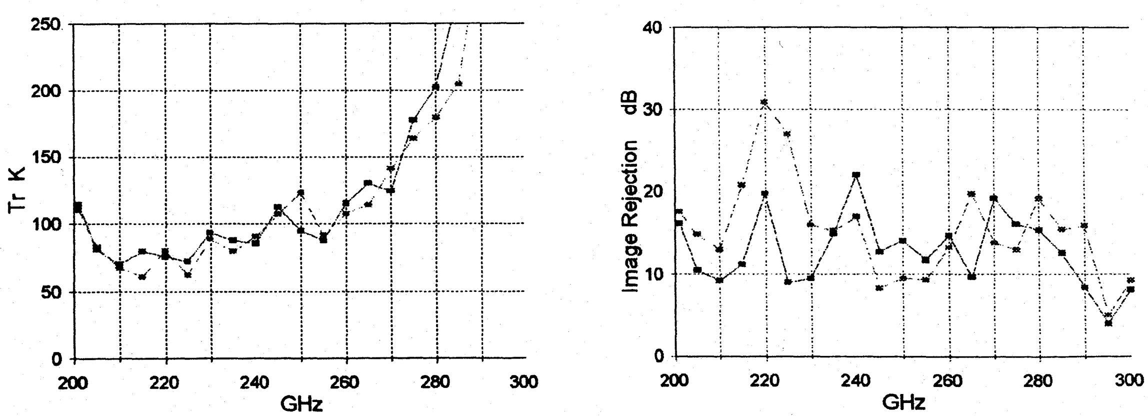


Figure VII-3. Single sideband noise temperature and image rejection of the sideband-separating mixer prototype. The two curves in each graph are for the individual sidebands.

The second new design is for a single-chip balanced, tunerless mixer. A prototype was fabricated by UVA and tested in early 1998. This prototype showed good balance, with the LO power requirement much reduced and the LO noise at the combined output reduced by about 10 dB. However, contamination of the Nb by an exhausted sputtering source resulted in a higher noise temperature due to losses in the upper Nb layer. A better wafer has been fabricated and is expected to yield good results in mid-1998.

A third project is the development of a mixer with an integrated IF amplifier. This technique has been successfully pioneered by CalTech (with design assistance from the NRAO) in order to achieve a bandwidth of ~ 4 GHz (as opposed to less than 2 GHz for other current designs). In cooperation with the University of Massachusetts (UMass), we have undertaken the design of an MMIC IF amplifier for the intended MMA IF range of 4–12 GHz. We anticipate chip fabrication and testing to take place in 1998.

The goal of these three developments (sideband separating mixer, balanced mixer, and integrated IF amplifier) is to prove the concepts, leading to a mixer design which will use four active mixing elements to produce a single-chip, sideband separating, balanced mixer with low LO power requirements, wide tunerless bandwidth, and 8 GHz instantaneous bandwidth per sideband, giving both lower and upper sideband outputs for a total instantaneous bandwidth of 16 GHz. We will also strive to improve the noise, which is now roughly four to five times the photon temperature ($h\nu/k$), down to about two times the photon temperature. At this point, for all MMA bands the atmospheric noise will be the dominant contributor to system noise, followed by miscellaneous electromagnetic losses, and further mixer noise improvements would not contribute significantly to MMA performance.

86 GHz HFET Receiver

At an observing frequency of 86 GHz, the VLBA has an angular resolution nearly twenty times better than at 5 GHz. Experiments by an *ad hoc* network of 86 GHz antennas over the last decade have yielded interesting results but have been limited by undersampled *u-v* coverage. Equipping all VLBA antennas for this frequency will cure this problem. With resolution of less than 100 micro-arcseconds, the accretion disks of active galactic nuclei in the local universe will be resolved at a frequency at which they are transparent; such observations will yield data complementary to the high-resolution maps expected at lower frequencies from Orbiting VLBI.

A prototype 86 GHz receiver using the newly-developed HFET amplifiers previously discussed has been built and installed on the Pie Town VLBA antenna. The performance of the antenna at 86 GHz is satisfactory and this system is in regular use for VLBI experiments. A second receiver is nearly complete and will be installed at Los Alamos. The third and fourth receivers are under construction. It is intended that the entire VLBA will be outfitted with these receivers over the next few years.

Electromagnetic Studies

An essential element of any radio telescope is the electromagnetic structure which guides the received energy from waves propagating in free space to the input of an active electronic device. This includes antennas, beam waveguides, feeds, polarizers, vacuum windows, and "widgets" which are placed in front of feeds to achieve LO injection and polarization separation at millimeter wavelengths. These may be collectively called "optics."

