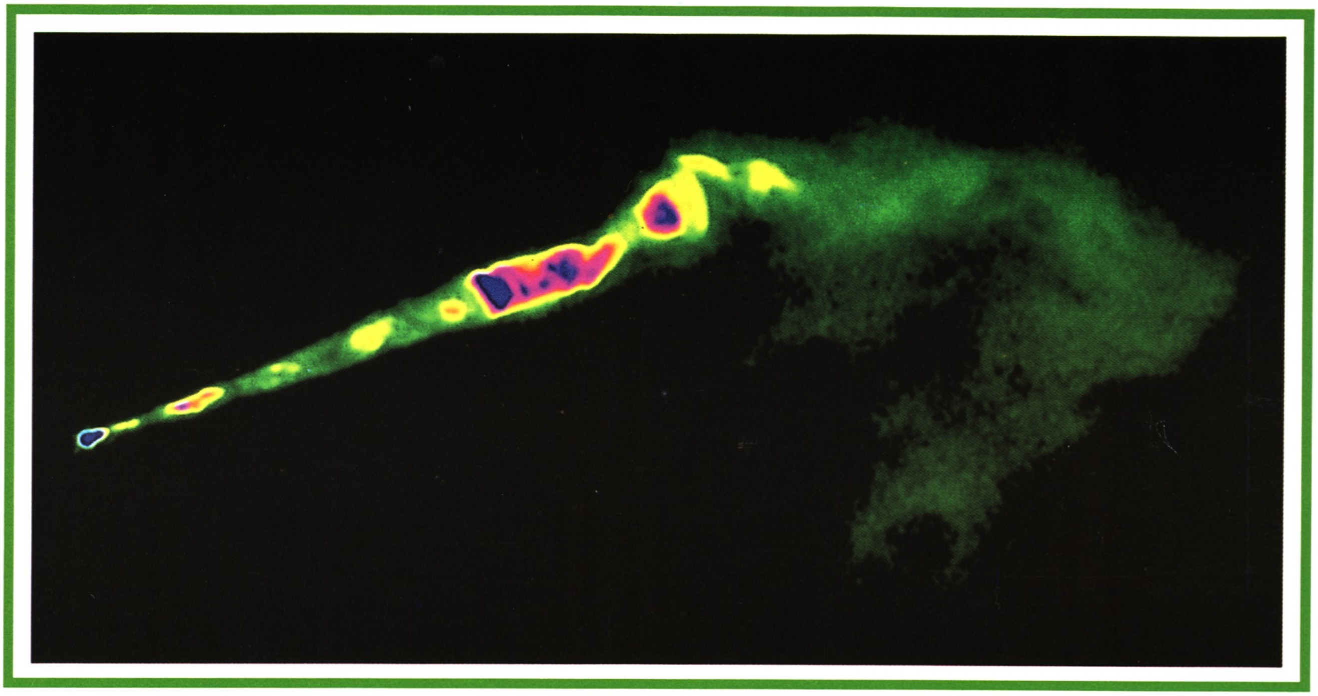

LONG RANGE PLAN
1996 - 2001

NATIONAL RADIO ASTRONOMY OBSERVATORY

Cover image: Radio emission from the relativistic jet in radio galaxy M87 (Virgo A). Gas flowing out of the center of the radio galaxy (the small left-most blue spot) is traced in this VLA image by its radio emission. The extent of the jet seen here is more than 7500 light-years. From repeated VLA observations made over 12 years it has been possible to see the bright radio clumps, or knots, of emission flow away from the galactic nucleus at a velocity of greater than one-half the speed of light. Observers: J. Biretta and F. Owen.

NATIONAL RADIO ASTRONOMY OBSERVATORY

LONG RANGE PLAN

1996 - 2001

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I. OVERVIEW

The long range plan of the NRAO is to provide the forefront observing facilities needed for research in radio astronomy by this and subsequent generations of scientists. This statement implies change: research drives and is driven by change and an instrument that is today at the forefront in time needs to be upgraded or replaced. The NRAO Long Range Plan takes this inevitability into account by recognizing as its hallmark the need to plan carefully for the research requirements of tomorrow's students and scholars.

Prior to embarking on the construction of such a plan, it is well to measure past performance in the light of these same criteria. The newest NRAO facility, the Very Long Baseline Array (VLBA), was completed in 1993 and is now achieving full-time operational status. It was built in the expectation that its imaging capability would be sufficiently better than that of the *ad hoc* VLBI network that one could realistically compare the large-scale Very Large Array (VLA) images with the fine-scale VLBA images and extract a reliable understanding of the common source physics. Figure I-1, an image of the radio galaxy M87, is one recent example of the realization of this expectation for the VLBA. The upper panel is the VLA image of the jet which extends more than 6000 light years from the nucleus of M87. A super-massive black hole is presumed to lie at the origin of the jet and to provide the energy driving the jet. With the VLBA we can look closer into the black hole as evidenced by the middle panel image and the lower image. In fact the lower image, a VLBA image made at a frequency of 22 GHz, is the highest resolution ever obtained of the region surrounding a super-massive black hole. The finest details in this image are only a few light weeks in size. Surprisingly, even at this extremely high resolution the structure of the jet is similar to that seen in the large-scale VLA image at the top. The same source physics operates on the scale of light weeks to a scale 100,000 times larger!

While the expectation with the VLBA was that images such as Figure I-1 would steer us to a clear picture of a super-massive black hole, we were surprised to see that it was in fact a VLBA image of the H_2O maser emission in the galaxy NGC 4258 that gave this picture. Figure I-2 is a plot of the velocity of the H_2O masers in the nucleus of NGC 4258 shown as a function of angular displacement from the nucleus. The line drawn through the observed points is a simple Keplerian curve. The H_2O masers are orbiting the galactic nucleus at a radius of 0.065 pc, just like planets around the sun. And just as with the solar system, the maser orbits can be used to determine the mass of the central object: It is 3.6×10^7 $M_\odot$, all confined to the interior of the H_2O

maser orbits. According to an editorial in Nature magazine accompanying the report of these VLBA observations, this is the first compelling evidence for the existence of a super-massive black hole anywhere in the universe.

The VLBA is successfully achieving the goals set for it in the long range planning of the NRAO. The 1996-2001 Long Range Plan of the NRAO sets out similar high expectations for the Millimeter Array, the Green Bank Telescope, and a project to upgrade the scientific capability of the VLA.

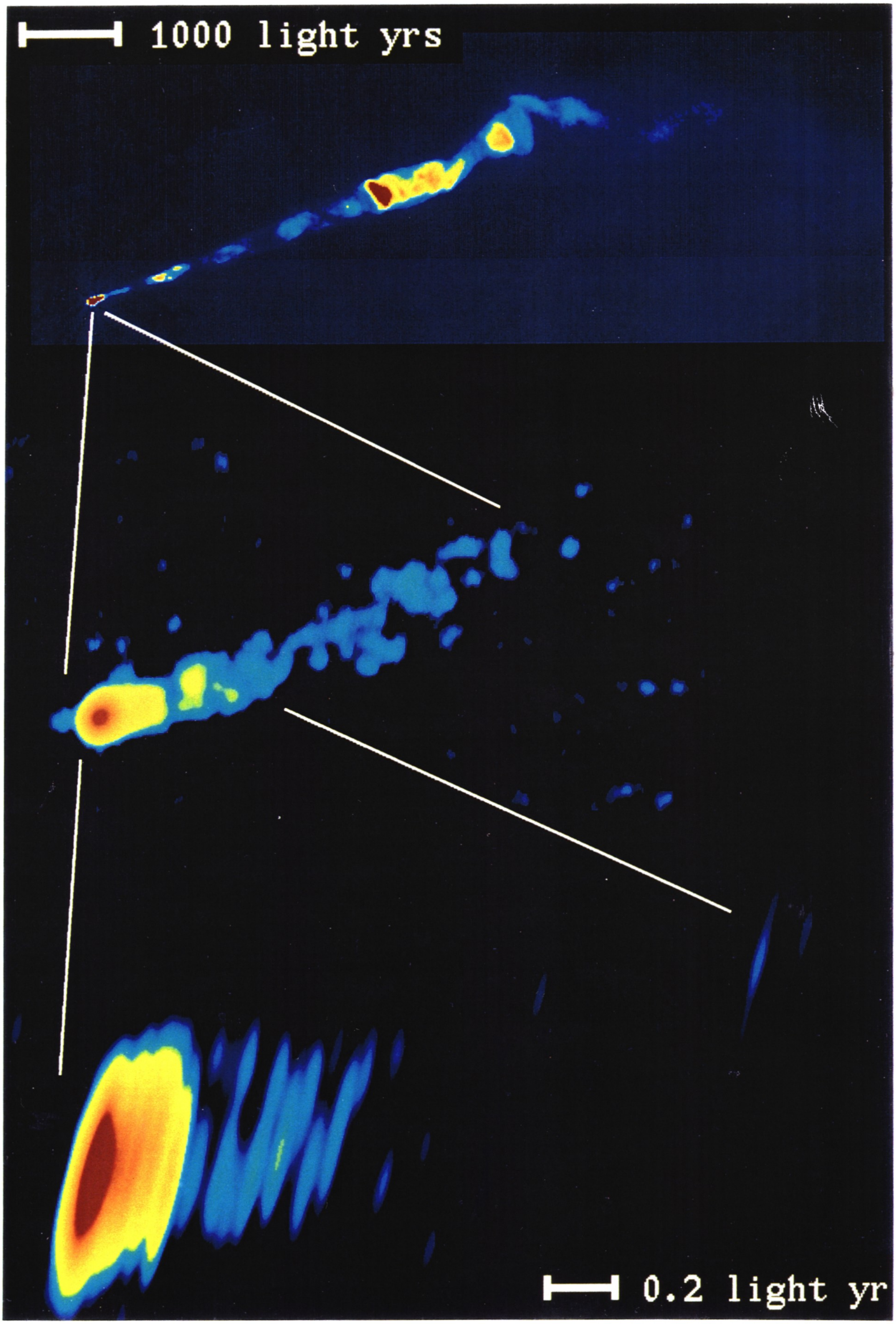

Figure I-1. Images of the jet in the radio galaxy M87: Upper panel shows the VLA image; lower two panels are VLBA images.

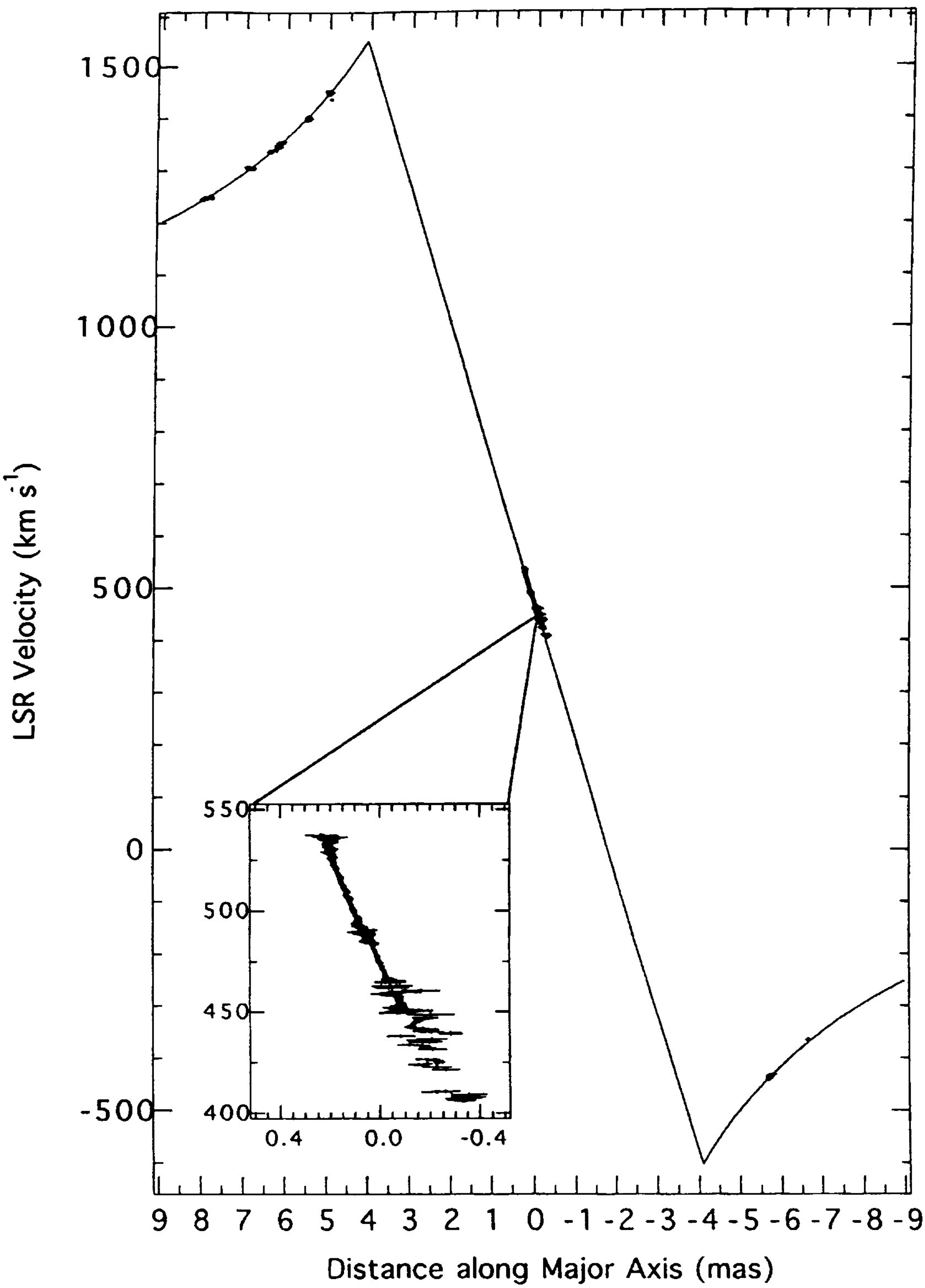

Figure I-2. Plot of radial velocity versus angular distance from the nucleus of NGC 4258 of the water masers orbiting the nucleus.

