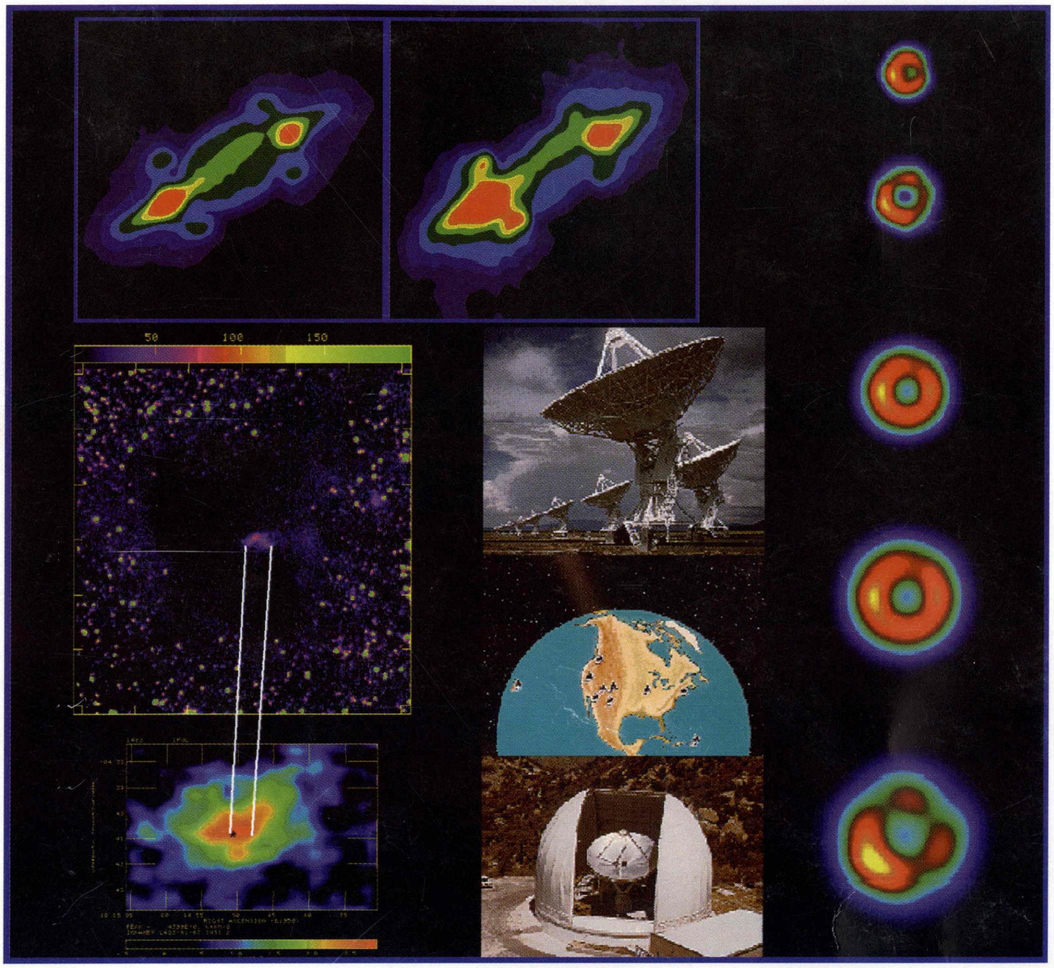

LONG RANGE PLAN
1998 - 2003

NATIONAL RADIO ASTRONOMY OBSERVATORY

Cover Image, clockwise from upper left: VLA images of Jupiter before and after the impact on Jupiter of comet Shoemaker-Levy; sequential VLBA images of supernova 1993J in the galaxy M81; the 12-meter telescope on Kitt Peak, AZ; a 12m telescope on-the-fly image of the CO emission in the L183 dark cloud together with an optical image of that cloud. The two center panels show the VLA antennas and the VLBA station locations respectively.

National Radio Astronomy Observatory

Long Range Plan

1998-2003

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I. OVERVIEW

For the National Radio Astronomy Observatory (NRAO) the period 1998-2003 will be a period of transition. In the timeframe of this Long Range Plan the NRAO will complete the replacement of all the 1960s-era telescopes in Green Bank—the 300 Foot transit telescope, the 140 Foot Telescope and the 3-element interferometer—and begin the Millimeter Array, a synthesis array telescope to supercede the last of the original NRAO telescopes, the 12 Meter millimeter-wave telescope. The transition will not only position U.S. radio astronomy for the next three or more decades of research but the power and versatility of the new instruments provide abundant new opportunities for scientific investigation by the next generations of students and scholars.

The highlight of the next five years will be the commissioning and scientific operation of the Green Bank Telescope (GBT). For observations of small objects such as distant stars and galaxies at microwave frequencies the GBT will be more than 30 times faster than its aging predecessor, the 140 Foot Telescope. In addition to being faster it will expand the frequency spectrum accessible to observers at Green Bank by a factor of four and expand the spectroscopic coverage available for analysis by more than a factor of ten. Together these capabilities will lead to a wealth of scientific discoveries that will make the next five years a particularly exciting time for users of the NRAO and for all of U.S. astronomy. An important goal of this Long Range Plan is to bring that hope to fruition.

Operational planning for the Green Bank Telescope is described in Section II. The initial design and development phase of the next major U.S. initiative in radio astronomy, the Millimeter Array, is outlined in Section III; this section also includes a summary of recent progress made at the 12 Meter Telescope and plans for this instrument over the next five years. The following two sections review plans for the evolution of the Very Large Array (VLA) with a major instrumentation upgrade and plans for enhanced operation of the Very Long Baseline Array (VLBA).

Research vehicles such as are represented by the VLA, VLBA, GBT, and MMA are fueled by technological advances. Technology makes progress possible. Development of technology for radio astronomy at the NRAO is described in Sections VI and VII for software and electronics hardware respectively.

The final section of this NRAO Long Range Plan outlines the personnel and financial resources needed in the period 1998-2003 to set in motion the transition to the research facilities of the next three decades and beyond.

II. THE GREEN BANK TELESCOPE

1. General Comments

In the second 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, world-wide in any number of analogous single dish instruments spanning the post-WWII era. An artist's conception of the completed GBT is shown in Figure II-1. Because the GBT will work over an unusually broad range of frequency, spanning nearly nine octaves from 300 MHz to 100 GHz, it will contribute to most of the many subdisciplines of radio astronomy. As such, it will serve as an intellectual center where researchers of widely-varying interests find both a meeting place and a common cause in observing.

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 for the Observatory and the community. 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.

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, and 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, a unique aspect of the GBT, will for the first time afford knowledge of the behavior of a telescope while it is used, independent of the astronomical objects which it observes.

2. 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 see the extent to which the GBT will contribute in unforeseen ways. Here are a few highlights of prospective scientific activities at the GBT, from both new and established genres.

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

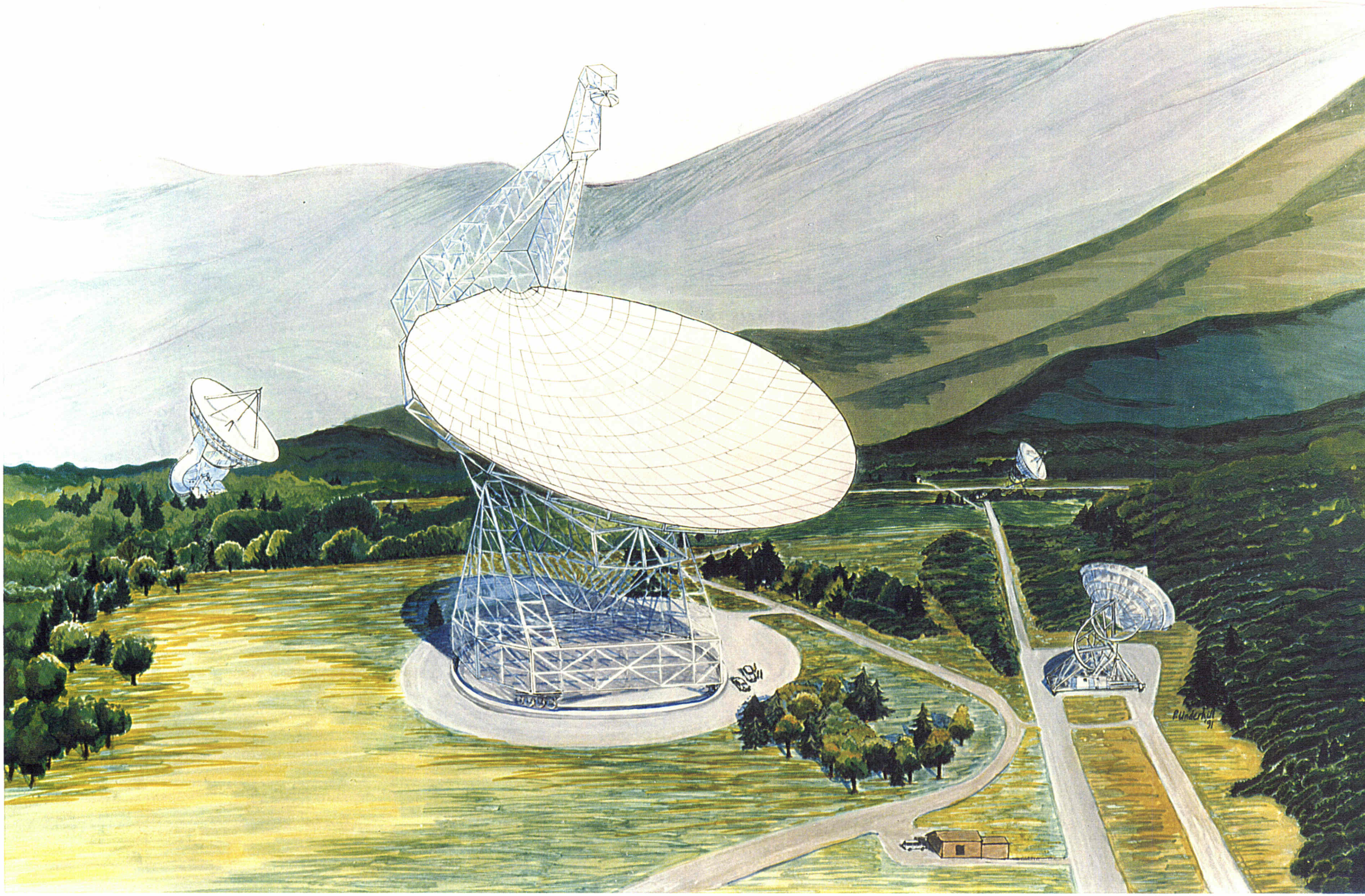

Figure II-1. An artist's conception of the Green Bank Telescope (GBT).

frequency searches will alleviate the constraints imposed by dispersion measure and interstellar scattering that plague low frequency observations and 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 superstrong (10^{12} gauss) magnetic fields.