The CDL has recently developed a new orthomode transducer and a new phase shifter for the 18–26 GHz band which show excellent performance as a full waveguide band polarizer. This is about twice the bandwidth of any other polarizer for this band. These developments are directly related to the proposed upgrade of the VLA to achieve complete frequency coverage and are being incorporated into a new prototype receiver. Along with an InP HFET amplifier, this has resulted in a noise temperature at the zenith of about 50 K for the prototype receiver, a factor of three improvement over the old system. The phase shifter is now being fabricated using electroforming, which gives excellent repeatability. New electromagnetic modeling software is being used to evaluate the design of this phase shifter and design new ones for the 26–36 GHz and 12–18 GHz bands. To complete the polarizer, new orthomode transducers have been designed for frequencies up to 110 GHz; these will be tested and will serve as prototypes for new, wideband receiver use.

For the 12 Meter Telescope and particularly for the MMA, we are developing feeds, diplexers, quasi-optical components, vacuum windows, etc. for the millimeter regime. These elements are critical for wideband performance. We will continue to research new window materials and construction techniques to achieve minimum RF loss combined with wide bandwidth and acceptable gas leakage. A prototype vacuum window using a PTFE-crystalline quartz-PTFE sandwich has been fabricated and tested, and shows great promise for extending the interval of time before refrigerators must be shut down due to leakage.

MMA Development Tasks

Much of the SIS emphasis and a significant fraction of the effort on high frequency HFET amplifiers had the needs of the MMA in mind. The fact that many MMA elements will be built in large quantities emphasizes the need to design devices which not only provide the best possible performance, but are relatively easy to build and maintain. In this respect, it is essential to invest in the design and development phase of the project in order to achieve savings in implementation and operation costs. For mixers, LO systems, and calibration systems this means we must stress wideband operation with as few moving parts as possible (preferably none). While these design parameters have always been important in other NRAO applications, they assume an even more central role for an instrument as complex as the MMA which will be located at a very remote site.

We have already discussed most of the elements which will go into the MMA: SIS mixers, HFET amplifiers, electromagnetic components, and cryogenics. Each of these elements is used in at least one other NRAO system, so that we have test beds for all these technologies. We will continue to use these systems and draw upon the operational expertise of the personnel responsible for telescope operations at the Green Bank, the VLA/VLBA, and the 12 Meter sites in evaluating the suitability of various technologies for MMA use.

In recognition of the fact that the MMA local oscillator system is a critical, costly, and potentially high maintenance part of the MMA, we are exploring alternatives to the multiplied Gunn oscillator system presently used at millimeter and submillimeter wavelengths on all radio astronomy systems. While a Gunn-based system can certainly be made to work, it is probably the most expensive and least reliable system we could build. We are looking at two alternatives.

First, it is possible that with an electronically-tuned YIG oscillator below 40 GHz, a high power amplifier, and frequency multiplier chains we can generate the necessary LO signals with no moving parts, high reliability, and cost lower than a Gunn system. However, such a system may have more LO noise than a Gunn system and its use may therefore depend on the success of the balanced SIS mixer described above, which will be much less sensitive to LO noise. Making such an LO system economical will require that the frequency multipliers be much less expensive than those now commercially available. We have embarked on a development project to produce wideband, tunerless frequency multipliers using planar diodes fabricated by UVA and JPL.

Second, we are investigating the possibility of an LO system in which the signal is generated in a photomixer by beating together two infrared lasers operating in CW mode at slightly different frequencies. This work is being performed jointly by Tucson and CDL personnel. In Tucson, a demonstration system using a low-frequency photomixer to generate either a 100 MHz or 1400 MHz beat tone has been successfully phase-locked to an external reference and has shown the required phase stability. The principal obstacles to using such a system in the millimeter and submillimeter bands are that photodiodes that operate efficiently at frequencies up to 900 GHz are difficult to design and fabricate, and that no efficient means has yet been demonstrated for coupling energy out of the photodiode at the frequencies of interest. We have contracted with the photonics and microwave groups at UCLA to design a structure which will permit three key processes: (1) efficient coupling of the laser energy into a photodiode element, (2) operating the photodiode element at the required power level without destroying it, and (3) coupling the resultant RF energy out through a waveguide. The RF power level required depends on the success of the balanced SIS mixer, which we expect to have relatively low LO power requirements. While the development effort for such a system is large, the potential savings in implementation cost and reliability are very large. We anticipate having the first prototype photomixer in early 1999.