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

1. The Millimeter Array

Design of the Millimeter Array (MMA) began at the NRAO in 1983 and was assembled from the ideas of more than seventy astronomers at three scientific workshops held at the NRAO from 1985 to 1989. A formal proposal for the MMA submitted to the NSF in 1990 culminated this phase of the effort. The MMA was highlighted by the Astronomy and Astrophysics Survey Report (the *Bahcall Report*) as one of the four major astronomical facilities for the decade of the 1990s.

The MMA is a high-resolution imaging array comprised of forty 8 meter transportable antennas located at a high altitude site. An artist's concept of the MMA is shown as Figure II-1. The Millimeter Array combines the sensitivity provided by the collecting area of a telescope 50 meters in diameter with angular resolution < 0".1, superior to that of the design goals of the Hubble Space Telescope, and it operates at frequencies 35-350 GHz at which thermal processes illuminate the sky. This unprecedented combination of sensitivity and angular resolution at short wavelengths will make available for astronomical investigation a wealth of unique opportunities and new science, including the ability to:

- Image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as z = 10.
- Reveal the kinematics of optically obscured galactic nuclei and QSOs on spatial scales smaller than 100 pc.
- Assess the influence that chemical and isotopic gradients in galactic disks have on star formation and spiral structure.
- Image heavily obscured regions containing protostars, and protostellar and pre-planetary disks in nearby molecular clouds, with a spatial resolution of 10 AU and kinematic resolution < 1 km s^{-1}.
- Detect the photospheric emission from hundreds of nearby stars in every part of the Hertzsprung-Russell (H-R) diagram.
- Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of stellar nuclear processing and envelope convection.

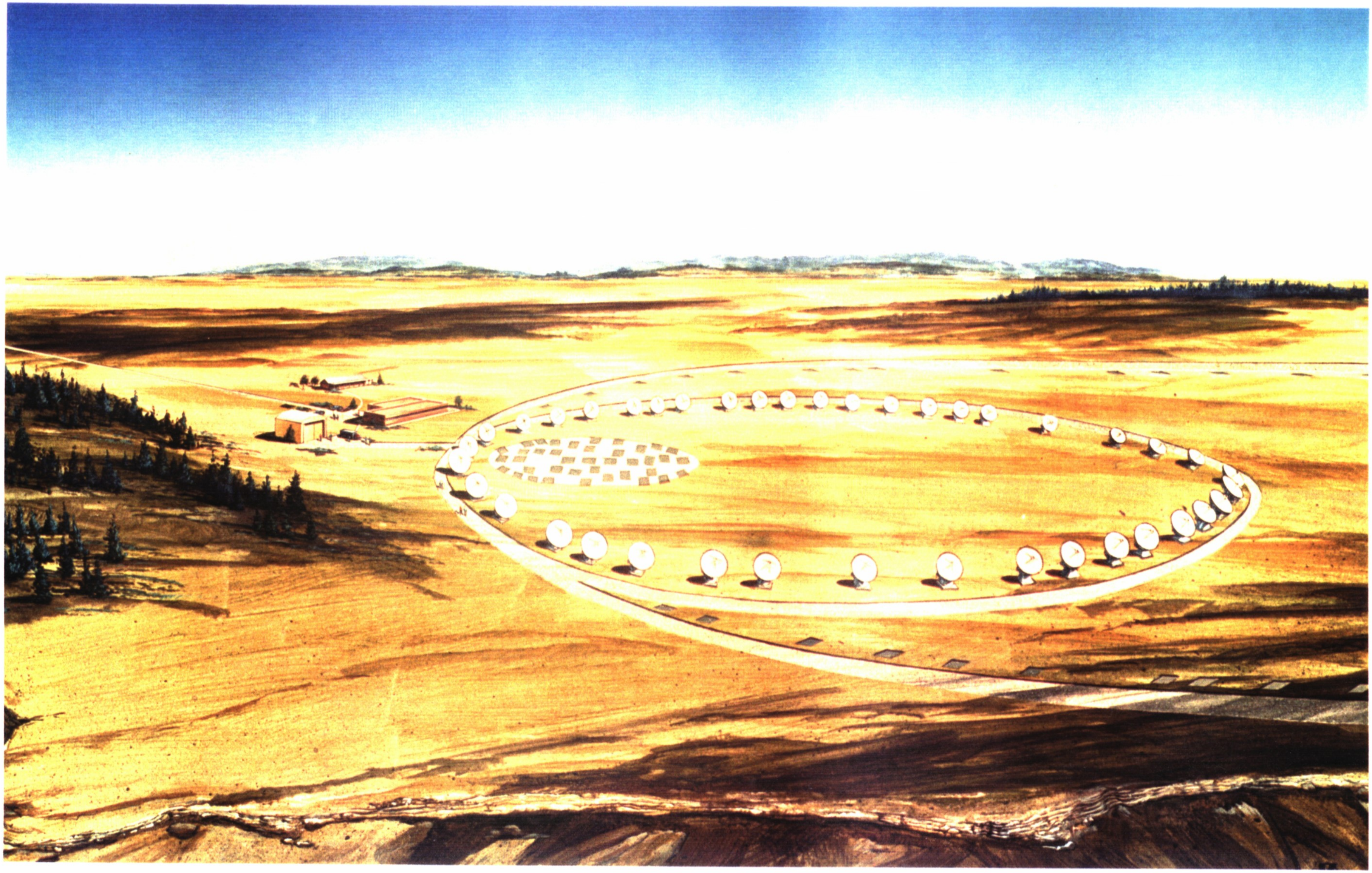

Figure II-1. Artist concept of the Millimeter Array.

- Resolve the dust formation region and probe the structure of the magnetic field in stellar winds.
- Establish the relative distributions of the large number of complex molecular species in regions of star formation, relating them to shock fronts, grain disruption, and energetic outflows – information which is essential to the understanding of astrochemistry.
- Obtain unobscured sub-arcsecond images of cometary nuclei, hundreds of asteroids, planetary atmospheres and surfaces, and solar regions of active particle acceleration.

The MMA is the first synthesis telescope to be designed as a complete imaging instrument, capable of measuring all spatial frequency components of the sky brightness from zero to the longest array baseline. Astronomical images with the highest angular resolution, less than 0".07, will come from the array in its largest configuration, and will be made using the Fourier synthesis algorithms that enable the array to simulate an aperture of 3 kilometers diameter. Low resolution images of large regions of the sky will come from a mosaicing mode, using the MMA in its most compact configuration much like a conventional single dish, the MMA antennas rapidly scanning the region to be imaged, in unison. These two capabilities have never been incorporated in a single instrument. The complexity of the sky at millimeter wavelengths and the unique interrelationship of astrophysical phenomena on a wide range of spatial scales that is characteristic of millimeter-wave scientific investigations make the melding of these capabilities a fundamental requirement for the MMA.

In specifying the scientific goals of the MMA, astronomers are calling for an unprecedented combination of sensitivity and angular resolution at short wavelengths, one that will make a wealth of unique astronomical opportunities and new science available for investigation. With the antennas spread over a 3 kilometer array, astronomers are able to observe in detail the formation of protostars and pre-planetary disks in molecular clouds. With the antennas clumped together in an area no more than 70 meters across, astronomers can observe the chemical evolution in molecular clouds which precedes, or perhaps initiates, star formation. Observations in widely separated frequency bands may be conducted simultaneously in support of studies of molecular excitation, with complete frequency coverage provided in all the atmospheric windows from 9 mm to 0.9 mm wavelength. With 40 antennas, the array is sufficiently fast, and the imaging characteristics of such high quality, that the astronomer will be able to see the results and modify the observing program as the observations are being made. The MMA is a unique and powerful instrument.

The burden of designing a powerful and unique instrument is that it requires an extension of existing technology. This is as true for the MMA – with its densely packed mosaicing configuration, broadband sensitive receivers, total power instrumentation, and precision antennas – as it was for the Keck Telescope with its segmented, optical quality primary mirror, and the GBT with its unblocked 100 meter aperture and real-time, laser-guided surface metrology. Application of significant technological advances is the *sine qua non* of the design of a forefront scientific instrument. Precise technical specifications of the Millimeter Array is the emphasis of the near-term planning for development of the MMA.

Millimeter Array Development Consortium

For several years we have developed the argument that a sensible way to fund the MMA was to begin with a design and development phase of three years, followed by six years of construction. The purpose of the design and development phase was to allow us to evaluate hardware options and to experiment with prototypes prior to committing to construction of multiples of 40 of each of the MMA instruments.

The utility of the MMA design and development phase has been additionally recognized as a means to address a number of technical issues (e.g., phase calibration) that the MMA concept either presents anew or carries to an extreme not previously experienced by existing instruments. Moreover, it is also possible to perform useful diagnostic work for the MMA problem areas with existing arrays. Given this, and the interest of our colleagues at the Owens Valley Radio Observatory (OVRO) and those affiliated with the Berkeley-Illinois-Maryland Association (BIMA), we began discussing a close collaboration between those of us at the NRAO working on the MMA and the university groups. The outcome of these discussions was formation of the MMA Development Consortium (MDC).

The MDC concept, while thought of originally in the context of a collaboration of the university groups in the early development stage of the MMA, has subsequently been broadened to include a longer term formal relation by which the California arrays serve a training function for students and postdoctorals, and they are used for MMA instrument prototyping in the operational phase of the MMA. It may also be possible and desirable for the two university arrays to be combined at a new, high elevation site in California so as to form a more powerful instrument. This may be particularly important if the MMA is built in the southern hemisphere.

The MDC has a steering committee of four members, two from the NRAO and one each from OVRO and BIMA, who define MMA development activities. Presently MDC working groups are being formed to evaluate the MMA development tasks. We believe the MDC concept is one that can be successful for the needs of the MMA and the university community, and that it could also benefit other large national projects where preservation of instrumentally related university groups was deemed important.

The MDC is organized such that it accomplishes its tasks by means of working groups composed of individuals at each of the three organizations. There are presently four working groups: antennas, receivers, phase calibration, and system. Progress is being made in all areas, but especially in the first two.

Antenna Design

Maintaining phase coherence of the array on the longest baselines requires rapid phase calibration. In the case of the MMA, this means switching rapidly between source and calibrator. The switch cycle may need to be as rapid as 10 seconds. Given this need, the antenna design has been concentrated on a very stiff slant-axis concept. Present work is being concentrated on an evaluation of materials given realistic thermal measurements we are currently making under the auspices of the MDC at Hat Creek on the BIMA antennas. Additional effort is being focussed on design of a conventional alt-az antenna as a comparison for the slant-axis design.

The scientific performance of the MMA will depend in very large measure on the site chosen for the array. This dependence is critical for the MMA, as compared with the VLA, for example, because the dominant contribution to receiver noise is the contribution from water in the atmosphere. The sensitivity of the MMA depends on the transparency of the atmosphere. Similarly, the ability of the MMA to produce images with good dynamic range and high fidelity depends on the phase stability of the atmosphere. The atmospheric transparency is wholly beyond our ability to control, but the stability is a property for which we can find some compensation if we can measure and correct for phase fluctuations. Any such compensation will place demands on the antenna design, and for this reason it is important that the antenna design be completed prior to the time that the site selection is made.

Receiver Design

The current generation of superconductor-insulator-superconductor (SIS) mixer receivers now on the 12 Meter Telescope meet the performance specifications for the MMA receivers. They do so however with mechanical tuners. Progress on simple tunerless mixers for the MMA is coming along well at the NRAO Central Development Laboratory (CDL); prototype 200-300 GHz tunerless mixers are now on the 12 Meter Telescope in the 8 beam receiver. A photograph of the prototype MMA SIS mixer is shown in the upper panel of Figure II-2.

The first performance specifications for millimeter-wave, 60-80 GHz heterostructure field effect transistor (HFET) receivers are also available from the CDL and look encouraging for the prospect of MMA HFET receivers throughout the 3 mm band. A prototype 7 mm HFET is also shown in Figure II-2.