Toward other 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, Near and Far. 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 extinction toward extragalactic objects such as quasars, which the GBT will determine with unprecedented sensitivity and freedom from systematic errors, is vitally important to researchers outside radio astronomy. For gas in the galactic core, the clean and relatively narrow 8.7' 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, redshift-deep surveys out to cosmological distances, tracing cosmic evolution. At its very lowest frequencies, there will be sensitive searches for emission from the first epoch of formation of galaxies and clusters in the early Universe.

Observations of Molecular Gas, Near and Far. 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 absorption. 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 small (10 m-15 m) millimeter-wave dishes. The 100 meter GBT will advance this field exponentially, 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 comparatively 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°/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 the most sensitive way to find mm-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.

3. GBT Construction

Completion of the GBT construction is expected at the end of calendar year 1998. Presently the alidade portion of the antenna (the rotating support structure) is complete and the box girder meant to support the reflector backup structure is also complete. This same box girder provides a sound attachment for the feed arms, the horizontal part of which is also complete and assembled on the antenna. A current photograph of the GBT construction is shown as Figure II-2. The remaining items needed to make the antenna whole are the reflector itself and the vertical part of the feed arm.

The reflector backup structure is being assembled on the ground adjacent to the antenna. It can be seen nearly complete in Figure II-2. This entire assembly, 120 by 110 meters in extent, is being welded together as 22 subassemblies; the subassemblies are bolted together. When the entire structure is complete in June of 1997 it will be unbolted and the 22 subassemblies will be raised onto the alidade and set in place on the structure. This activity is scheduled to occur between June 1997 and February 1998. The task of lifting the backup structure subassemblies will require continual adjustments to be made in the counterweight system of the antenna.

When the 22 backup structure subassemblies are welded together on the antenna it will be possible to 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. Set on top of all of this is the subreflector and its supporting structure.

This will complete the assembly of the entire antenna and the support needed for the reflector panels. The final major task will then be to install the 2200 reflector panels and the actuators that will be used to position the panels accurately. After that major event the surface panels will be aligned and the telescope is ready for acceptance testing.

4. GBT Operations

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;
- 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;

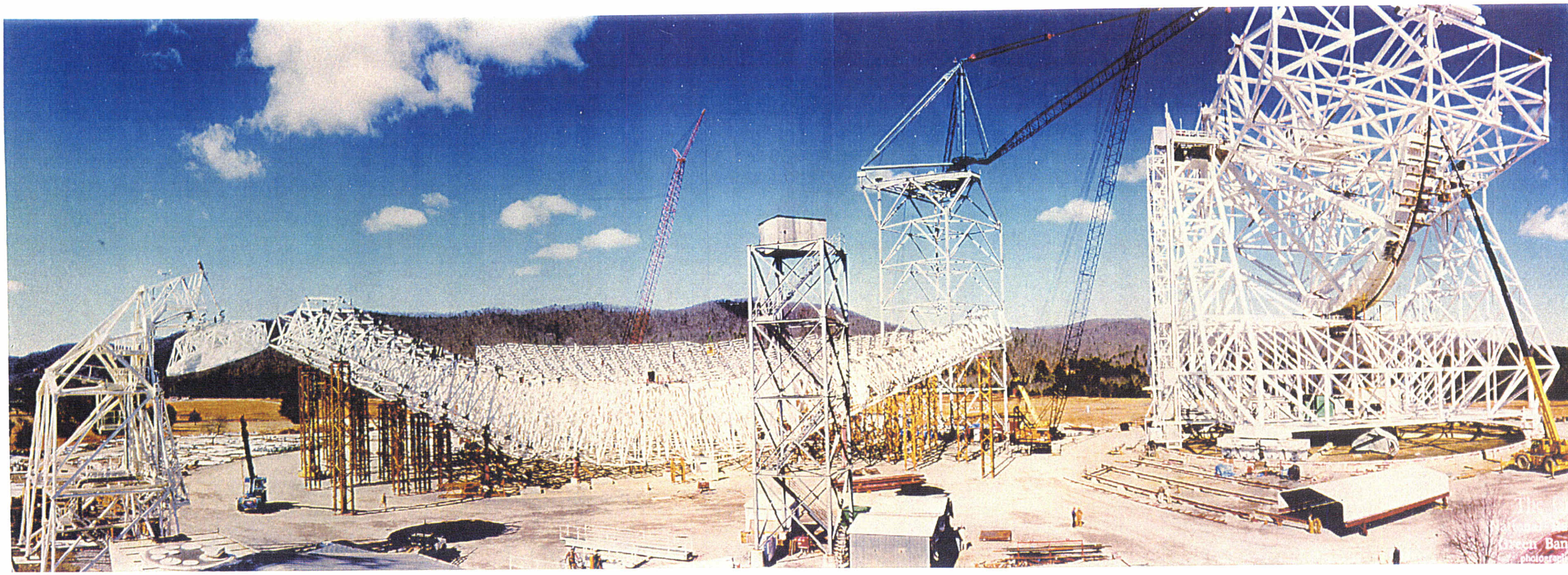

Figure II-2. The Green Bank Telescope construction. The reflector backup structure is being assembled adjacent to the alidade.

- 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. 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. 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
0.3 - 1.2	Jan 1997
1.2 - 1.8	Jan 1997
1.8 - 2.6	Feb 1999
2.6 - 4.0	July 2000
4.0 - 5.8	July 1997
5.8 - 8.2	July 1998
8.2 - 10.0	Jan 1996
10.0 - 12.4	Feb 2003
12.4 - 15.4	Jan 1996
15.4 - 18.0	July 2002
18.0 - 22.0	Jan 1996
22.0 - 26.5	Jan 1996
26.5 - 33.0	Jan 2001
33.0 - 44.0	Jan 2001
40.0 - 52.0	July 2000

The optics systems on the GBT will present special operational challenges. The active surface alone has more than 2200 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 2048 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 8 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 may be available shortly after the GBT comes into operation. It will have a maximum bandwidth of 800 MHz, 8 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.

The GBT Correlator

Maximum bandwidth: 800 MHz

Samplers: 8 at 1600 MHz; 32 at 400 MHz

Total number of channels: 256k

Sensitivity: three level always; nine level at narrower bandwidth

The GBT has an extensive 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 application. 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.

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 that have to be maintained. Its HVAC systems will add 50 percent to the site capacity. The maintenance load rises in proportion. Special devices (large cherry pickers, etc.) 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 full time just 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 çapabilities through the next five years. The budgets to support this growth are included in the NRAO long range plan summarized in Section VIII.

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

1. The Millimeter Array

Overview

In February 1997, we were very pleased to learn that the National Science Foundation (NSF) plans for FY1998 include funding for the Design and Development (D&D) phase of the Millimeter Array (MMA). The D&D work is a three-year program addressed to the detailed design and prototype of major MMA subsystems. At the conclusion of this phase we expect to be able to demonstrate the technical performance of the critical MMA instrumentation and to use the experience to anchor the construction cost estimate for the array. The NSF FY98 plan requires Congressional approval and the funds for the MMA and other NSF programs will have to be appropriated by Congress. The Congressional authorization and appropriation process will occur over the next six months.

The MMA construction itself, a project that will require an additional six years, will need separate approval both by the NSF and through Congressional appropriation.

It is interesting to consider what we are trying to design: it is an array to be complete in the three years of the D&D phase plus the six years of actual construction; together this brings the completion date to 2006. This timescale makes the project very much like a space project with the same liability, namely that one designs an instrument at the state-of-the-art today even though it will inevitably be well behind the state-of-the-art by the time it is complete. We don't want that to happen. The alternative is to be aggressive with the technical design with some well defined fall backs built in. We will adopt the latter approach which we believe can lead us to a state-of-the-art instrument in 2006.

The hallmark of an innovative design is the sound ideas of creative people and to this end we hope to recruit to the MMA D&D project the participation of many experienced people in the U.S. millimeter-wave community. A vital aspect of this is a broadening of the involvement of the MMA Development Consortium (MDC) through the MDC working groups and via specific design tasks done on the existing arrays and later on the merged university array. In the next several months the details of this collaboration will be defined in a way that we anticipate will strengthen all of U.S. astronomy.