Another crucial element of the MMA is the correlator. As part of the MMA conceptual design, we have considered various correlator architectures which could meet the MMA needs, and settled on a conceptual design for a lag correlator which requires the minimum number of interconnecting cables. It will require the development of a new correlator chip with 4,096 lags, a factor of four greater than the "Quaint" chip used in the GBT spectrometer. We intend to build a GBT spectrometer copy (configured as a cross-correlator) for first MMA use with two antennas. The prototype of the final correlator is intended to be ready in 2003. In conjunction with the correlator development, we are investigating the use of a digital FIR filter in place of analog baseband filters to cut costs and eliminate the uncontrollable systematic errors inherent in an analog filtering system.

Feed Arrays and Interference Issues

At present, single-dish radio astronomy systems with multiple beams on the sky use multiple conventional channels, each with its independent feed and receiver. Due to feed interactions, it is difficult to place the individual beams closer together than about 2.5 beamwidths. Thus, for mapping radio sources which are only slightly extended, a multiple-beam receiver does not achieve a significant speedup in observing compared to a single receiver. We have developed a prototype of an array feed receiver which packs planar feeds close together and achieves multiple beam synthesis by weighted combination of multiple feed outputs. This system was tested on the 140 Foot Telescope and showed that multiple beams with good beam shape and efficiency can be synthesized from appropriately phased linear combinations of the basic feed elements. An advanced version of the receiver will be developed in 1998.

Also being explored is the technique of adaptive interference canceling. In a prototype receiver being developed for the FM radio band, an antenna separate from the radio astronomy feed receives the in-band interfering signals with high signal-to-noise ratio. A weighted fraction of this signal is digitally subtracted from the radio astronomy receiver output (which receives the RFI in its sidelobes) in order to subtract it from the desired signal. The amplitude of the subtracted signal is determined in real time by adaptive feedback. A test on the 140 Foot Telescope at 90 MHz showed some benefit, but less than complete elimination of unwanted signals due to equipment interface problems and, probably, to an insufficient number of reference feeds. These problems are being addressed in preparation for further testing.

Radio frequency interference is an increasing problem for radio astronomy. Probably the single most destructive source of RFI is increasing satellite traffic, with downward pointing beams which we cannot escape even by going to remote sites. Our only chance to preserve an observing capability which will last well into the 21^{st} century is to participate in the regulatory process and negotiate with operators of spaceborne transmitters to minimize RFI effects on our observations. To this end, the NRAO will continue to participate in regulatory committee deliberations and publicize the need to preserve spectrum space for astronomical research. We will also pursue technological improvements, such as the use of balanced amplifiers in the crowded low frequency spectrum and the use of HFET amplifiers instead of the more RFI-susceptible SIS mixers at frequencies below 100 GHz. Tests of the interference to the protected radio astronomy band around the 1612 OH line from the Motorola IRIDIUM system have been conducted and are being analyzed. This work will continue in an effort to eliminate the effects of harmful interference due to this low-earth-orbit system.

VIII. BUDGET AND PERSONNEL PROJECTIONS

(NSF Funds, $ in 000s)

	1999	2000	2001	2002	2003	2004
OPERATIONS:						
Base Operations	32,140	33,600	35,100	36,700	38,300	39,500
GBT Commissioning	700	300				
Capital Equipment	1,300	1,300	1,400	1,400	1,500	1,500
Operations Total	**$34,140**	**$35,200**	**$36,500**	**$38,100**	**$39,800**	**$41,000**
CONSTRUCTION:						
Millimeter Array (MRE)	9,000	8,000	25,000	41,000	41,000	41,000
VLA-VLBA Link (MRI)	Funded in 1997 ($466)					
VLBA λ3mm Rx (MRI)	Proposed Funding in 1998 ($1,070)					
VLA λ7mm Rx (MRI)	Proposed Funding in 1998 ($870)					
VLA Upgrade I (MRE)		3,000	6,000	10,000	10000	5,000
VLA Upgrade II (MRE)					3,000	10,000
Construction Total	**$9,000**	**$11,000**	**$31,000**	**$51,000**	**$54,000**	**$56,000**
PERSONNEL:						
Operations	390	390	396	396	400	400
Millimeter Array	54	54	60	70	70	70
VLA-VLBA Link	3	2				
VLBA λ3mm Rx	2	2	1			3
VLA λ7mm Rx	1	1	1			2
VLA Upgrade I		6	10	20	20	10
VLA Upgrade II					3	25
Non-NSF	19	17	5	5	5	5
Personnel Total	**469**	**472**	**473**	**491**	**498**	**515**