MMA Advisory Committee

Definition of the MMA Development Consortium meant the MMA project needed a redefined advisory committee structure – the former advisory committee included members from OVRO and BIMA that should not, of course, be advising the MDC and hence themselves. The Advisory Committee was therefore reconstituted with members suggested by the MDC. The present membership is:

Fred C. Adams
University of Michigan

Thomas M. Bania
Boston University

John H. Bieging
University of Arizona

Edward B. Churchwell
University of Wisconsin

Neal Erickson
University of Massachusetts

Neal J. Evans
University of Texas

Paul Goldsmith
Cornell University

Richard Hills
Cavendish Laboratory

Gillian R. Knapp
Princeton University

Colin R. Masson
Center for Astrophysics

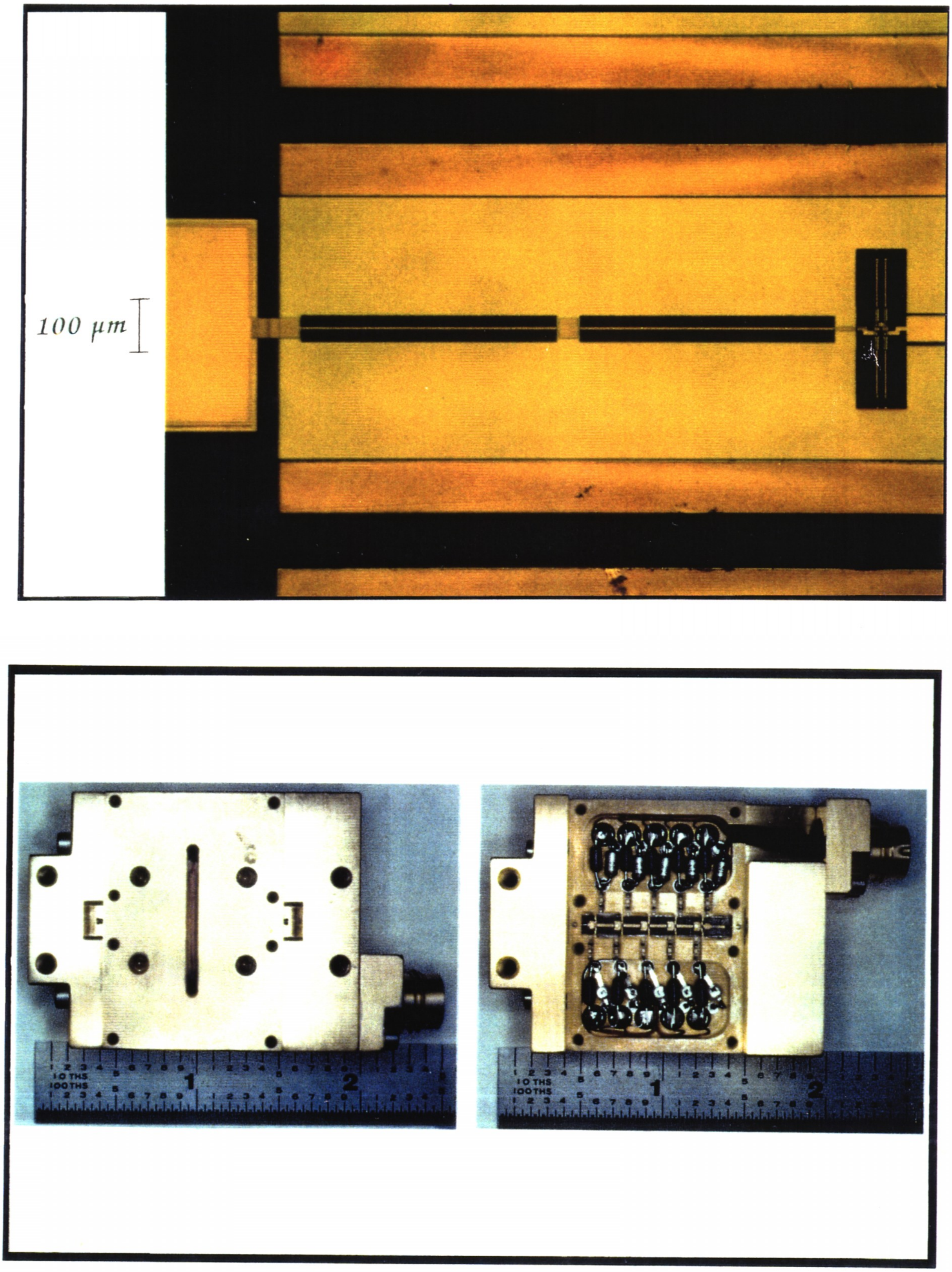

Figure II-2. Prototype MMA electronics: Upper panel shows an SIS mixer; lower panel a 7 mm HFET amplifier.

F. Peter Schloerb
University of Massachusetts

Ewine van Dishoeck
University of Leiden

Philip Solomon
SUNY, Stony Brook

Robert W. Wilson
Smithsonian Astrophys. Observatory

Jean Turner
University of California

Gareth Wynn-Willlams
University of Hawaii

International Collaboration in the MMA

The NSF desire for an international component of the MMA, both as a way of cost sharing of the capital costs and of sharing continuing operating expenses, has motivated us to seek international partners. We began by talking to the Japanese in meetings held in Tokyo and Washington. The Nobeyama Radio Observatory (NRO) is planning the Large Millimeter and Submillimeter Array (LMSA), a 50 element array with distinct but similar scientific goals to the MMA. The NRO group is considering sites in Mauna Kea and in Chile for the LMSA. Partnership between the MMA and the LMSA could take the form of one array built on Mauna Kea and the other in Chile; both arrays built independently on a common site or even a combined instrument more powerful than either alone. These discussions are on-going.

There has also been interest in the MMA expressed by astronomers in Canada, Mexico, and Europe. As a mechanism for discussing possible participation on a common basis we have drafted, and are circulating, a *Prospectus*. The prospectus outlines the partnership terms and defines partnership roles for participants interested in the capital project with a continuing commitment to the MMA operating expense (MMA Associates) and participants interested in contributing annually to the operating expense but with no capital investment (MMA Affiliates). Informal discussions have been held with astronomers in three or four countries. A proposal is being written by the Dutch astronomical community requesting funds to join the MMA.

Site Studies

In recent years we have come to appreciate how important the MMA site is to the performance of the array. Specifically, for a user facility such as the MMA, the mean performance of the array is the important criterion, not the peak performance that transitory atmospheric conditions can allow. The MMA must be sited where the annual mean atmospheric transparency and stability are exceptionally good. For this reason we have focussed our site studies in the northern hemisphere on Mauna Kea, and in the southern hemisphere on northern Chile, both areas lacking pronounced seasonal variations. Presently we have a database of 14 months of atmospheric transparency data for Mauna Kea, and we are operating an interferometer to assess the phase stability. Similar equipment, a 225 GHz tipping radiometer and an interferometer to measure atmospheric phase, has been shipped to a site at 5000 meters (16,400 feet) elevation east of the village of San Pedro de Atacama in northern Chile. We expect to have the Chilean instruments running by April 1995, and we intend to obtain and analyze a year's data for comparison with the data from Mauna Kea. We hope to be in a position to make a site decision for the MMA by June of 1996.

Long Range Plan

With approval of the NSF for funding of the MMA as one component of the NSF Major Research Equipment Program, we plan to complete the MMA design and development phase in three years, FY1997-1999. In the first year contract work on the first prototype antenna will begin; in the second year engineering tests of that antenna will be made and a second prototype will be built. At the end of the third year two of the MMA antennas will be built, equipped with MMA prototype electronics, and tested as an interferometer. The construction phase of the project will begin in FY1999, with the principal activity that year related to site and local infrastructure development. Cost and personnel figures for both phases of the MMA project are included in the table of Section VIII.

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. During 1994-1995 the biggest single impact on observing has been the introduction of on-the-fly spectral line mapping for extended areas. This has proved extremely popular with observers, enabling high quality data to be obtained over relatively large sources within a reasonable amount of observing time.

The new 8-beam, 1.3 mm SIS receiver system provides a unique mapping capability that will be much in demand throughout the years of the current long range plan. Construction has begun on a new 8-receiver, 4-beam receiver 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. Recently, there has been some progress in this area, and several observers are intensely pursuing this line of research at the 12 Meter. Recently MgCN has been detected. Another area of astrochemical research has involved molecules with the elusive N-O bond. Recently, only the third interstellar member of this family, N_2O was detected. Other active areas of astrochemical research involve diffuse and cirrus clouds, where polyatomic species are being detected and studied.

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, an on-the-fly observing mode has been developed and is now available both for continuum observations and for spectral line observations using the filter bank spectrometer. 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. This new method has been applied to many sources, two of which are shown on the accompanying figures (Figures II-3, II-4, and II-5). Figure II-3 is an observation of CO in a dense, cold molecular core, a possible protostar, in the dark cloud L483. In the upper

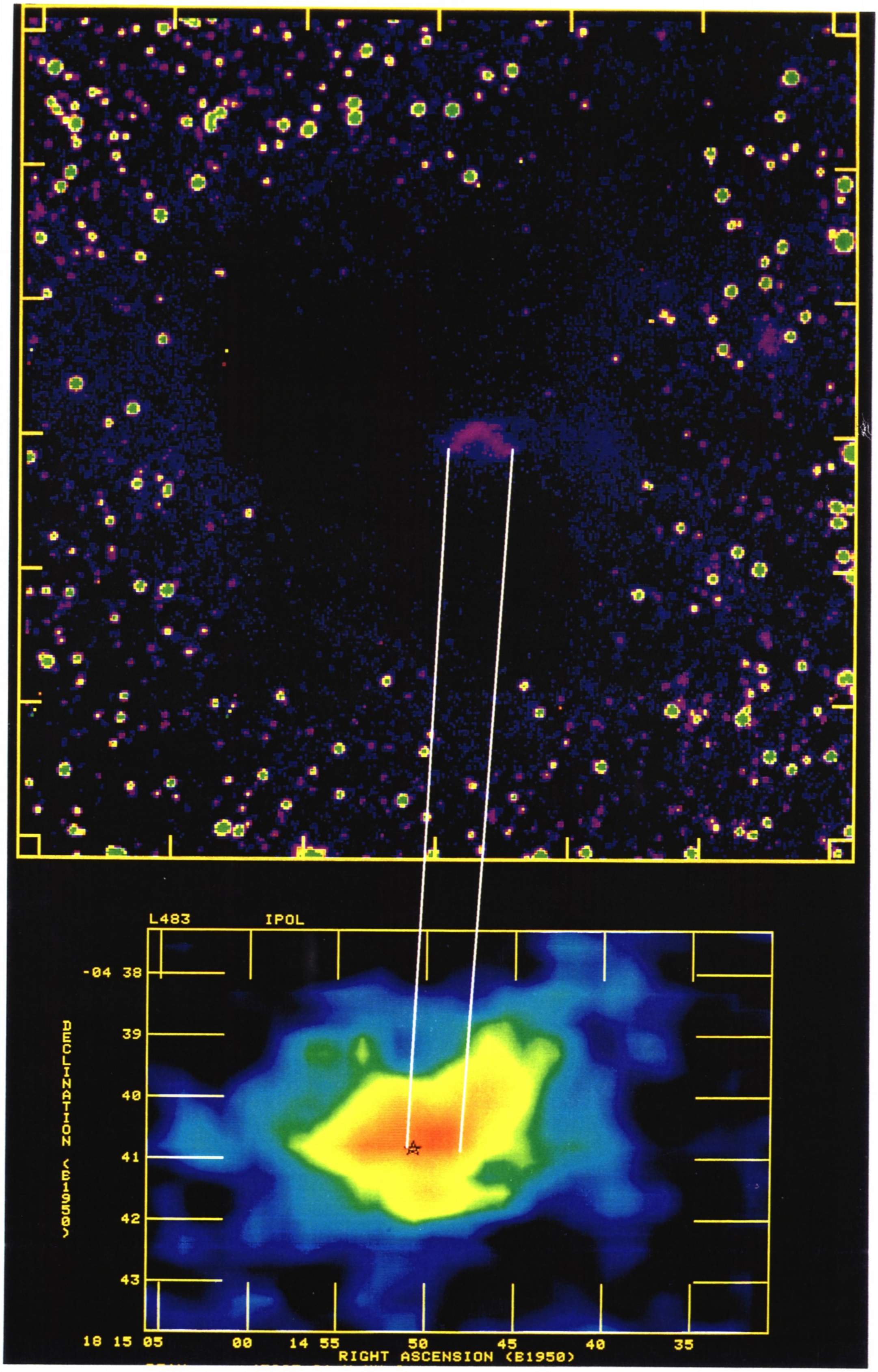

Figure II-3. The molecular cloud L483. The top image is a superposition of an optical photograph and the CO emission; the lower panel is an expanded view of the CO emission.

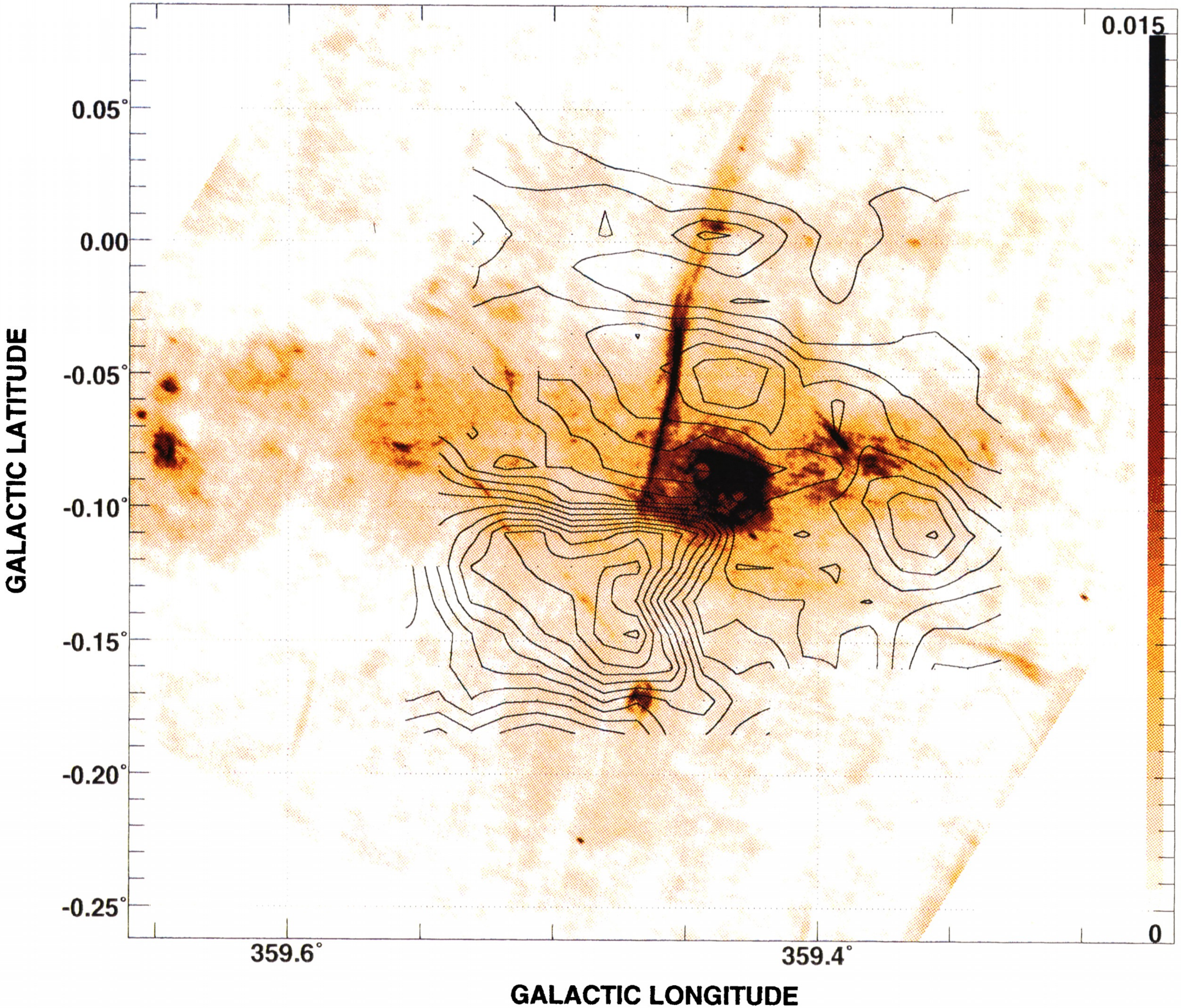

Figure II-4. ^{13}CO emission in Sagittarius A, including all velocities.