Planning for the MMA Design and Development Phase

The way the NSF is structuring the MMA project—a design and prototyping phase followed by actual construction—brings with it some real inefficiencies. Most particularly, it is not possible now to hire people and assemble equipment at a site dedicated to MMA construction because we have no assurance that there ever will be a construction project. Moreover, the D&D phase funding is regarded as part of the total cost of the array by the NSF; this means everything done in the D&D phase must end up on the MMA. Finally, the timescale is fixed: the D&D phase is three years. The management of such a project is challenging. The NSF is looking for three things as an output of the D&D phase and as input to their decision making process regarding construction of the MMA. These are:

- a definitive site choice;
- an auditable cost estimate for construction and operations;
- arrangements for at least 25 percent participation in the project by partners not funded by the NSF.

Accepting these NSF goals, our own goals for the D&D phase go somewhat further and include preparing ourselves for the construction phase of the project that we optimistically expect to follow. To this end, and in recognition of the limitations of the two phase approach that is imposed on us, we are planning to incorporate into the project tasks expertise at all the NRAO sites and in the MDC universities as well. The details of the plan are still very much in discussion but the general outline is the following:

- The project will have a Project Director and a Project Manager. The Project Director will report to the NRAO Director and will be responsible for defining what is to be done; this includes negotiation with the host country and partners in the project. The Project Manager will be responsible for determining how the work is to be done.
- The Project Manager will make decisions in concert with the MDC Executive Committee. Together they will decide how resources are to be allocated and how the work is to be accomplished.
- Working groups comprised of MDC and MMA people will do the actual design work. The MMA Working Groups (MWG) will evolve from the present MDC Working group structure by the assignment of a MMA staff person to head each group and to be responsible for timely completion of the tasks. People hired to the MMA project, or assigned to the project, will be supervised by the head of one of the MWGs. The working groups will include:

Receivers
Local Oscillator
Antenna
System
Computing and Information Flow
Imaging
Administration

- Overall external project oversight specific to the MMA will be provided by the MMA Advisory Committee (MAC) that meets annually and reports to the NRAO Director. We also anticipate the appointment by the NSF of an MMA Oversight Committee, much the same as exists for the Gemini and LIGO projects.

MMA Activities in the Next 12 Months

The following are the principal MMA tasks in the next 12 months:

- Cement a mutually beneficial relationship with the MDC universities for participation in the development of the MMA.
- Refine the antenna design. Review that design with the MAC including all tradeoffs affecting the antenna diameter.
- Contract for the first two MMA antennas, to be evaluated as prototypes.
- Establish a receiver group to complete the design of the MMA SIS mixers and build prototype devices.
- Establish a facility to test the photonic local oscillator concept. Contract with university groups for design and fabrication of photodiodes to be mounted in fundamental waveguide.
- Appoint heads of all the MMA Working Groups and draw up a complete tasking plan for each MWG for the duration of the D&D phase.

Recommended Site for the MMA

The Millimeter Array (MMA) will extend the techniques of radio astronomy for precision astronomical imaging to frequencies approaching 1 THz, beyond which the Earth's atmosphere is opaque. At such high frequencies ground-based astronomical imaging is limited by absorption of the cosmic signals by atmospheric water vapor and by image distortion owing to turbulence in the atmosphere. Thus the array site is crucial to the MMA performance. The atmosphere above the array must be stable, dry and transparent.

For the past decade tests and evaluations of possible sites for the MMA have been carried out in the continental United States, on Mauna Kea in Hawaii, and in Chile. In addition to clear and stable skies the MMA requires a site at least 3 km in extent in order to accommodate an array configuration capable of providing astronomical imaging with a clarity of detail comparable to that obtained from the Hubble Space Telescope. The site must also be flat enough for routine reconfiguration of the antennas into the different array sizes that give the MMA its "zoom lens" capability. It must also be possible to provide the site with the infrastructure and logistical support that the array will need.

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 a site at 5000 m elevation in the altiplano of northern Chile, Llano de Chajnantor, meet the minimum requirements for the MMA. The site testing program shows Llano de Chajnantor to be the superior site for operation of the MMA. Its advantages over Mauna Kea include the following:

- an annual mean atmospheric opacity at 225 GHz approximately half that of Mauna Kea. A program of MMA science observations requiring 12 months on Mauna Kea can be done in as little as six months on Llano de Chajnantor;
- better atmospheric stability for more precise imaging;
- benign site topography and adequate space for future expansion of the array to dimensions of 10 km or more for even higher resolution imaging;
- ease of site access via a major international highway;
- the site latitude, 23 degrees S, permits full view of the entire disk of the Milky Way galaxy, the Galactic center and the closest galaxies to us, the Magellanic Clouds.

The construction and operating costs of the MMA on the two sites are estimated to be comparable. Since the MMA science may be done 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, we recommend Llano de Chajnantor as the MMA site. A panoramic view of the site is shown here as Figure III-1.

The Chajnantor site in the Chilean Altiplano is located on fiscal (public) land. The Executive science agency in Chile, CONICYT, has requested that the land be reserved for science. If this request is approved by the land ministry (Bienes Nacionales) then we would get access to the site by means of a lease agreement with CONICYT. We have delayed seeking the site lease at the request

Figure III-1. A panoramic view of Llano de Chajnantor, the proposed site for the Millimeter Array (MMA).

of the NSF, owing to the unsettled situation regarding Chilean payment for their share of the Gemini project.

Meanwhile, fearing that land speculators or others in northern Chile would be tempted into making a claim on the site, Associated Universities, Inc., (AUI) has acquired an exploratory mining claim to approximately 200 square kilometers of the site. This is more than enough room for the MMA, access roads, and room even for companion array projects on the same site. The mining claim was filed with the approval and encouragement of CONICYT. It expires in March 1998, by which time we expect CONICYT to have received concession of the entire site as a science reserve.

A document describing the site choice recommendation is being reviewed by the MAC and other NRAO and MMA committees.

National and International Collaborations

The Atacama Array

The addition of a submillimeter receiving capability to the MMA makes the MMA project similar in scope to the array being planned in Japan by the Nobeyama Radio Observatory called the Large Millimeter and Submillimeter Array (LMSA). In principal, were the MMA and the LMSA to be located on the same site the two instruments could be used together for some class of scientific studies. The specific outlines of a MMA/LMSA collaboration have been discussed for three years in semi-annual meetings. The most attractive of several collaboration options is creation of the *Atacama Array* from the combined MMA and LMSA.

The premise of the Atacama Array is the location of both the MMA and the LMSA on a common site, but the arrays should be located approximately 10 km apart. Most of the year the two arrays operate independently in response to the demands of their respective communities. But for some period of the year all the antennas of both arrays are moved out to stations around the locus of a circular or triangular pattern 10-15 km in diameter. This MMA + LMSA in a very large configuration is the Atacama Array. Observing time on the Atacama Array, and management of the operation, will be issues to be discussed in the next few years. Figure III-2 shows how the Atacama Array could be configured on the Chilean site under study for the MMA.

For a 12 km Atacama Array such as that given in Figure III-2 which operates at all the MMA and LMSA frequencies, the angular resolution varies over the range from 60 to 6 milli-arcseconds. The table below illustrates this and includes the corresponding linear resolution at the distance of some important astronomical sources.

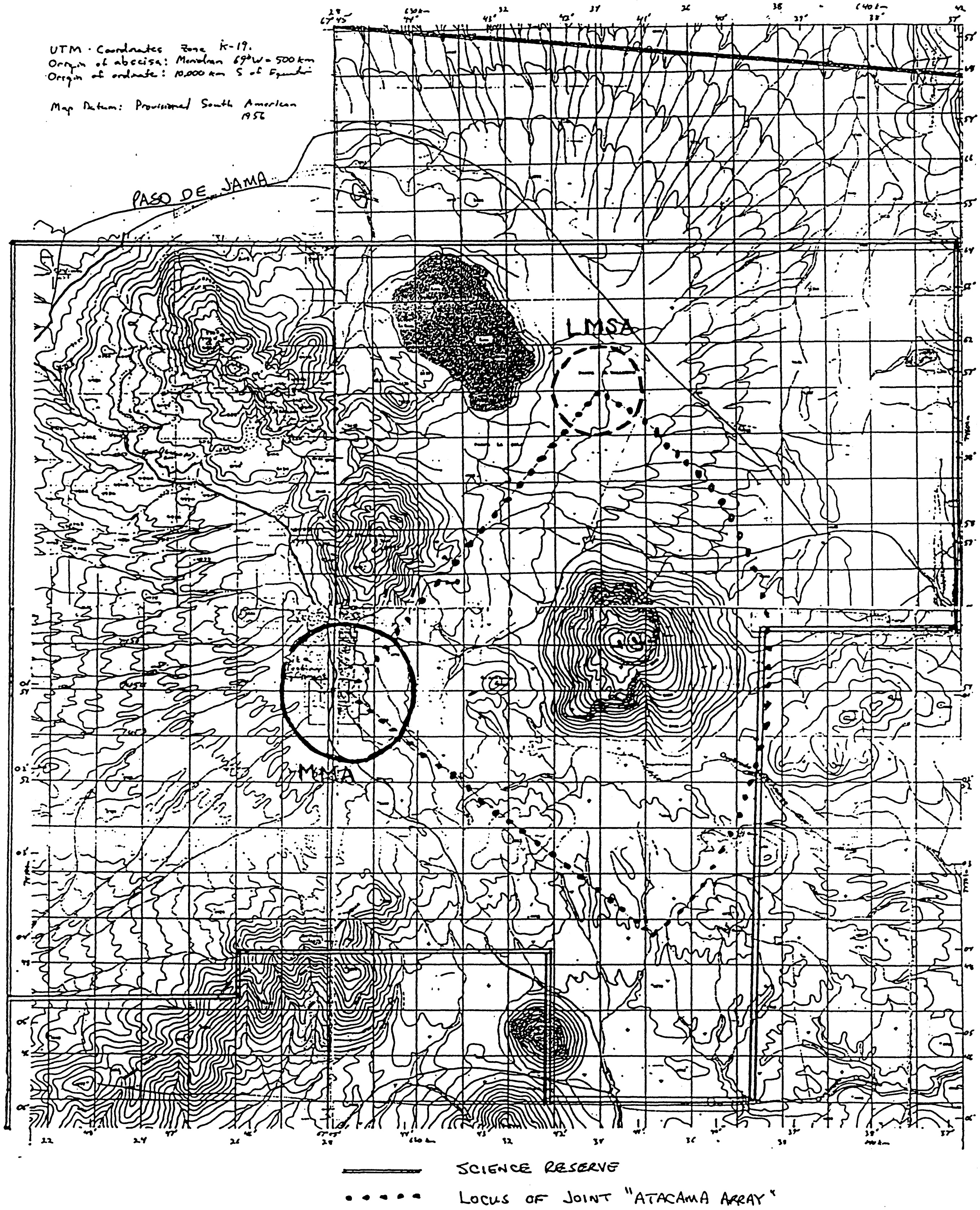

Figure III-2. Locus of stations for the Atacama Array to be formed from a combination of MMA and LMSA antennas.