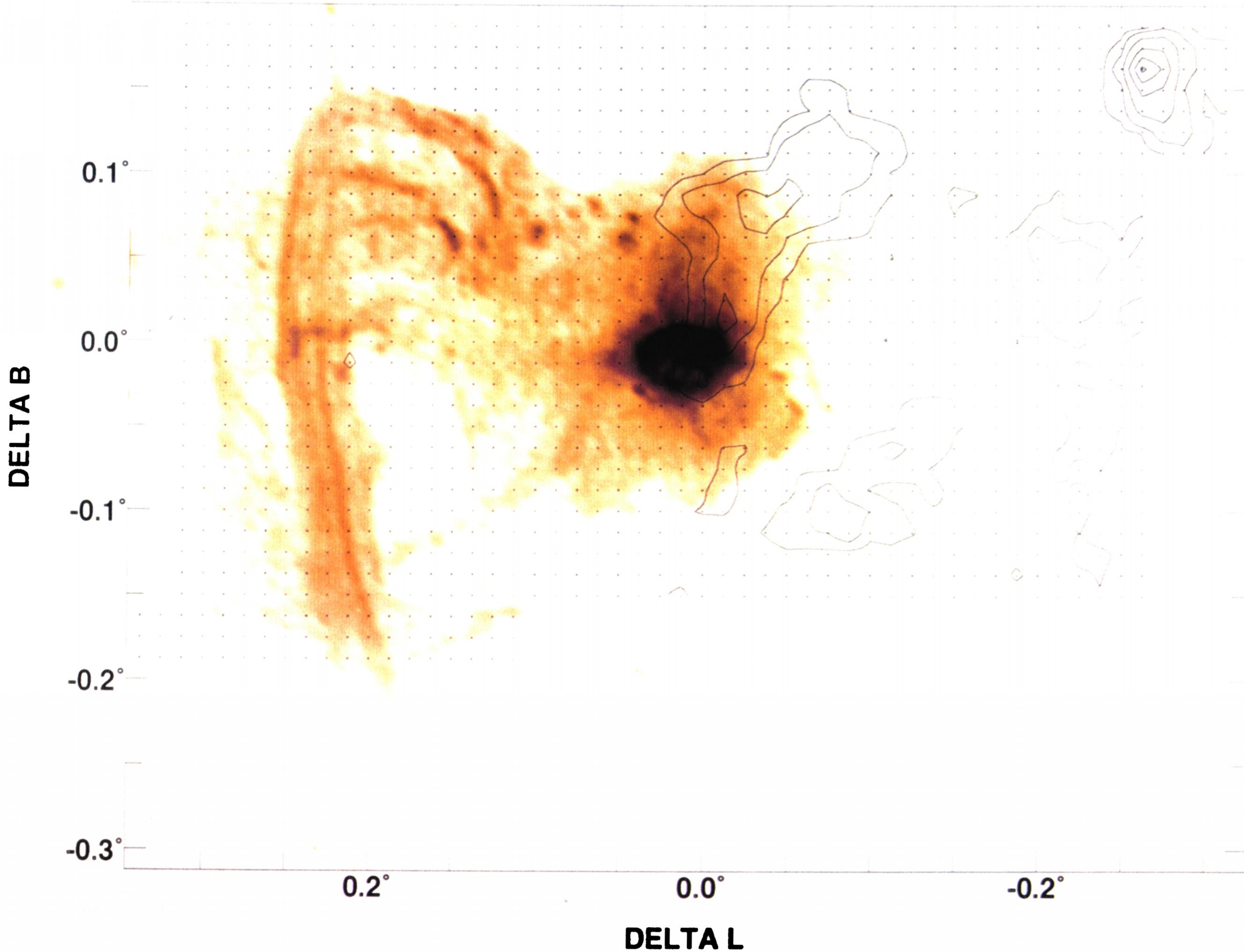

Figure II-5. CO emission in Sagittarius A at extreme negative velocities.

panel of the figure the CO map is shown projected on an optical photograph of the region; in the bottom panel the CO emission region is expanded. Figures II-4 and II-5 are images of the CO emission in the region of the galactic center. Two different Doppler velocity intervals are shown, both projected on a VLA continuum image of the galactic center, SgrA. Note how the CO (v = -190 km/s) emission, cold molecular gas, has an arc-like morphology that mirrors the non-thermal arc of relativistic gas on the other side of SgrA itself. A similarity of two very different species, spatially separate, such as this provides powerful clues as to the nature of the central region of our galaxy. The on-the-fly technique will ultimately be used with the 1.3 mm and 3 mm 8-receiver systems to provide extraordinarily efficient mapping tools; as part of this project, on-the-fly data acquisition is being implemented with the hybrid spectrometer as well as with the filter banks.

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 the 12 Meter 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 addition to continued improvements in the 12 Meter, 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. Many of the projects already underway in support of the 12 Meter Telescope will become prototypes for, or otherwise contribute to, the eventual MMA project; in fact every new project for the 12 Meter Telescope is now being planned and implemented with a view to using the telescope as a testbed for the MMA.

Specific improvements to be made to the 12 Meter Telescope instrumentation in the period of the Long Range Plan include the following:

SIS Receivers

We will change receivers to use a new IF center frequency of 3 or 4 GHz. This will support a 1 GHz total bandwidth for each polarization. The existing hybrid spectrometer supports up to 2.4 GHz of total bandwidth, 1.2 GHz per polarization, but because of the receiver IF systems we have been limited to 600 MHz until now. The change affects IF filters, circulators, and our fundamental LO reference.

Local Oscillators

The current implementation, using phase-locked Gunn oscillators, has some limitations; the Gunn devices are expensive, and the phase lock circuitry limits observing flexibility in some respects – for example, limiting the rate and range of frequency switching. Until now there has been little choice in available technology, but recent developments in MMIC devices may offer a reasonable alternative of direct frequency synthesis and multiplication, eliminating the need for phase-locked Gunn oscillators. Although not yet proven, potentially the L.O. sources, at least at 3 mm, may become much cheaper, reliable, and more versatile. This option is being pursued in conjunction with the Central Development Laboratory; if successful it will have an important application on the MMA.

Wideband HFET Amplifier

Experimental HFET amplifiers have been tested in the CDL which may be capable of a performance which is competitive with SIS devices at 3 mm. As soon as feasible, a specialized continuum receiver using HFET devices will be built for the 3 mm band. This receiver will have an instantaneous bandwidth of up to 20 GHz, and will give a continuum sensitivity far higher than any existing coherent receiver or bolometer.

Polarimeter

A polarimeter has been constructed for the 12 Meter Telescope, which has been used to study linearly and circularly polarized emission in both the broad-band continuum and the spectral line mode. The design uses an adjustable grid and plane reflector combination, and can in principle be adjusted to cover both the 1 mm and 3 mm bands, although a finer grid is required for the shorter wavelengths. The design is reasonably compact and will become a prototype design able to give similar capability to the MMA.

III. GREEN BANK: THE GREEN BANK TELESCOPE AND THE 140 FOOT TELESCOPE

1. General Comments

In 1995 the Observatory at Green Bank, West Virginia made the transition from being an observatory which was operating the 140 Foot Telescope, several instruments for the U. S. Naval Observatory (USNO), and building the Green Bank Telescope (GBT) to one which is building the GBT and doing a few other things on the side. Virtually everyone on the staff is involved with the GBT to some extent, even the 140 Foot personnel. The entire complement of 140 Foot Cassegrain receivers, which cover frequencies above 5 GHz, has been replaced by the receivers built for and destined for the GBT. By the end of 1995 there will be a significant amount of GBT software running at the 140 Foot during routine observations. The scheduling of that telescope is now evolving toward a model that is a prototype for the GBT.

The challenge for 1996 and the years beyond that will be to insure that the various parts of the GBT project are well integrated into the site capabilities and to set up an organization ready to begin testing and operating GBT components. The GBT operations staff will be assembled and working to plan for routine maintenance of the instrument. Despite the austere financial condition of the Observatory, the heightened activity on the GBT project and several other new activities around the site make Green Bank a very exciting place to be.

2. The Green Bank Telescope (GBT)

The GBT has a fully steerable clear aperture collecting area of 100 meters diameter, to operate from 300 MHz to 43 GHz, eventually to ~100 GHz. Construction began in 1991, with completion of the foundation in June, 1992. An artist's concept of the telescope is shown in Figure III-1. In early 1994 the alidade, the lower structure that rotates in azimuth, was completed.

Late in 1993, the final design of the elevation tipping structure was received from the contractor and approved by NRAO. The development of the design model had taken three years to complete. The last structural computer model, Model 95-2, resulted from over 100 iterations of the design and included inputs from an optimization analysis conducted by NRAO in association with JPL's Ground Antennas and Facilities Engineering Group. The tipping structure was one of the most challenging aspects of the GBT project because of the unique clear aperture geometry of the telescope's reflector, the size of the total structure, including the offset feed arm,

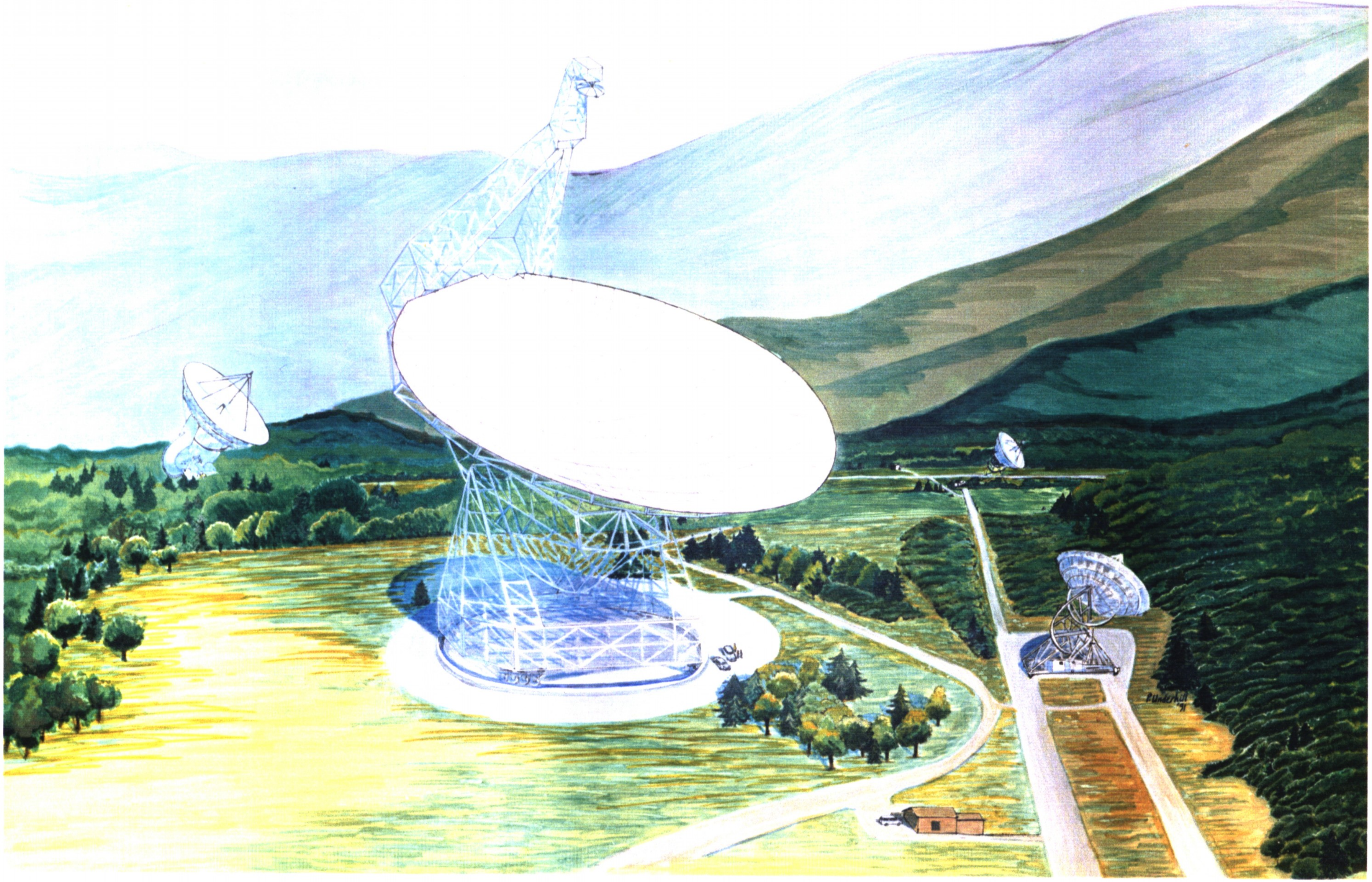

Figure III-1. Artist concept of the Green Bank Telescope.

and the high degree of surface and pointing accuracy required. The tipping structure consists of 11,208 individual members, 2,004 surface panels, and 6,106 joints, and weighs 9,400,000 pounds, including 2,440,000 pounds of counterweights.

To assure the efficacy of the completed telescope, NRAO has conducted a wide range of analyses and subprograms. They include wind tunnel tests, concrete and grout studies, exacting shop and field welding controls, and joint design and fatigue study. Additionally, exacting weight control of critical members and a complete quality assurance program covering the contractor, subcontractors, and all field operations have been instituted. All of these are instrumental in assuring that the antenna will perform in all aspects as specified, calculated, and predicted.

Antenna

The alidade is now virtually complete up to the elevation bearing level. Figure III-2 is a recent photo of the construction. The electrical power system, which includes installation of the antenna cable wrap, power lines, and transformers on the antenna alidade, was successfully completed and the switch-over to permanent power was made.

The structure has been rotated several times in azimuth using one of the four actual servo cabinets and two 30 horsepower motors along with their gearboxes, brakes, and tachometers. The elevation bearing support weldments, at approximately 80 tons each, have been installed at the top level of the alidade towers, about 165 feet above the ground. The alidade manlift has been finished and now extends to this level as well. The elevation bearing platforms also have been installed.

The current major effort at the GBT construction site is the preparation of the elevation shaft to be installed on to the completed alidade. The stub shafts have been aligned and welded onto the axle, and approximately 80 percent of the welds have been completed on the members attached to the stub shaft spiders. The contractor, COMSAT/RSI, completed this phase of the welding in March 1995. Trial erection of the elevation shaft and center section of the box structure is underway.

Eighty percent of the members of the box girder have arrived at the site and the subassembly of joints and beams has started. After the elevation shaft is in place the box girder subassemblies will be raised and welded. It is planned that no additional scaffolding will be required to erect the box structure. Portions of the elevation wheel are being trial erected at Mexia, Texas. The elevation wheel and box installation is scheduled to start May 15, 1995, and

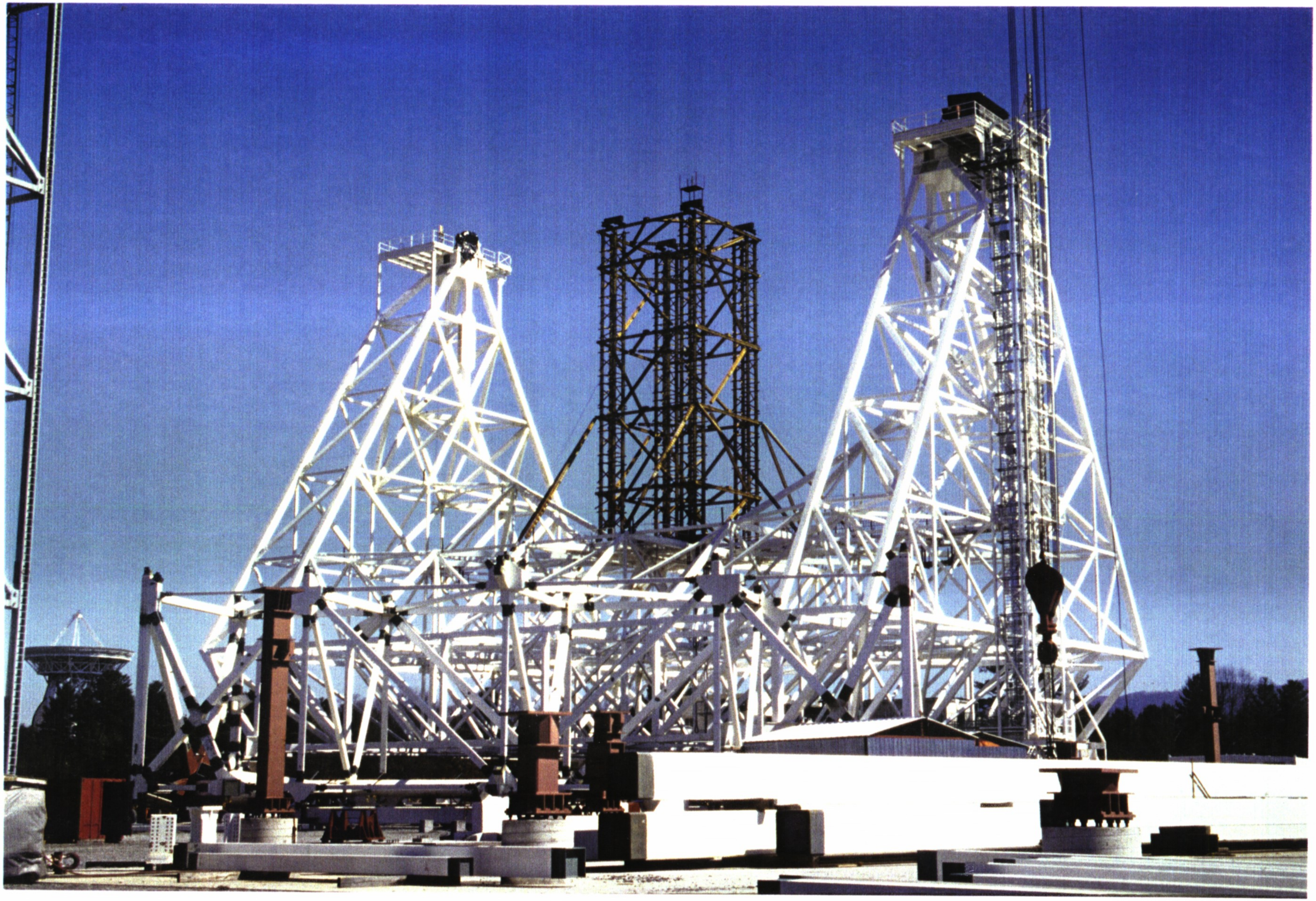

Figure III-2. Recent construction photograph of the GBT.

will be completed in August 1995. The 22 counterweight boxes will be installed in September of this year.

Preparation for the on site construction of the reflector backup structure (RBU) include the 150 foot x 150 foot reinforced concrete assembly pad with steel beam standoffs to support the RBU; the 90 foot measurement tower located at the vertex of the RBU; and a production aid (150 feet x 35 feet) to be used for assembly and welding of the rib trusses in a horizontal position. Trial erection, *i.e.*, construction on the ground of the RBU, is scheduled to be completed by the end of the year.

The actuator control room has been received at the site, and the contractor has installed electrical power, lighting, RFI filters, and the HVAC system. The active surface group is installing and ground testing major components of the open loop system.

At the contractor's plants, fabrication of all remaining parts of the structure continues, including the counterweight boxes, main reflector panels and the subreflector truss assembly, and panels. The servo system is being prepared for acceptance testing.

The tip of the vertical feed arm above the receiver room level is in detail design. It will be fabricated and assembled on a concrete foundation at the contractor's plant in Mexia, Texas for interface with the prime focus and subreflector adjustment mechanisms. This will be disassembled, shipped, and reassembled in Green Bank on a similar foundation for feed arm servo tests and NRAO use and calibration before installation.

Phases

Completion of the construction project and operation of the GBT as a radio telescope has been divided into phases for clarity and understanding. Phase 0 is the current construction phase and involves the construction and delivery of a fully operational antenna. It will be considered complete upon issuance of a provisional acceptance to the contractor by NRAO that the antenna and control system comply with the GBT contract specifications.

During Phase I, the antenna will be transformed into a functioning radio telescope, complete with 2,200 active surface actuators (installed by the contractor during Phase 0), a local control center, an integrated monitor and control system, and a complement of primary and secondary feeds, receivers, back-ends, LO, IF, and cryogenics along with all associated interconnecting cabling. The performance of the Phase I telescope will be suitable for scientific operation up to 15 GHz.

Phase II will be complete when the active surface system is operational and can compensate for gravity deflections of the reflector surface as commanded by a computer program based on data provided by the contractor and verified by NRAO. It is planned that the laser ranger surface measurement system will become operational during this phase. The Phase II telescope will allow operation for scientific observations to frequencies as high as to 43 GHz.

Phase III will extend into the future and involves operation of the telescope at millimeter wavelengths. This will be accomplished using NRAO provided enhancements involving the laser ranger surface-measurement system and the precision pointing system which will take the telescope to its ultimate high frequency operation.

Schedule and Budget

The antenna contractor has requested a delay in antenna delivery until December 15, 1996. The project delay was created initially by the extreme complexity of the design. Over 100 finite element model analyses were made to develop a structure which would comply with the NRAO specifications. Additional delay was realized as the design carried over into the detailing, fabrication and installation tasks. A fuller understanding of the intricacies and sheer magnitude of this unique structure has led to a recalculation of the time required to achieve completion.

The schedule slippage does not come without a cost. In order to extend the budget to cover the extra costs incurred by the delay in project close-out until early 1997, NRAO has combined a reduction in personnel charged to the project with a reduction in certain technical aspects of the project. On January 1, 1995, twelve GBT employees were transferred to operations payrolls. Two additional GBT employees will leave the construction payroll by mid-year (one resignation and one transfer to operations). The remaining nine employees consist of the project administration staff, engineering staff, and technical personnel dedicated to construction.

The technical reductions in the project include the placement of the autocollimator on hold until the completion of the 140 Foot Telescope pointing tests. It is anticipated the tests will be successful and the autocollimator will be dropped, saving in excess of $211,000. Also, the 40-52 GHz receiver will be moved to the 1995 and 1996 Research Equipment budget for Green Bank, saving the project approximately $210,000. Finally, the spare parts and components for the project, budgeted at $250,000, will be bought into the Observatory inventory and expensed against operations budgets as they are used in the future. By taking these personnel and material actions, the project will be able to carry on to the early 1997 project completion and still carry a contingency in excess of $1 million.

Science Program

The science program anticipated for the GBT is most naturally divided into five areas: stars, particularly pulsars, and the solar system; neutral hydrogen studies; spectroscopy; continuum radiation; and very long baseline interferometry. This research depends on the following features of the GBT.

- Sensitivity of roughly 2K Jy^{-1} will result in integrations of only minutes rather than the hours now required at the 140 Foot.
- Broad frequency coverage from 300 MHz to 52 GHz, eventually 100 GHz, gives the flexibility to observe at the frequency demanded by the science.
- Unblocked aperture will yield superior spectral baselines and improved immunity to radio frequency interference. Stray radiation in galactic HI observations will be greatly reduced.
- Broadband spectrometer will make possible the simultaneous observation of several spectral lines, searches for lines of uncertain redshift or frequency, and the observation of lines expected to be very wide (*e.g.,* the fine structure lines of HI).

Pulsar timing will measure the gravitational radiation from close binary systems. A number of millisecond pulsars serving as clocks distributed along the ecliptic plane will be used to detect or set strong upper limits to long wavelength gravitational radiation originating at the Big Bang. Surveys of new pulsars, particularly in globular clusters, will increase the sample of known objects in the final stages of stellar evolution and will probe neutron star physics.

A great variety of radio stars will be detectable with the GBT. Broadband dynamic spectropolarimetry will be used to study thermal stellar winds, plasma effects in sunspots and in the intra-stellar magnetospheres of close binaries, and precessing radio jets fueled by accretion onto neutron stars or black holes. Multifrequency imaging of the Sun will help to define conditions in the upper chromosphere and transition region above coronal holes as well as in quiet and active solar regions.

The GBT will be sufficiently sensitive to detect HI emission from more than 10^4 galaxies distributed over 85 percent of the celestial sphere. Surveys for these galaxies will map the large-scale spatial distribution within $D \approx 100$ Mpc, as well as their motions relative to the smooth Hubble flow. The HI profiles of nearby galaxies also yield global properties (total mass, HI mass, mass-to-light ratio, surface density, etc.) which trace dark matter, reveal environmental effects, and show the effects of tidal interactions occurring in clusters or groups. In addition, protogalaxies and other gas-rich extragalactic objects of low optical luminosity will be detectable. The evolution of galaxies at high redshifts will be probed by observations of HI in absorption against distant continuum sources.

Within the Milky Way the 9 arcminute beam of the GBT at 21 cm will resolve structures as small as 20 pc at the distance of the galactic center. It will therefore be used to make HI maps of activity in the nuclear (central 1 kpc) region. The partition of gas between the spiral arm and interarm regions, HI envelopes around star forming molecular clouds and supernova remnants, and the flaring and warping of the galactic disk outside the solar circle are other likely areas of investigation.

The unequaled sensitivity, high resolution, and frequency agility of the GBT at short centimeter and long millimeter wavelengths will allow the detection of CO in starburst galaxies and quasars at cosmological redshifts (up to $z \approx 3$), an important new field of study – the molecular content of galaxies from the epoch of galaxy formation. Multifrequency observations of CS, HC_3N, and CH_3OH transitions in the 30-50 GHz range will contribute to our understanding of molecular processes and provide the data needed for detailed multilevel models of density and temperature in the molecular clouds of our own and nearby normal galaxies. Spectroscopy of OH, H_2, CH_3OH, and H_2CO masers will probe the kinematics and energetics of the most intense starbursts in the nuclear regions of galaxies.

In our own galaxy, maps of the stellar disk based on the 10^5 OH/IR stars detectable by the GBT will be combined with existing and CO maps of the atomic and molecular gas disks. The structures of these disks perpendicular to the plane are the basic data needed to determine the total mass of the galactic disk, the existence or not of the thick disk, the nature and distribution of galactic dark matter, the history of star formation, the gravitational scattering of stars by molecular clouds, and the stability of molecular clouds to star formation. Both the physics and chemistry of the dense molecualr clouds in which stars are born will be probed by multilevel spectroscopy of a wide range of molecules detectable in the $\lambda \approx 8$ mm atmospheric window. The high sensitivity and resolving power of the GBT will be important for such studies. Detection observations seeking the weak deuterium line at 327 MHz and the $^3He^+$ line at 8.7 GHz will critically test various cosmic nucleosynthesis models.

The GBT will be able to make continuum sky maps covering ~10 steradians of the celestial sphere, with enough sensitivity and resolution to detect ~3×10^5 sources stronger than $S \approx 5$ mJy at $\nu = 5$ GHz. The maps will be used to discover intrinsically rare objects, to detect radio emission from nearby galaxies, to provide archival records of the radio sky at various epochs, and to permit comparison with sky maps in the infrared, optical, and X-ray bands.