Table 1. Atacama Array Resolution

Frequency	Angular Resolution	Linear Resolution At: Ophiuchus	Sgr A	Magellanic Clouds	Cen A	QSO z ~ 1
90 GHz	60 mas	10 AU	520 AU	0.06 pc	1.5 pc	1. 5 kpc
230	20	3.4	170	0.02	0.5	0.5
345	15	2.6	130	0.015	0.4	0.4
650	8	1.4	70	0.008	0.2	0.2
850	6	1	50	0.006	0.15	0.15

With a resolution of a few milli-arcseconds to a few tens of milli-arcseconds, the Atacama Array provides an imaging capability comparable with that of centimeter-wave VLBI instruments, but it does so as a connected phase-stable interferometer and it operates at wavelengths where thermal sources are bright. For thermal sources, the only instruments of comparable angular resolution are the optical interferometers, but these instruments give only visibility functions, not high-fidelity images.

The Large Southern Array

The European Community has also been studying concepts for an imaging instrument at millimeter wavelengths. The study group, led by the European Southern Observatory and the IRAM millimeter astronomers, also includes participation by the Swedish Onsala Space Observatory and the German Max Planck Institute for Radio Astronomy. Their instrument concept, the Large Southern Array (LSA), presently has as its principal goal provision for an enormous collecting area (10,000 square meters) at millimeter wavelengths. The scientific focus of the instrument is on imaging cosmologically-distant galaxies over a narrow range of millimeter wavelengths. The LSA, as presently described, and the MMA are complementary instruments. The MMA intends to cover a broad spectral range from centimeter wavelengths to submillimeter wavelengths, and a broad spectrum of science including mosaic observations of the sun, planets, and galactic molecular clouds. The scientific focus of the LSA is more restricted. Nevertheless, there are opportunities for the MMA and the LSA to collaborate in ways that will benefit both projects.

The LSA is considered as a necessary complement to the ESO Very Large Telescope (VLT), four 8 m optical/IR telescopes under construction now on Cerro Paranal near the port city of

Antofagasta. Under good seeing conditions, and certainly with some modest adaptive optics, the VLT will achieve sub-arcsecond imaging of starlight from distant galaxies. The LSA will achieve the same sub-arcsecond imaging of the gas and dust content of the same galaxies. In this way the two instruments are highly complementary, a strength the European community both recognizes and intends to exploit scientifically.

As is the case with possible MMA-LMSA collaborations, a collaboration between the MMA and the LSA could take many forms ranging from an intimate MMA/LSA partnership to a collaboration at a distance involving a common sharing of infrastructure. Discussions are in progress now on such issues and will be resolved early in the term of this Long Range Plan.

NASA

Figure III-3 illustrates the angular resolution achievable by the next generation of telescopes, both ground-based and space-based, that will be available for astronomical research. Imaging with the resolution of the Hubble Space Telescope, imaging with 0.″1 resolution, will be possible from space at visible wavelengths, it will be possible from the ground in the near infrared with the next generation of optical telescopes (Gemini, VLT, LBT, Magellan, Keck) and it is possible at radio wavelengths with the VLA and at millimeter/sub-millimeter wavelengths with the MMA. But in the middle to far infrared, approximately 10 to 300 microns, the only imaging possible will be that from space and it will be done at resolutions of 10-100 arcseconds, that is resolutions 100 to 1000 times worse than achieved at the other wavelengths. Figure III-3 illustrates this point.

The European community, which has primary responsibility for the FIRST space mission (FIRST is a European Space Agency cornerstone mission) and has actively encouraged construction of the LSA as a scientifically enabling adjunct to FIRST. The only way to image the objects FIRST will discover is with an instrument such as the LSA or the MMA or the LMSA. Precisely the same conclusions apply to the NASA missions SIRTF and SOFIA. To realize the scientific return inherent in SIRTF and SOFIA an incremental NASA involvement in the MMA is not only wise but necessary. Discussions to these ends are in progress.

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 currently use SIS junctions, but we are watching closely the developments in HFET and monolithic microwave integrated circuit (MMIC) technology.

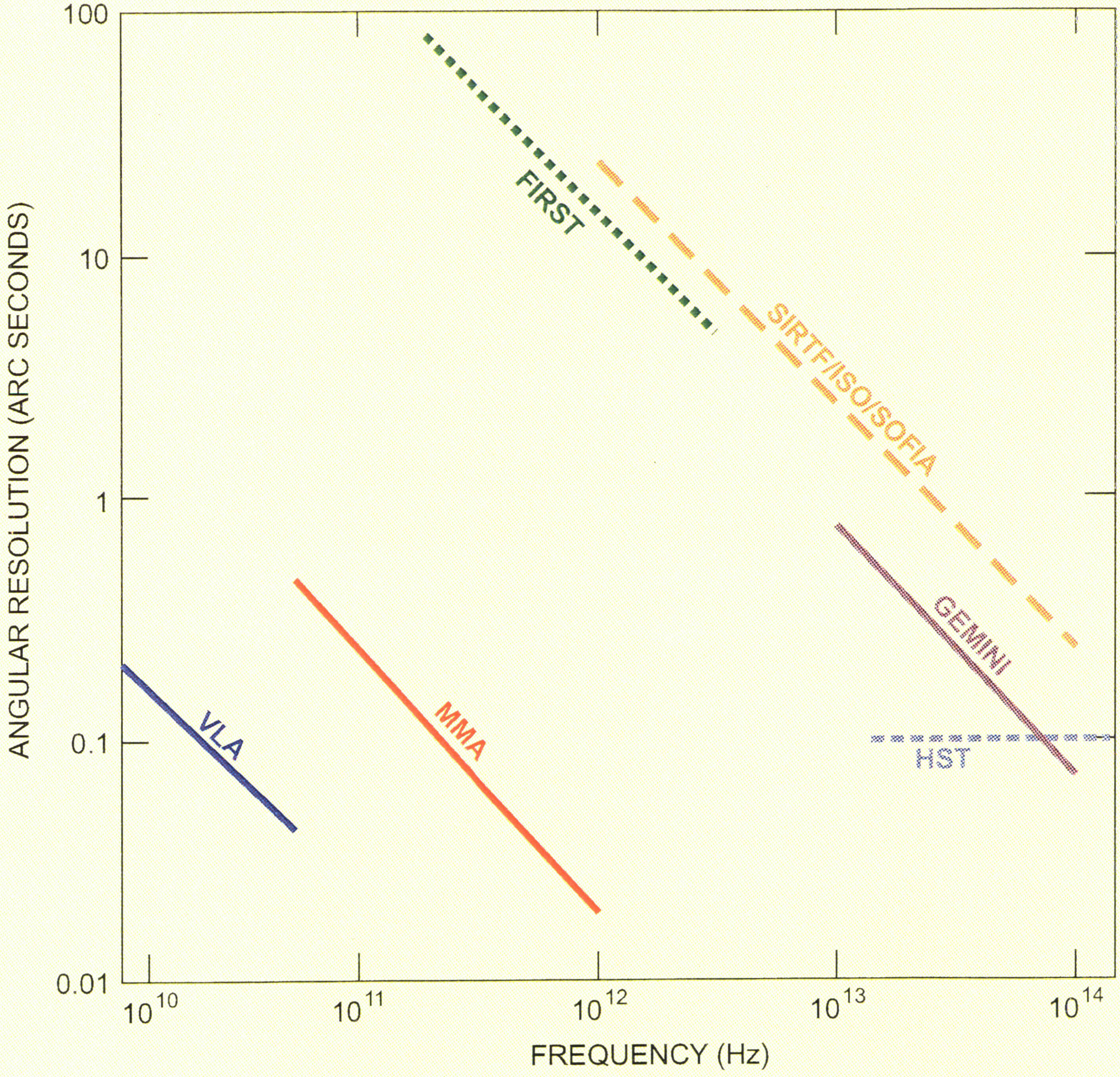

Figure III-3. The angular resolution, or imaging detail, shown as a function of frequency, of the major astronomical research telescopes that will be in operation shortly after the turn of the century.

The new 8-beam, 1.3 mm SIS receiver system is now fully operational. This system provides a unique mapping capability that will be much in demand throughout the years of this long range plan. 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 heavy 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 12 Meter has been a leader in the detection and study of high redshift line emission from galaxies, and significant effort will continue in this area. Studies of CO and CI are used to investigate the process of galaxy formation itself. So far, infrared-bright, molecular-rich objects have been seen at redshifts as large as $z = 2.9$. The objects thus far detected in CO will be examined for emission from other molecules and from atomic carbon, and searches will be made to find other forming galaxies.