Sensitive searches for primordial fluctuations in the cosmic microwave background radiation on 1-10 arcmin angular scales will be made, exploiting the high beam efficiency of the GBT. The telescope will be able to map temperature decrements in the microwave background produced by Compton scattering in the hot intracluster medium of rich clusters of galaxies (the Sunyaev-Zeldovich effect). This effect measures the intracluster medium's electron density and may eventually yield a direct measurement of the Hubble constant.

The GBT will be an important adjunct to the VLBA and Orbiting Very Long Baseline Interferometry (OVLBI) experiments because of its high sensitivity, frequency agility, and wide sky coverage. With the addition of the GBT, the VLBA will have the same collecting area as the VLA, permitting long, coherent integrations on weak sources – such as faint structures in superluminal objects, 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 to nearby external galaxies.

3. The 140 Foot Telescope

Telescope Usage

The 140 Foot Telescope will continue to be operated as a user instrument until the GBT begins scheduled observations in 1997. Observations are now scheduled for 86 percent of all possible hours, maintenance and equipment changes take about 10 percent of the time, and the remainder goes for tests and calibrations, including tests of GBT software and a program of operator training. The breakdown of observing by frequency is:

Frequency (GHz)	% of Observing Time
0.3-1.0	32
1.4	36
1.7-5.2	6
8-10	10
18-26	12
25-35	4

Representative Scientific Results

Jupiter. During 1994 the 140 Foot Telescope was fully involved in observations of the comet Jupiter crash. A group from Berkeley began regular monitoring at 1400 MHz two months before impact and measured Jupiter's flux and polarization whenever the planet was above the horizon for much of July. Observations are continuing with short sessions scheduled every few weeks. The well-known result that the largely nonthermal L-band flux increased during the impact, rather than decreased as expected, is still not well understood. The spectrum also hardened. In the weeks following the impacts, the flux density began to subside towards its usual level. In some way the resident particle population was energized by the cometary impact.

Pulsars. An all-sky search for pulsars by a group from Princeton and NRAO has discovered ten new pulsars so far, including one in a rare relativistic binary system. The 40 ms pulsar is in a moderately eccentric ($e = 0.25$) orbit with a period of 8.6 days in a system that appears to consist of two neutron stars. Timing observations are continuing on the 140 Foot. By making a precise measurement of the relativistic advance of the orbital longitude of periastron, a mass measurement with uncertainty of 5 percent should be attainable with a few months of observations.

Spectroscopy. Recent maps of the galactic soft X-ray background by the ROSAT satellite have revealed a number of "shadows" – regions where the X-rays appear to be absorbed by intervening interstellar matter. Measurements of the HI 21 cm line using the 140 Foot Telescope have shown that most of the shadows can be identified with distinct HI clouds whose velocity can be measured precisely. Given the velocity, a cloud's distance can be determined by searching for the cloud's absorption in optical lines against stars at different distances. The first results of a program of this sort in the Eridanus region indicate that most of the absorption occurs at a distance of about 100 pc, consistent with the model in which the bulk of the observed soft X-ray background originates in a hot bubble of gas surrounding the sun.

The Condition of the 140 Foot Telescope

By early 1994 it had become clear that there were several major maintenance procedures that needed to be done to keep the telescope operating reliably. These were some years overdue, but had been postponed by budget pressures. Only a modest amount of money was available for this maintenance, but by a combination of hard work and luck, a nearly total overhaul of the telescope's hydraulic systems was accomplished at a small fraction of the initially projected cost. As of this writing only one pump remains to be rebuilt, and it will be sent out shortly. During a week-long summer maintenance period the cables bracing the feed support legs were replaced, and the epoxy filling of the cracks in the concrete pedestal was completed. The brakes still do not have adequate spares, but with this exception the telescope is now in excellent mechanical shape.

The 140 Foot As A Testbed for GBT Systems

In 1994 the Cassegrain receiving system at the 140 Foot, including the masers, upconverters, most FETs, the beamsplitter and so on, was ripped out and replaced by receivers built for the GBT. Only the 28-35 GHz receiver remains from the old system, and it was repackaged into a GBT dewar. The upgrade makes it now possible to switch among Cassegrain receivers in a few moments, and this is allowing us to test novel scheduling methods that will be useful for the GBT. The experience with the GBT receivers has been very encouraging: in every respect they are equal or superior to the older systems. Typical system temperatures on the telescope in decent weather are excellent, and the figures are expected to be even better when the receivers are installed on the GBT owing to the GBT clear aperture.

140 FOOT TELESCOPE AS A GBT TESTBED

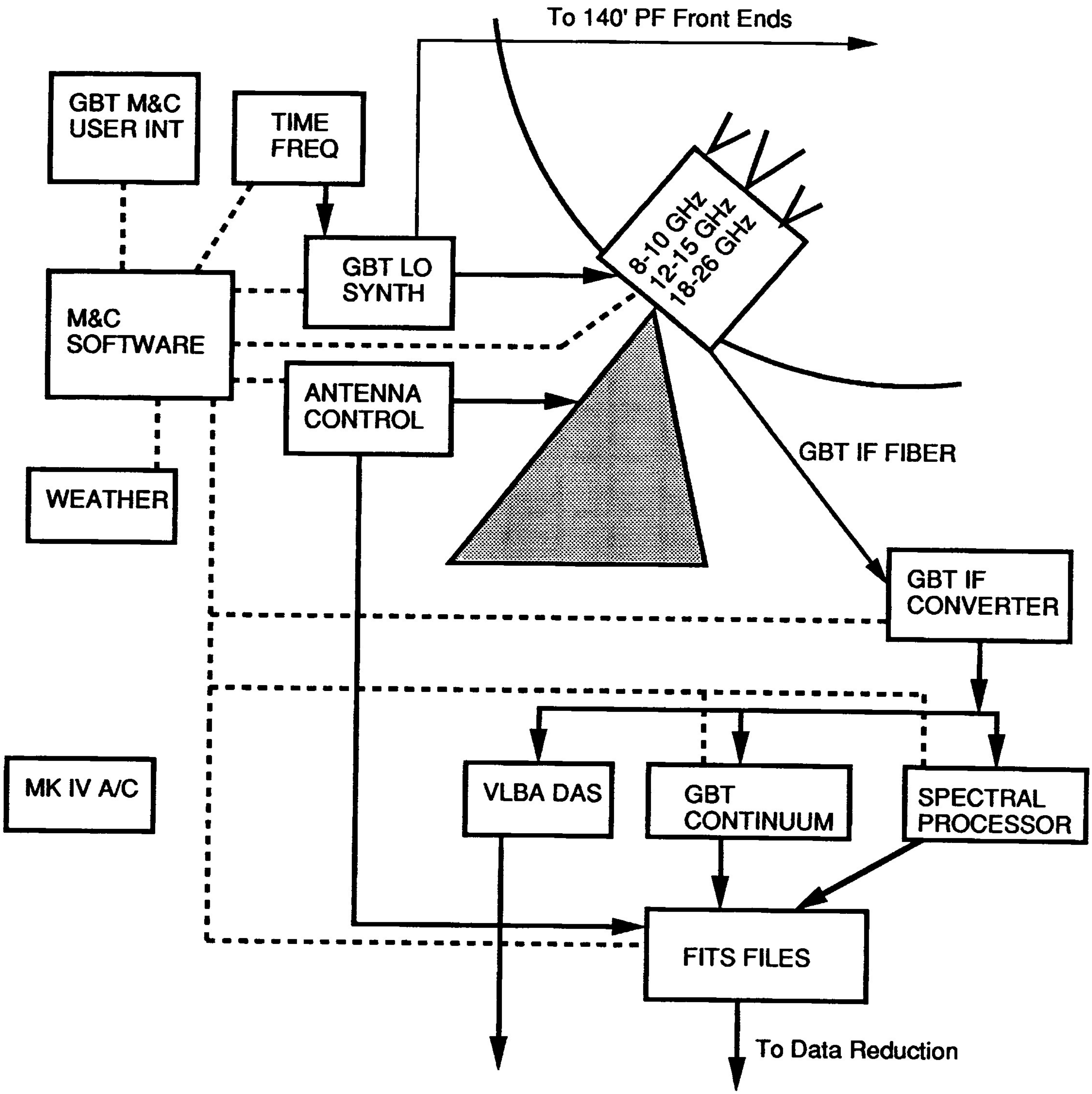

Figure III-3. Outline of 140 Foot Telescope use as GBT testbed.

Freq (GHz)	140 Foot T_{sys}(K)	GBT T_{sys}(K)
8-19	25-30	21
12-15	28-33	24
18-22	40-55	36

A program to install GBT monitor and control software at the 140 Foot will continue in the next two years, and visiting observers will be encouraged to exercise major portions of the GBT software, including synchronization of telescope motion and data taking. Control of the spectral processor and of the new GBT continuum receiver for routine observations will be implemented this autumn and, later, pointing and focus calibration and control of the LO. The goal is to make the 140 Foot Telescope a realistic testbed for the GBT as illustrated in Figure III-3.

Several concrete piers have been installed around the 140 Foot, and this summer retroreflectors will be mounted at various points on the telescope. It will then be used to develop and test the GBT laser pointing system.

A database management system has been put into place to handle incoming telescope proposals, and another program has been developed to access archival 140 Foot data. These systems are not strictly necessary now, but they allow us to gain experience that will be valuable for operating the GBT.

Operations

In preparation for the GBT operations, we have started a program of telescope operator training at the 140 Foot. The operators are being taught about workstations and UNIX, about observing techniques, and about data analysis. One goal is to have operators to be able to carry out a series of test observations to insure that the telescope systems are properly functioning and to be able to diagnose problems if they are not. This training should lead to creation of a group of operators who are qualified to run the GBT. Because so much GBT hardware and software will be installed on the 140 Foot in the next two years, they should have a lot of direct experience with some of the equipment they will be responsible for. The hope is that much of the software will be debugged and optimized on the 140 Foot so that in 1997 the operators can transfer to the GBT.

IV. VERY LONG BASELINE ARRAY

Status

The VLBA is now operational in all its major observing modes. It is routinely scheduled in response to observing requests that are received at three proposal deadlines annually (1 February, 1 June, 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 things such as mis-matched IF filters 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 that now is the reality. Figure IV-1 is a recent VLBA image of the Seyfert radio galaxy 3C 120. In this image one can see not only the bright central source (the black hole?) that is the origin of the energetic activity in this galaxy, but one can also see clearly the relativistic jet of matter being expelled from the nuclear region. The fidelity of the image is sufficiently good that one can see that the elongation of the shock waves in the jet are not orthogonal to the jet flow; some appear to be almost parallel to the flow. Such a source morphology is reasonably consistent with a physical description of the source in which expelled material follows a helical trajectory. If this is correct we are led by the high fidelity VLBA image to a proper understanding of the source physics: this was **the** principal goal for the VLBA.

Figure IV-2 is another recent VLBA image of a relativistic jet of material being expelled from a massive black hole in the nuclear region of an energetic galaxy. In this case the galaxy is Markarian 501, a galaxy that is very blue in its optical color, suggesting that star formation is on-going in the galaxy. The fact that the galaxy also harbors a nuclear black hole and an energetic radio jet may be causally related. The on-set of jet activity may initiate the burst of star formation. Indeed, the remarkable feature of the jet shown in this VLBA image is its twist through nearly a right angle. The cause of the twist is almost surely a deflection of the jet by its interaction with a cloud of gas in the disk of Markarian 501; one would expect to see the onset of a burst of star formation at the point of impact. Unfortunately the best

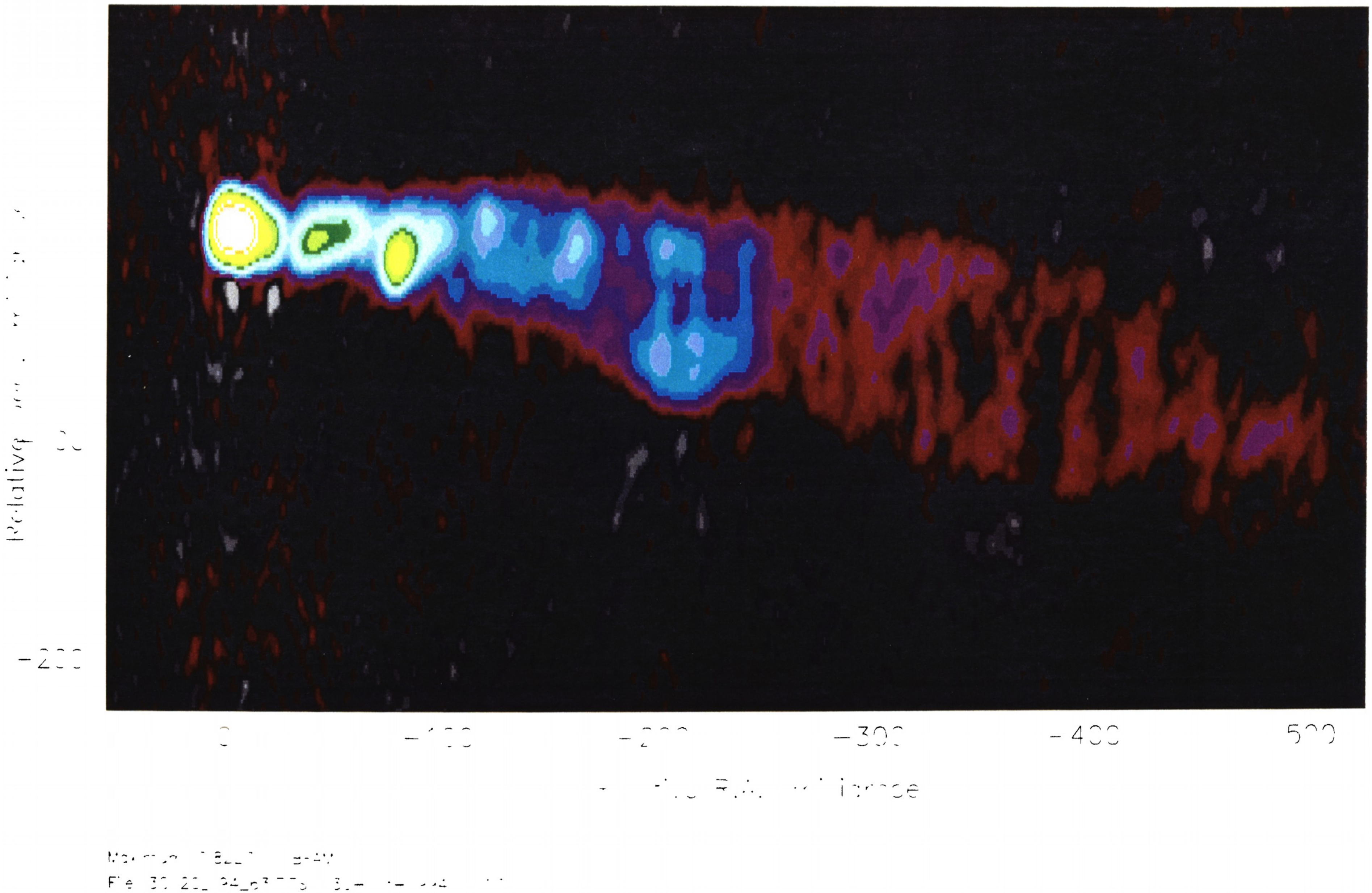

Figure IV-1.   VLBA image of the radio galaxy 3C 120.

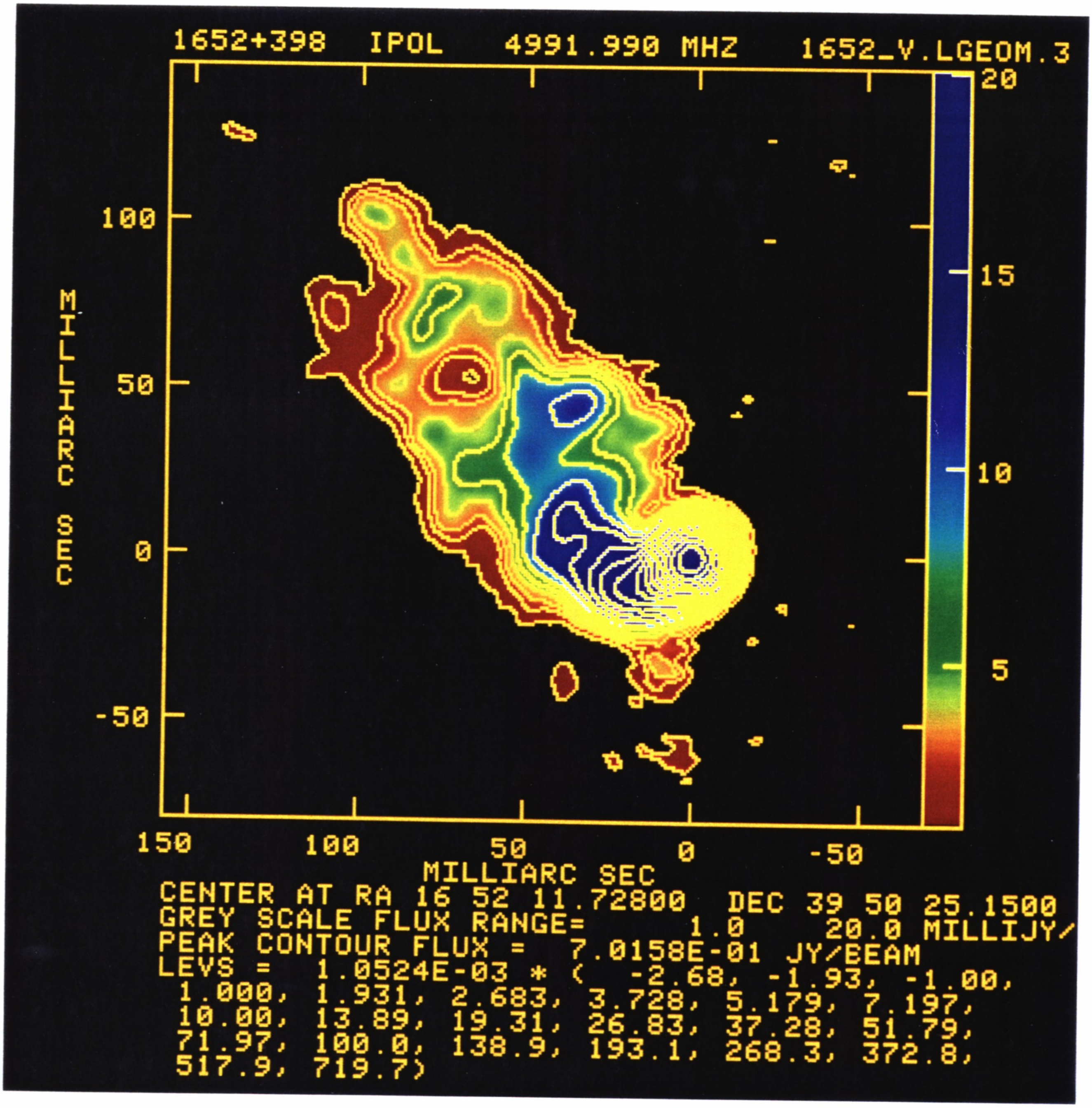

Figure IV-2. VLBA image of Markarian 501.

optical photographs still lack the resolution needed to discriminate fine details such as this on milli-arcsecond scales.

Still another of the design goals of the VLBA was an operational goal: the ability provided by a full-time VLBI telescope to respond quickly to targets of opportunity. Figure IV-3 is a VLA (not VLBA) superposition of images of the radio emission from the galactic gamma ray source GRO J1655-40. This *time-lapse* radio photograph shows the source brightening in time and ejecting a secondary source away from a central object. Since the object is also a source of energetic gamma rays, we expect that it is characterized by a very deep potential well – it is a black hole of stellar mass. We are observing here a *local*, that is, galactic example of the physical phenomenon seen in 3C 120 and Markarian 501 above, namely, a black hole presumably surrounded by a confining accretion disk that periodically ejects matter relativistically. We know this much from the VLA image; to learn more we need the angular resolution of the VLBA.

Figures IV-4 and IV-5 are successive VLBA images of GRO J1655-40 made contemporaneously with the VLA images of Figure IV-3. On short notice, once it was realized that the source was in an active state, the VLBA schedule was re-written to make room for this series of observations. With the VLBA we see clearly that the material ejected from the central source is expelled as a jet. Further, one can see that the bright points in the jet, the shock waves, appear at varying angles to the flow direction. Here the trajectory of the jet is clearly helical. From a physical standpoint the capability provided by the VLBA to make images such as these which enable us to watch the evolution of an accretion-powered black hole is invaluable. It makes the case visually that the galactic stellar sources and the extragalactic monsters, the radio galaxies and quasars, share a common physical mechanism. Knowledge gleaned from one class of object is germane to the other. The attention to image fidelity given in the overall technical design of the VLBA and the scheduling flexibility that full-time operation of the VLBA provides, makes scientific advances such as the above possible. The next five years should be very productive indeed.

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

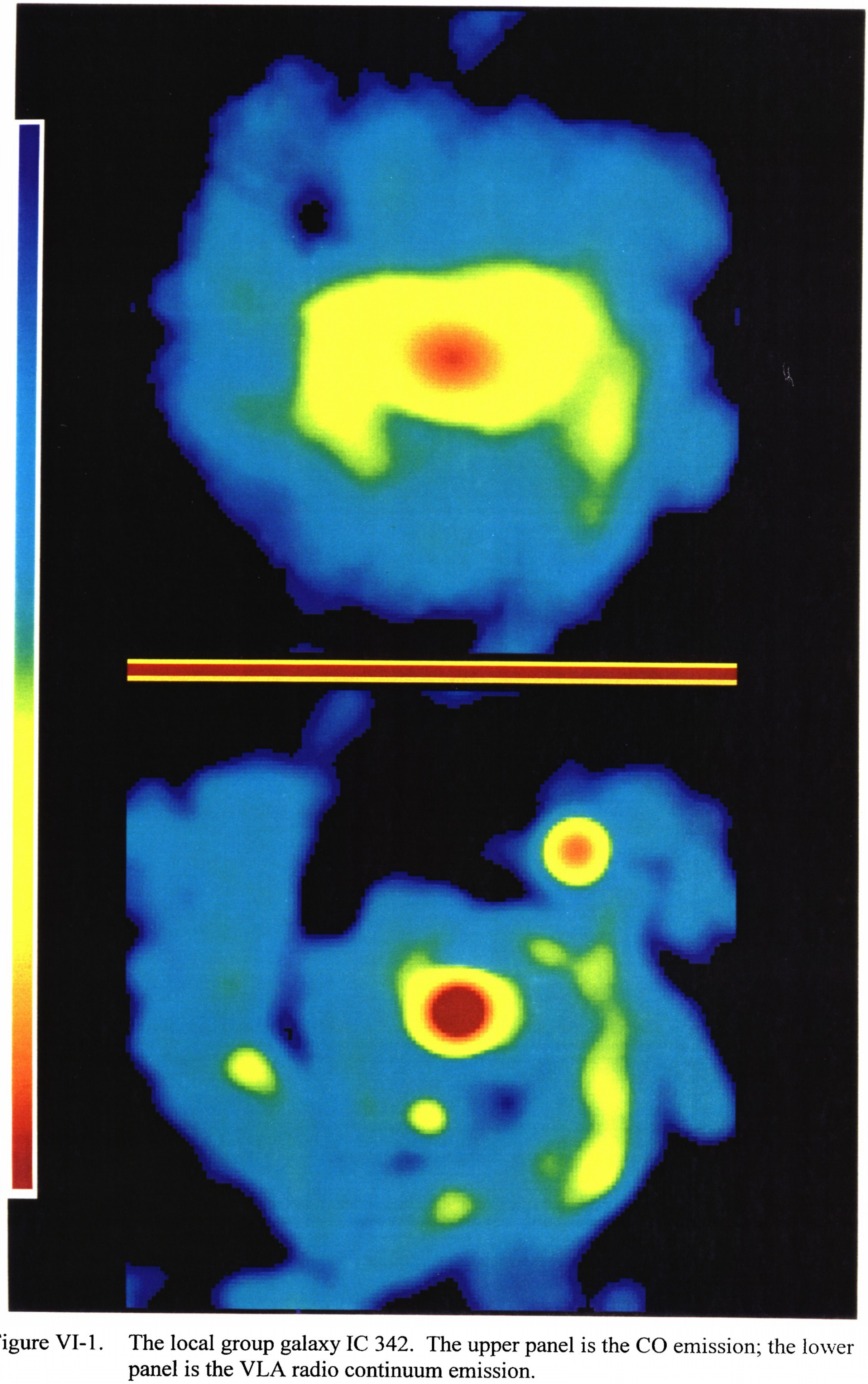

Figure VI-1. The local group galaxy IC 342. The upper panel is the CO emission; the lower panel is the VLA radio continuum emission.

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.

Table III-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 III-1. All receivers are dual polarization. The receivers at 1.4 GHz and above contain cooled

HFET amplifiers from the 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 future 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 fringe mapping and utilization of the pulse calibration system. Documentation of the system is now the major goal. 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 IPX and IBM RS/6000-560 and RS/6000-580 classes.

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, 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 will require fine-scale debugging of the correlator real-time software and streamlining of correlator operations. Most major modes of the correlator are now supported by the software and have been tested. In late 1994, some of the core correlator code will be re-written with the goal of improving reliability to a level such that the correlated data can be expected to be correct with high probability. This level of reliability is needed to avoid slowing the throughput of the correlator by excessive scrutinizing of the output.

In the longer term, over the period of this long range plan, emphasis will be given to improving our knowledge of the array geometry and to enhancements in high frequency observing capabilities.

The performance of the VLBA as a geodetic/astrometric instrument will be 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 will depend 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. During 1995, we expect to achieve full phase coherence by using a more complete and accurate geometric model based upon extensive geodetic and astrometric observations.

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 figured as well as possible, within the technologies used, to permit observations at this frequency. Present measurements gave an efficiency near 40 percent at 86 GHz, which is adequate. We plan to install two 86 GHz receivers in the last quarter of 1995, thereafter adding two per year. 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 will consist 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.

Three tape-recording formats have been in use for Global VLBI and VLBA observations: MkII, MkIII, and VLBA. The old MkII video cassette system is no longer supported.

V. VERY LARGE ARRAY: UPGRADE PROJECT

1. Overview

The Very Large Array is approaching the fifteenth anniversary of its dedication. Conceived in the 1960s, constructed during the 1970s, and dedicated in 1980, the VLA continues to be 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 (e.g., the expansion from two to four IFs in 1983 and the expanded support of spectral line modes in 1989). Others arose as an extension of the original design (e.g., the 90 cm and 3.6 cm bands, completed in 1988 and 1989, respectively). Still others came from advances in available technology (e.g., 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 improvements have been made in receiver components, correlator design, and the transmission of broadband signals, rendering many elements of the VLA obsolete. Furthermore, many components are becoming increasingly vulnerable to failure – and are increasingly difficult to repair or replace.

2. Technical Summary of the Upgrade

The VLA Upgrade will lead to significant gains in four broad areas: sensitivity, frequency coverage, spectral line observing, and angular resolution. As presently conceived, the VLA upgrade includes the following key elements:

- 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.
- 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 (≥ 32).
- 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 the Pie Town VLBA antenna, and possibly between the VLA and the Los Alamos VLBA antenna. Add four 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.

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 ten 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 3.

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 lower frequencies.