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 multifeed 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 could now be built, for a fraction of the cost of the original 12 Meter hybrid spectrometer. In collaboration with the CDL, we are now starting construction of such a correlator, using the existing GBT design. This will give 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. We are investigating collaboration with other millimeter-wave groups for the construction of the analog part of this spectrometer. We hope to have this new correlator operational within about two years.

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 it1 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 the 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 VLBA is operational in all its major observing modes except one. It is routinely scheduled in response to observing requests that are received at three proposal deadlines annually (1 February, 1 June, 1 October). The VLBA supports Global VLBI Network sessions interspersed during the year among the scheduled VLBA-alone observing.

Among the principal reasons the VLBA was built was to provide high fidelity imaging on milli-arcsecond 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 mis-matched 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.

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, presumably a black hole of 30 x 10^6 $M_\odot$. 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 first demonstration of a picture proposed by theorists for almost 20 years.

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 distance. Monitoring of the continuum emission will enable an examination of the physical processes occurring very close to a super-massive black hole.

For galaxies at cosmological distances, the size scales of the nuclear radio sources are one to a few parsecs; even for radio emitting material expelled from those nuclei with relativistic velocities, the corresponding time scales for change are one to a few years. Hence, VLBA observations repeated annually are sufficient to allow us to follow source changes. On the other hand, for some highly luminous objects such as supernovae the characteristic size scale is far smaller and the corresponding time scale for change so brief that they could not be studied prior to the existence of a dedicated VLBI instrument such as the VLBA. Figure IV-2 shows such an example. It is a series of VLBA images of the radio emission from the supernova 1993J in the nearby galaxy M81. These VLBA observations were made over the course of a year following the supernova outburst, and they illustrate one of the operational strengths of the VLBA and indeed also of radio astronomy. The VLBA was able to follow the expansion of the supernova remnant with enough resolution to see the

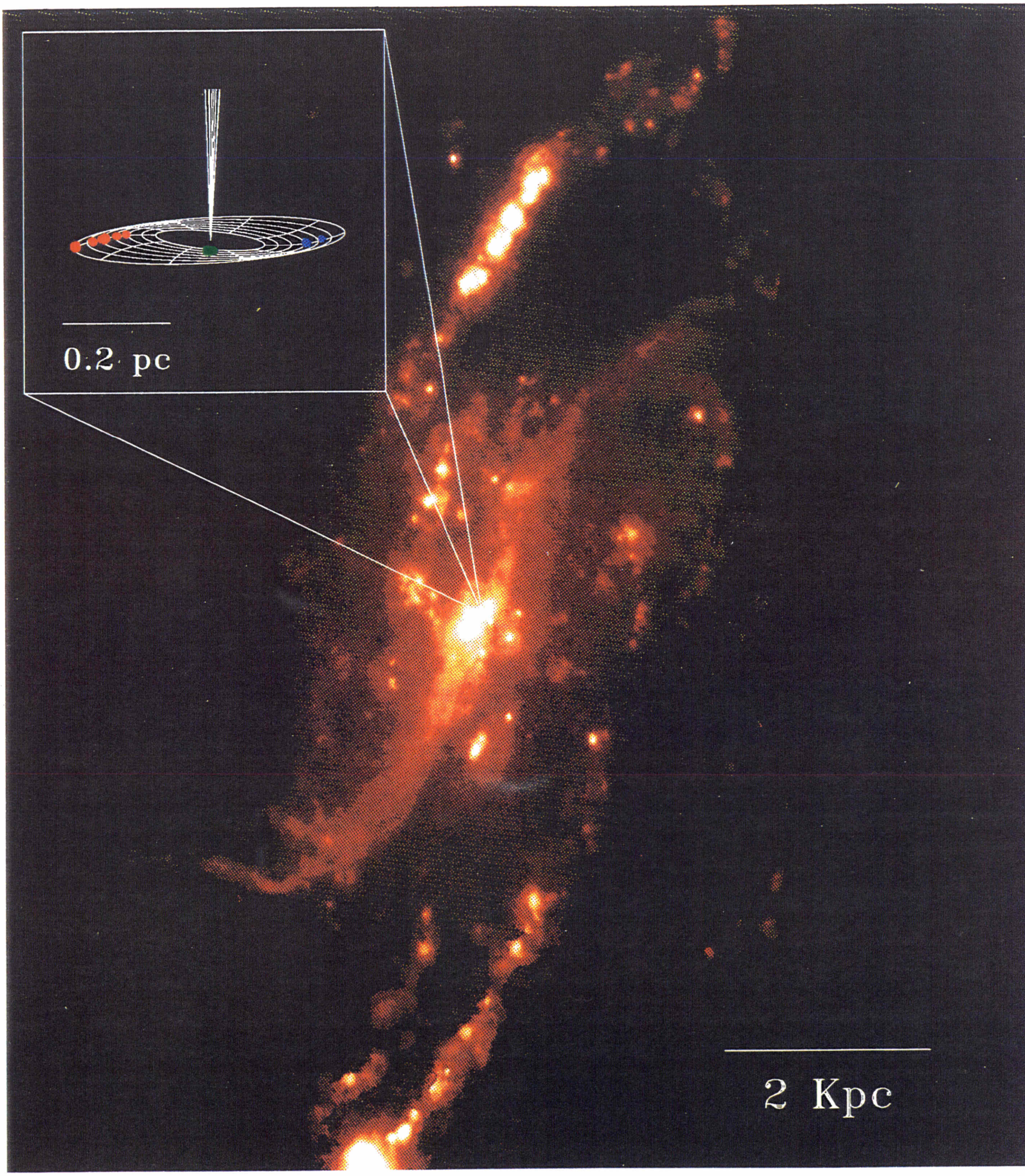

Figure IV-1. A composite image of the central engine of the active galactic nucleus of NGC 4258.

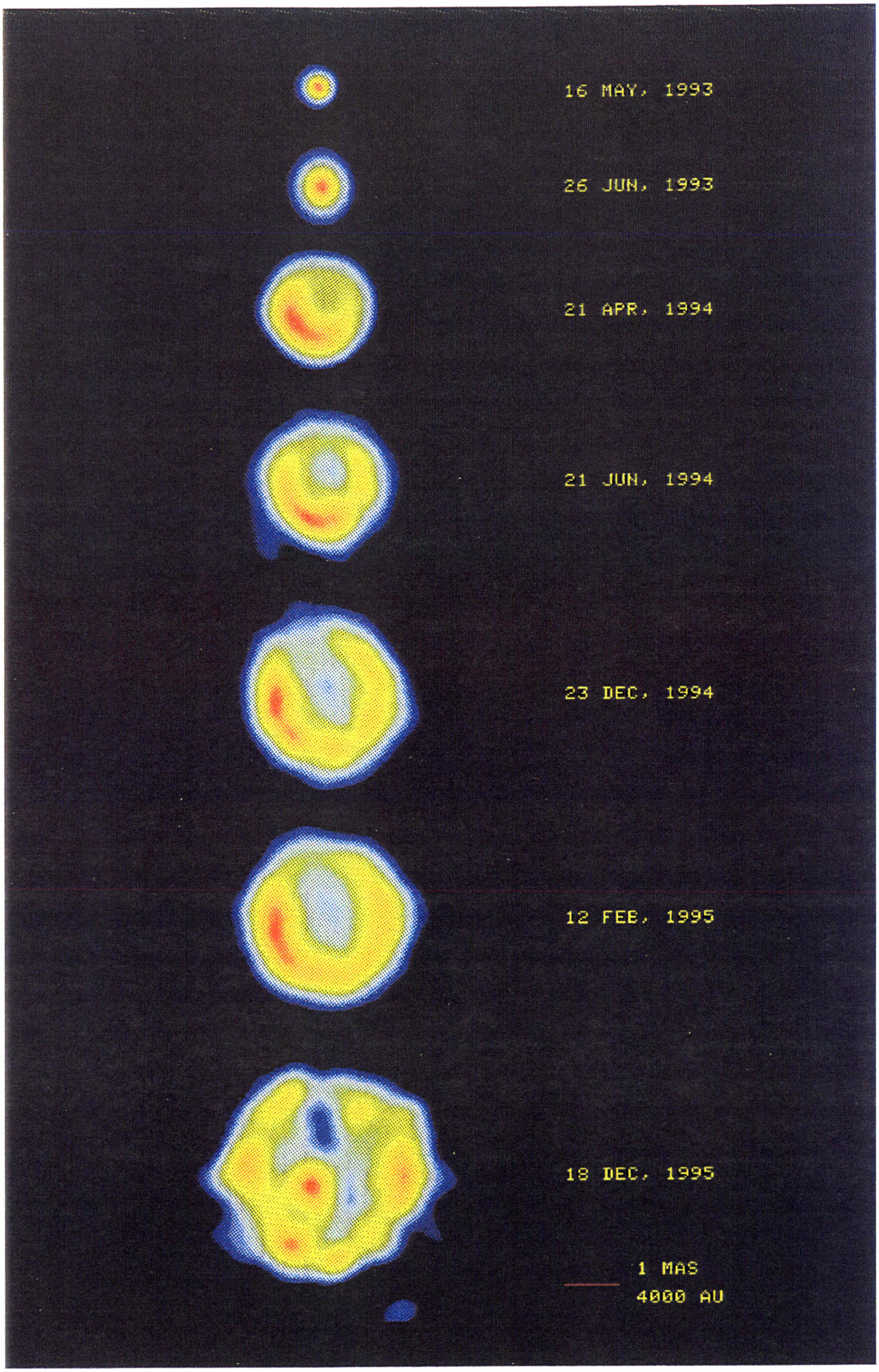

Figure IV-2. A series of VLBA images of the radio emission from the supernova 1993J in the nearby galaxy M81.

formation and evolution of the supernova shell in the first year after outburst and it was able to go throughout that year—no time was lost for the six months M81 was a daytime object and hence not observable with optical telescopes.

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. Figures IV-3 and IV-4 illustrate the ability of such incredibly high resolution for explorations of stellar physics. These two figures are VLBA spectral images of SiO emission from the AGB star TX Cam. The first figure shows the distribution of SiO masers in the stellar atmosphere. Here we see that the SiO forms at approximately twice the stellar diameter where the atmosphere has cooled sufficiently for refractory molecules to form and be stable. Repeated observations show these masers to change position as the clumps of gas aggregate and disperse. Spectral polarimetry of the SiO maser spots allows us to map the magnetic field in the stellar atmosphere. This is shown on Figure IV-4. This is a VLBA image of the electric vectors obtained from full Stokes parameter imaging of TX Cam. The tangential distribution of electric vectors indicates that the magnetic field is principally poloidal. Detailed information such as this mapped across a stellar disk with a resolution of a small fraction of the stellar radius comes uniquely from the VLBA.

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 8000 km are covered, which provides resolutions up to 0.2 milli-arcsecond 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.

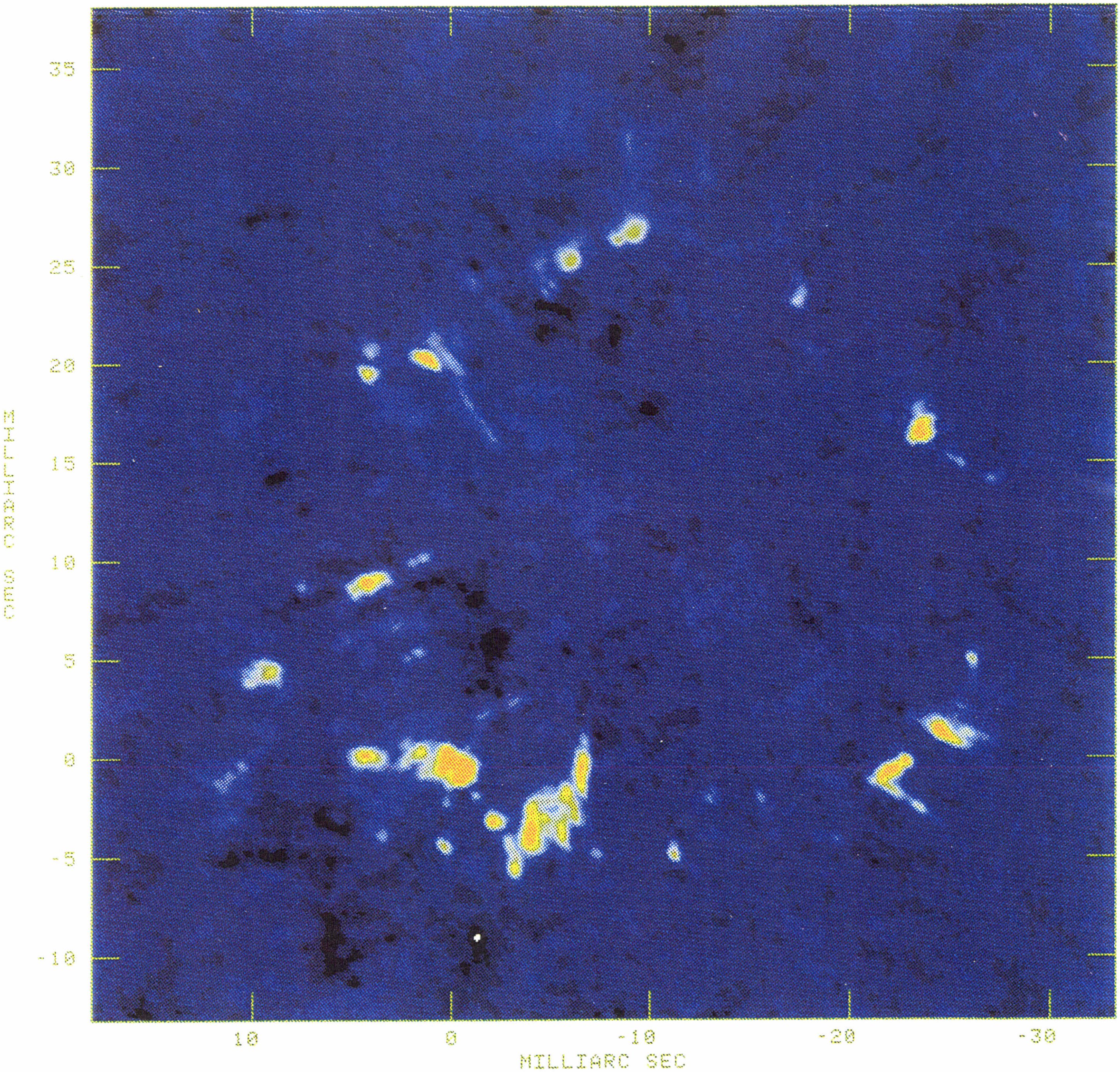

Figure IV-3. Clumps of SiO maser emission in the atmosphere of the star TX Cam.

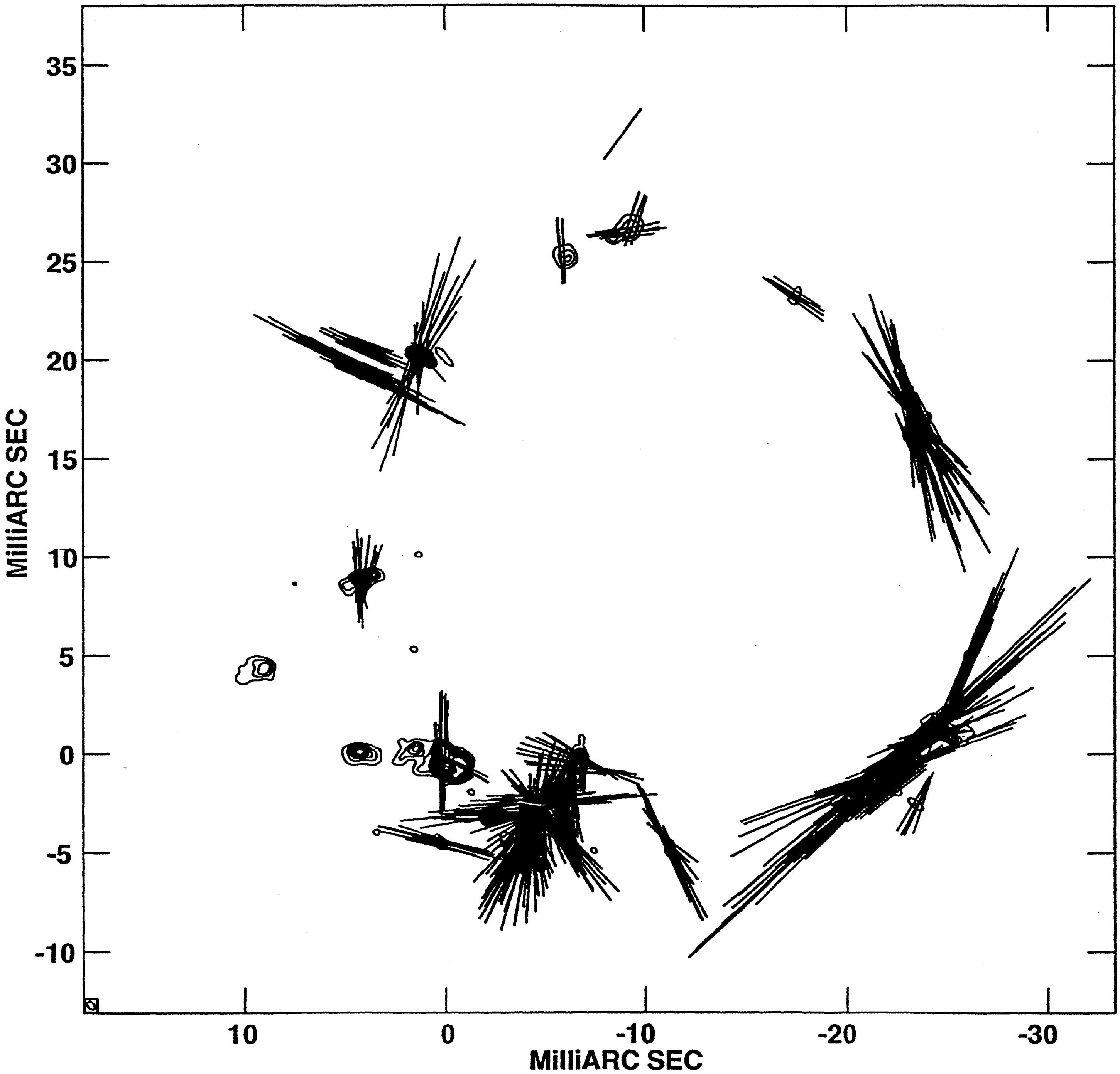

Figure IV-4. The electric vectors of the polarized SiO emission in the atmosphere of TX Cam.

Table IV-1. VLBA Receiving Systems

Band Designation (Note 1)			Frequency Range (GHz)			Aperture Efficiency (Note 2)	System Temp [K] (Note 3)
330	90	P	0.312	-	0.342	0.45	195
610	50	P	0.580	-	0.640	0.40	200
1.5	20	L	1.35	-	1.75	0.57	32
2.3	13	S	2.15	-	2.35	0.50	34
4.8	6	C	4.6	-	5.1	0.72	40
8.4	4	X	8.0	-	8.8	0.70	35
14	2	U	12.0	-	15.4	0.50	73
23	1	K	21.7	-	24.1	0.60	100
43	0.7	Q	41.0	-	45.0	0.45	100

Notes:
1. Megahertz/gigahertz frequency; centimeter wavelength; conventional radio (or VLA) letter codes.
2. Overall aperture efficiency and total system noise temperature at zenith. Values are representative of those measured on several VLBA antennas.
3. Single-frequency performance (without dichroic) shown.

The VLBA is outfitted for observations in nine 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, 1024 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 postprocessing 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.

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 correlator, when fully operational in all its modes, will be capable of correlating data from the 10-element VLBA at four times faster than real time (a factor of two from the number of correlator inputs available compared to the number of VLBA stations, and another factor of two by replaying the tapes at twice the recording speed). 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 except one are now supported by the software; they have been tested, and they are being used in science observations. The remaining function, pulsar gating, is next on the list of software functions to be implemented, after correlation of space VLBI data has been 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 in handling 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 1 mm 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 have 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 1997. 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.

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. Both these developments will involve substantial testing before they can be made available for routine observations.

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, following debugging of orbiting VLBI operations software and preceding pulsar gating.

V. VERY LARGE ARRAY: UPGRADE PROJECT

1. Overview of the Project

The Very Large Array has passed the fifteenth 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 and a much wider bandwidth (> 1 GHz/polarization), and add two new observing bands, with a primary goal of obtaining continuous frequency coverage from 1 to 50 GHz.
- To design a removable subreflector mounting which will permit installation of up to three prime-focus UHF feeds to cover to 250-1000 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 (> 1 GHz/polarization) and to provide improved resolution and flexibility for spectral line work. The new correlator will support a larger number of antennas ($\geq$ 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 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, and for the thirteen antennas operating at 45 GHz 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 per polarization bandwidth, 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 observations at frequencies below the current limit of ~1280 MHz.

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. 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 system is located at the prime focus, as is a 73.0 - 74.5 MHz system on eight antennas. The current plan is to build a rotating turret at the prime focus, on which would be mounted the current subreflector, and three 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	1.0 - 2.0	1.0	2.0	Upgrade
S	2.0 - 4.0	2.0	2.0	New
C	4.0 - 8.0	4.0	2.0	Upgrade
X	8.00 - 12.0	4.00	1.50	Upgrade
Ku	12.0 - 18.0	6.00	1.50	Upgrade
K	18.0 - 26.5	8.50	1.47	Upgrade
Ka	26.5 - 40.0	13.50	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's 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	.05	20-35	150	120
50	45-90	.10	9-18	-	-
30	25-32	.2	2.7	-	-
20	30	.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. The chief limitation on observational stellar radio astrophysics is sensitivity. Consequently, one of the most important elements of the proposed upgrade for stellar research will be the order of magnitude improvement in sensitivity afforded by the improved receivers and greater bandwidth. Several hundred stellar radio sources are now known. The sensitivity upgrade to the VLA will increase this number by over an order of magnitude. Sensitivity at the micro Jansky level has the potential to increase the number of radio detected stars from the current value of a few hundred to thousands or, perhaps, tens of thousands. This phenomenal increase cannot help but revolutionize the field of stellar radio astronomy. New classes of radio stars and previously unknown phenomena relating to stellar radio emission are almost certain to be discovered.

A New Correlator

The current VLA correlator is limited to a bandwidth of 4x50 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, and searches for redshifted spectral lines are extremely inefficient. Similarly, a 50 MHz bandwidth at high frequencies
(350 km/s at 43 GHz) makes observations of extragalactic lines difficult, if not impossible, and excludes many components of those molecular lines which are split into multiple transitions.

Current specifications for the correlator call for a minimum of 512 channels in each of the four 500 MHz IF channels returned from the antennas, although the identification and excision of radio frequency interference may require significantly more channels. 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 at high frequencies. 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 intermediate to those contained in the VLA and 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 possibility is to 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 four 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, NM), the angular resolution of the VLA could be improved by an order of magnitude in some cases. 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 six 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 milli-arcseconds. 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

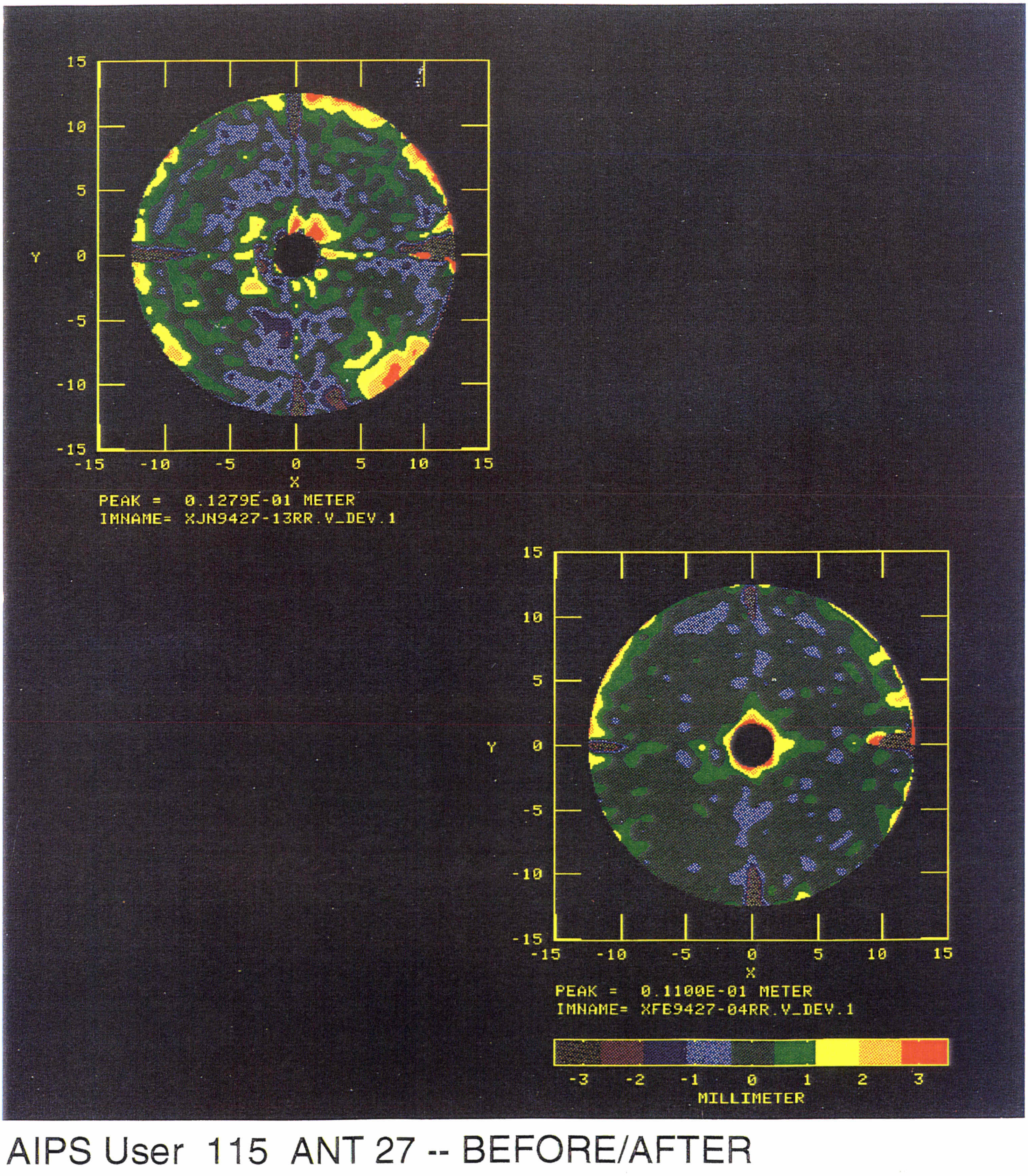

Figure V-1. Holographic maps of the surface of a VLA antenna before and after the surface shape has been adjusted.

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 35-40 percent.

3. Major Research Instrumentation Program

The NSF has recently announced a new 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 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. The second proposal 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. The funding partner for this proposal was the State of New Mexico, but the current legislative session failed to pass the required bill despite strong support. The total amount requested is $667K; alternative matching funds are being sought.

The two proposals were submitted to the NSF in February, 1997, and a decision from the NSF is expected by about September of the same year.

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. As one measure to this end, a VLA Upgrade Science Workshop was held in Socorro in January 1995. Since then the VLA Upgrade Project has been formally organized with a Project Scientist and Project Engineering Director. Nine working groups are being appointed. A memo series has begun. The goal is to produce a design study by the end of 1997, in time for consideration by the next decadal survey committee.

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 principle 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 1980's. 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 the long range plan, the MMA will be close to 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, 140 Foot) and also to be prepared for the future instruments: the GBT, the MMA, and the VLA upgrade.

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 over ten 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 or 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, the NRAO will plan and implement storage technologies which both relieve current bottlenecks and also prepare a foundation for handling the volume of date 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 2002, the standard machine that users and staff members at NRAO are likely to need will be a 4 to 8 processor machine with 128 to 256 MBytes of memory, 10-20 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 MMA.

The AIPS++ Project

The Astronomical Information Processing System (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, New Mexico, and an NRAO staff member, Tim Cornwell, is the project manager.

AIPS++ is now moving from principle development into distribution to the astronomical community. This will occur via a series of major releases starting in late 1997 and followed by one major release per year thereafter. As part of this planned release process, a beta release was made in February 1997 to the member sites of the AIPS++ consortium, and to a number of external sites. We plan to use this beta release as a test bed for approximately six months before the first major release. This first public release will be targeted towards astronomical use of the system, with the next release targeted towards code developers as well. To aid and encourage use of the system by both astronomers and code developers, in 1998 we plan to hold workshops on the astronomical use of AIPS++, and 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 Green Bank Telescope.

AIPS++ is advised by a Scientific and Technical Advisory Group (STAG) that is planned to meet annually. The first meeting of the STAG occurred in November 1996. The report is available at URL http://aips2.nrao.edu/aips++/docs/notes/198/198.html.

A development plan for AIPS++ covering the first three major releases, up to late 1999, is available at URL http://aips2.nrao.edu/aips++/docs/notes/202/202.html and more general information is available 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 is performed primarily at the Central Development Laboratory (CDL). The CDL works collaboratively with the engineering staff at all the observing sites, and for this reason the technical tasks undertaken at any particular time at the NRAO involve work done principally at the sites as well as work done at the CDL. 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 an 86 GHz receiver for the VLBA;
- development of advanced electromagnetic structures;
- MMA technology development and demonstration tasks;
- correlators and spectrometers;
- development of advanced cryogenic capabilities;
- new concepts in feed arrays and interference canceling receivers.

HFET Amplifiers

It was predicted in the previous Long Range Plan that small area HFET amplifiers on Indium Phosphide (InP) substrates could be fabricated with noise figures roughly half of that attainable with commercial Gallium Arsenide (GaAs) HFETs. This prediction has been fulfilled. Recently developed amplifiers have been fabricated which cover full waveguide bands with unprecedented low noise. Figure VII-1 shows the performance of such amplifiers, compared with the theoretical performance and with the performance of SIS mixers. 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 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 6000 such devices are available from the two wafers thus far built for the NRAO.

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

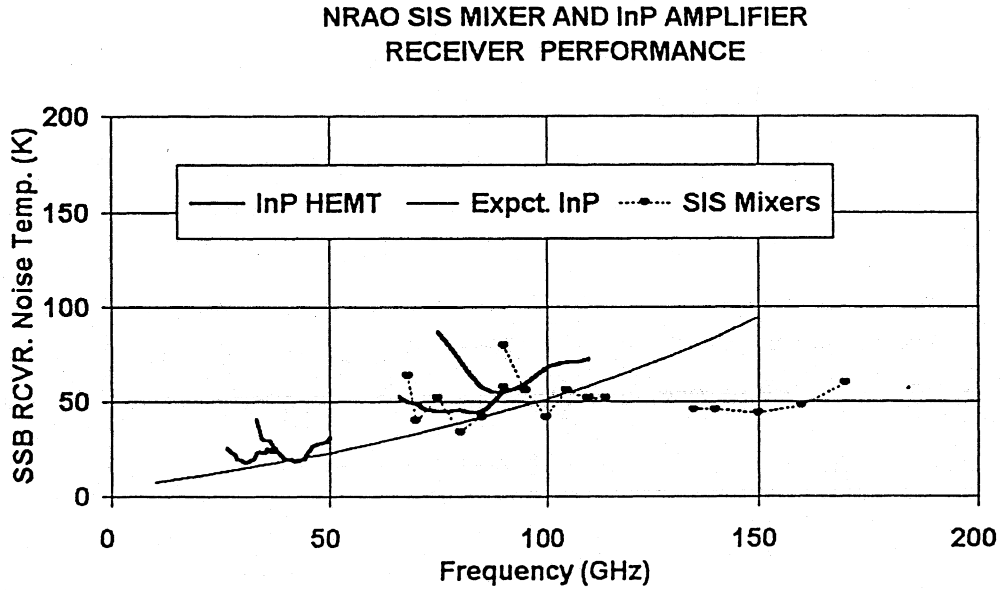

Figure VII-1: HEMT amplifiers

tested; another is under construction. 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 antenna can be made to work at that frequency. At the least, the MMA will use these amplifiers for phase calibration and scientific observations at frequencies between 27 and 100 GHz. HFET amplifiers also have the advantage of a larger dynamic range than SIS mixers and thus reduced susceptibility to the effects of interference.

As a result of this successful amplifier development, the CDL has undertaken a large cooperative project with NASA Goddard Space Flight Center and Princeton University to develop flight amplifiers for the Microwave Anisotropy Probe (MAP) satellite. NASA will pay for amplifiers at frequencies of 22, 30, 40, 60, and 90 GHz to be flown in the year 2000. The NRAO will then possess proven designs extending the use of InP devices to these frequencies, and will acquire the expertise needed to make designs at even lower frequencies, reducing dependence on finding the best commercial GaAs devices, whose availability has been variable. These amplifiers are being fabricated with InP devices from a new wafer which has a surface passivating layer and will be less susceptible to degradation from humidity during storage. Preliminary results indicate these devices have a lower requirement for illumination when cold and that they have a more consistent $1/f$ noise spectrum than those from previous wafers. About 40,000 devices will be available from this wafer.

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 devices 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 are developing balanced amplifiers using Lang couplers fabricated on printed circuit boards. 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 much reduced. Current designs work very well up to 520 MHz 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 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 image separating (single sideband) mixer which has been fabricated at JPL and is currently undergoing testing. The objective is to provide at least 15 dB of sideband rejection so that atmospheric noise in the unwanted sideband can be greatly reduced.

The second new design is for a single-chip balanced, tunerless mixer. This design will be undertaken in mid-1997 and is expected to yield results before the end of the year. In a balanced design, the requirements for LO power are greatly reduced (by about 17 dB), easing the problem of supplying sufficient LO power at these high frequencies. Furthermore, a balanced design should greatly reduce sensitivity to LO amplitude noise, a problem which plagues mixers using only a single mixing element. This design will be fabricated by UVA.

A third project is the development of a mixer with an integrated IF amplifier. This technique has been successfully pioneered by Caltech in order to achieve a bandwidth of 4 GHz (as opposed to less than 2 GHz for other current designs). The Caltech effort used a very simple matching network between the mixer and the amplifier which we plan to improve in order to achieve a bandwidth of 8 GHz.

The goal of these three developments (image separating mixer, balanced mixer, 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, image 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 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 which is 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 at the Pie Town VLBA antenna. The performance of the antenna at 86 GHz has not been fully evaluated but it appears to be good enough to be useful. A second receiver is under construction and will be installed by mid-1997. 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 upgrade of the VLA to achieve complete frequency coverage and are being incorporated into a new prototype receiver.

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 acceptable gas leakage.

MMA Development Tasks

Much of the SIS emphasis and a significant fraction of the effort on high frequency HFET amplifiers has been done with the needs of the MMA in mind. The fact that many MMA elements will be built in multiples of 80 (40 antennas, 2 polarizations) 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. 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 is likely to 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, electromagnetics, 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 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 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 is likely to have more LO noise than a Gunn system and its use is therefore probably dependent on the success of the balanced SIS mixer described above, which will be much less sensitive to LO noise.

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 a 100 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 sub-millimeter bands are that photodiodes that operate efficiently at frequencies up to 900 GHz are difficult to design and fabricate, and that no good means has yet been demonstrated for coupling sufficient energy out of the photodiode at the frequencies of interest. We will seek a collaborative effort with either a commercial or academic group skilled in photomixers and combine their knowledge with our own RF expertise 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.

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. Since a special correlator chip (or chips) will probably have to be designed for the MMA, and since fabrication technology is presently improving rapidly, it will be advantageous to wait as long as possible before committing to a particular design. This means that some sort of interim correlator will be needed for testing during the development phase of the project, and perhaps a second interim correlator for early operation at the MMA site. We are investigating use of a copy of the GBT spectrometer as the development correlator while the new system is further studied and developed.

Cryogenic Capabilities

NRAO receivers have traditionally employed two types of mechanical refrigeration: the two-stage Gifford-McMahon (GM) cycle which achieves a working temperature of about 15 K, and the addition of a Joule-Thompson (JT) stage to the GM cycle in order to reach 4 K. Niobium SIS mixers require 4 K, whereas HFET devices require only 15 K. Both these systems have many moving parts, consume large amounts of electricity, and require regular maintenance.

In recent years, there have been new developments in cryogenic technology which hold out some hope of achieving these low temperatures at lower cost and with greater mechanical simplicity and higher reliability. We intend to learn about these systems and, in promising areas, acquire equipment and perform experiments to determine if any of these new technologies should be substituted for the present GM and JT systems, particularly for the MMA.

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 are presently developing an array feed receiver which packs planar feeds close together and achieves multiple beam synthesis by weighted combination of multiple feed outputs. A prototype system for operation at 1.2-1.8 GHz is being built which will provide proof-of-concept operation and help determine if it is worth pursuing such a system for operational use on the GBT.

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 twenty-first 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.

Another technological possibility being developed for future use 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. We will determine if such a system can be used to mitigate the worst effects of RFI in real observations.

VIII. BUDGET AND PERSONNEL PROJECTIONS

(NSF Funds, $ in Thousands)

	1998	1999	2000	2001	2002	2003
OPERATIONS						
Base Operations	$30,050	31,600	33,100	34,425	35,800	37,230
Research & Oper. Equip.	0	1,400	1,500	1,500	1,600	1,600
NSF Operations	$30,050	$33,000	$34,600	$35,925	$37,400	$38,830
NEW INITIATIVES (Major Res. Equip.)						
MMA Design & Dev.	$ 9,000	$ 9,000	8,000	--	--	--
MMA Construction	--	--	--	25,000	41,000	41,000
Total New Initiatives	$ 9,000	$ 9,000	$ 8,000	$ 25,000	$41,000	$41,000

Personnel Projection (Full-Time -- Year End Ceiling)

Operations	400	400	405	405	405	405
MMA Design & Dev.	24	24	24	--	--	--
MMA Construction	--	--	--	40	50	50
Non-NSF Research	18	18	7	7	7	7
Personnel Totals	442	442	436	452	462	462