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

The improved low noise receivers packaged independently like the VLBA receivers will contribute significantly to improvements in the fidelity of VLA images at all frequencies. Not only will the lower noise figure of the new receivers make for improvements in sensitivity but the greater gain stability of the HFET amplifiers and greater phase stability resulting from the rigid receiver mounts with short waveguide runs will make for dramatic improvements in calibration accuracy and hence image fidelity. These improvements can be illustrated in a quantifiable way. Figure V-1 is an image made of the Sgr-B2 star forming region in which a large collection of spatially complex, but independent HII regions, are visible. This image was made with the 8 GHz VLBA style receivers. Previous VLA images of the same region made with the older style 5 GHz receivers failed to distinguish the various HI regions as separate entities. Just as the science realized here with the new receivers changes with the improved technology so also we expect to see similar improvements at the other VLA observing frequency bands with the new receiving equipment.

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 (e.g., redshifted CO), 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 our most sensitive system for study of steep spectrum, nonthermal sources. Table V-1 summarizes the proposed siting of new and upgraded VLA observing bands at the Cassegrain focus.

Less well defined are prime focus receiver systems. At present, the 333 MHz system is located at the prime focus, as is a 74 MHz system on eight antennas. Three possibilities for prime focus systems have been discussed.

- The addition of a new receiver system covering 580-640 MHz (matches the VLBA).
- A broadband UHF system covering $\leq$ 150-600 MHz.
- A sensitive 800-1200 MHz system.

Table V-1. VLA Upgrade Observing Bands

Band	Range (GHz)	Bandwidth (GHz)	BW Ratio	
L	1.20 - 1.75	0.55	1.46	Upgrade
S	2.13 - 2.70	0.57	1.27	New
C	4.80 - 6.70	1.90	1.40	Upgrade
X	8.00 - 9.10	1.10	1.14	Upgrade
Ku	12.00 - 18.00	6.00	1.50	Upgrade
K	18.00 - 26.50	8.50	1.47	Upgrade
Ka	26.50 - 40.00	13.50	1.51	New
Q	40.00 - 50.00	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. The total bandwidth assumed for 90, 50, 30, 20, and 11 cm is 50, 100, 200, 500, and 1000 MHz, respectively. All other estimates assume 2 GHz net bandwidth.

The new observing bands, particularly the continuous frequency coverage shortward of 1 cm wavelength will open up the capability of the VLA to study objects emitting much of their energy by thermal processes. Two examples of objects which will be amenable to study with the upgraded VLA are protoplanetary disks and minor planets in the solar system.

Table V-2. VLA Sensitivity

	Upgraded	VLA	Current	VLA
Band (cm)	T_{sys} (K)	ΔS (μJy)	T_{sys} (K)	$\Delta S_{current}$ (μJy)
90	80-135	40-70	150	120
50	45-90	13-25	-	-
30	25-32	5.3	-	-
20	30	2.7	33	6.0
11	31	1.9	-	-
6	29	1.3	45	6.7
3.6	31	1.3	31	4.4
2	37	1.7	110	20
1.3	50-70	2.6	160	37
0.9	38	2.0	-	-
0.7	55	3.5	80	165
0.6	170	15	-	-

Young stars are expected to form surrounded by protoplanetary disks, flattened structures of gas and dust from which planets form. These disks can be studied with unprecedented angular resolution with the upgraded VLA. In particular, the upgraded VLA is the only instrument capable to observe the inner few AU of the disk, the region where terrestrial planets are formed, since the disks should be transparent at Q band.

Present estimates suggest that within 200 pc of the sun there are about 100 protoplanetary disks with total Q band flux densities in the order of 1 mJy. The disks are expected to have diameters of about 100 AU (0.5 arcsec at 200 pc). In the A array an angular resolution of 0.05 arcseconds can be achieved at Q band, equivalent to a dimension of 10 AU. Within a beam of 0.05 arcseconds, about a flux of 0.1 mJy/beam is expected.

The full Q band upgrade will provide a factor of 36 improvement over the present system (a factor of three for all 27 antennas, two from improved aperture efficiency, three from a total bandwidth of 2 GHz, and two from better receivers). In speed, this represents an improvement of 1300. In a 12-hour on-source integration, the upgrade will bring the rms noise from 0.2 mJy/beam to 5 microJy/beam, making it possible to image the disks with a signal-to-noise ratio of 20 in this time period. At Q band and with the largest VLA configuration, a technique to correct for atmospheric phase noise becomes imperative. Schemes such as the fast switching or accurate total power measurements should be explored to provide phase stability.

Thermal emission has been detected from the four largest asteroids: Ceres, Pallas, Vesta, Hygiea, at wavelengths from 1 mm to 20 cm and from a few smaller asteroids at 2 cm wavelength. Such measurements place constraints on the thermal and electrical properties of those objects surface layers. The existing observations indicate that the asteroids studied so far are covered with fine grained regoliths, which are expected to result from meteoroid bombardment (sand blasting) of the surfaces over hundreds of millions of years. Differences in the microwave spectra of Ceres, Pallas, Vesta, and Hygiea suggest variations in the dielectric properties of those regoliths and/or variations in the regolith thicknesses. However, those few objects represent just a tiny fraction of the thousands of main-belt asteroids, most of which are beyond the detectability of the current VLA. In addition, there is a gap in the wavelength coverage from 1 mm to 1 cm. Over this range, the spectra show a distinct drop in brightness temperature. The proposed VLA upgrades in continuum sensitivity and wavelength coverage should make a large number of these objects detectable at several wavelengths. Of particular importance is the Q band, which fills the 0.1-1.0 cm wavelength gap.

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. This fact is highlighted in Figure V-2, which shows the log$N$ - log$S$ curve for radio detected stars. The figure shows the number density per millijansky of detected stars listed in the literature. The data have not been normalized per unit area on the sky. Although the counts will be reasonably complete over the whole sky at Jansky levels,

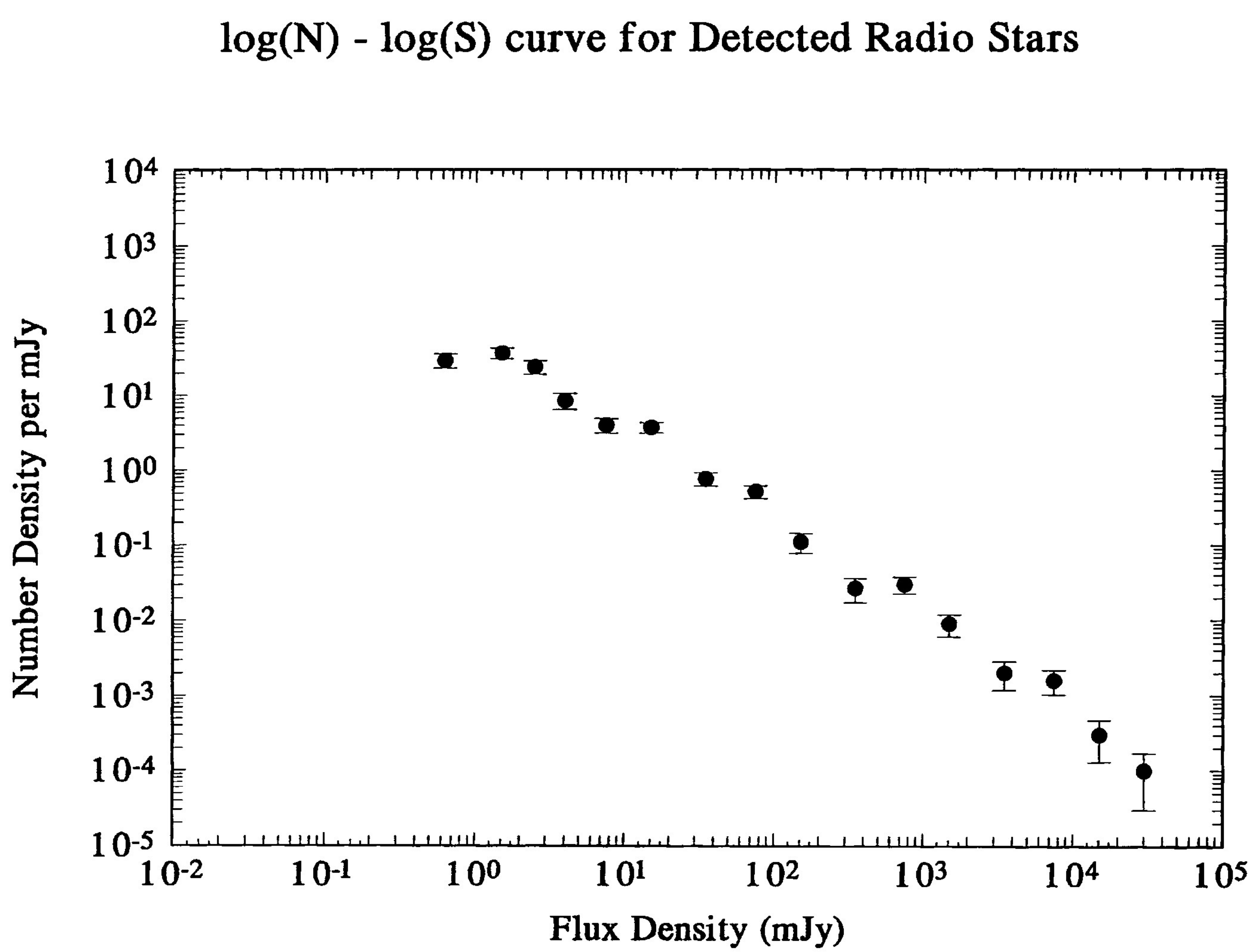

Figure V-2. The logN-logS curve for detected radio stars.

at low flux densities, the counts must significantly underestimate the true areal density of radio stars. Despite this fact, the number of radio detected stars rises very rapidly as flux density decreases. Sensitivity at the μJy 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 (e.g., 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 widest 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 at least 32 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 up to four new antennas on baselines intermediate to those contained in the VLA and VLBA.

The new correlator will benefit all VLA observations either by its wider bandwidth, larger number of spectral channels, or more flexible IF configurability. It will revolutionize studies of extragalactic absorption lines.

Observations of gas seen in absorption against the continuum emission of AGNs in the nuclei of galaxies provide a powerful way to study the circumnuclear gas. Limited studies of the gas kinematics along the narrow line of sight toward compact sources (which have typical sizes of milliarseconds) have provided some evidence for infall and an estimate of the accretion rate of gas, that might eventually fuel the black hole. If on the other hand the radio source can be resolved then the rotation velocity of the circumnuclear disk can be measured, providing some estimate of the mass of the central black hole.

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. About nine new stations would be necessary.

Such an E array would 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 combined with the total power system discussed above would make mosaicing practical with beams to 4-9 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 galactic halos.

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. With the addition of four new antennas plus the innermost VLBA antennas (at Pie Town and Los Alamos, NM), the VLA's angular resolution 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 at least 32 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 the four new antennas. The additional correlator cost is very modest.

The increased angular resolution provided to the VLA will principally benefit studies of stellar emission (thermal and nonthermal) and studies of the details of extragalactic radio jets. In the latter case, not only is the resolution needed but so also is good imaging capability on the scale of a few to several tens of milli-seconds. This capability will be provided by the four new antennas and complementary observations with the existing VLA and VLBA. With it we can expect direct measurements of the velocity of material in radio jets and perhaps even a direct measurement of the Hubble constant.

3. 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. The proceedings of that workshop will form the basis for the next iteration of discussion of the project. Once the scientific ideas and desires converge and priorities are set a proposal for the upgrade will be submitted to the NSF. We expect this to occur within the time frame of the present long range plan.

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 requird for astronomical research must, as a necessity, be written in-house. There are no commerical 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.

Unfortunately, relentless budgetary pressures over the past few years have resulted in decreased investment in computing at NRAO. The last major investment in computing hardware at NRAO occurred with the completion of the VLBA; significant computer purchases in 1992 and early 1993 were the result. Both 1994 and 1995 have turned out to be relatively lean years for the Observatory, forcing hard choices which ultimately impose limits on the kinds of science which can be accomplished with Observatory facilities.

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.

A number of exciting developments at the NRAO will place new demands on NRAO's computing facilities and personnel over the coming few years. 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 during 1995. 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 in early 1997. Efforts are underway to insure that software will be in place to handle GBT data reduction. The funding levels in 1994 and 1995 have forced a difficult choice between fully supporting existing single dish instruments in Green Bank and Tucson or preparing adequately for the GBT.
- 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. Hardware to handle these data are not yet in place at the NRAO; necessary software developments have also been delayed.
- Scientific visualization techniques are going to become essential for dealing with the large data volumes from new instruments and receivers. Personnel limitations have prevented any significant 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 decade, we expect that the MMA will be under construction. 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 huge 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 only three to five years, due to the rapid increases placed on computing and to the rapid improvements in available computing capability. In light of this, the NRAO needs to move from a feast and famine approach to a more efficient strategy 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 main emphasis in software development at the NRAO has been in two areas: supporting the main NRAO instruments in an operational sense, and developing and supporting software systems for use by users of the instruments in analysis of their radio astronomical data.nstruments.

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 to users its current flagship software products, AIPS and UniPOPS. Significant new effort will be directed towards developing the algorithms required by the VLBA and orbiting VLBI software development.

Single Dish Computing

The largest effort in single dish computing is focused on designing and implementing the control system for the GBT. That effort will begin the transition from implementation and integration to operational status during the 1995-96 time frame. GBT computing is the highest priority in the single dish area. Unfortunately, budgetary restrictions during 1993 and 1994 have forced a choice to be made in the development of the GBT control software and further development of the single dish analysis software. The main analysis package for observational data from the NRAO 140 Foot and 12 Meter Telescopes is the UniPOPS package. UniPOPS is relatively stable, but is inadequate in the face of rapidly developing observing techniques such as on-the-fly mapping or multi-beam observations. Although AIPS++ will deal with these types of new observing within the next two years, this has left a gap in the support of current techniques. On-the-fly mapping at the 12 Meter Telescope is a technique shown to produce wide-field images form the 12 Meter Telescope at millimeter wavelengths that are comparable with VLA long-wavelength images. But they do so at the expense of an enormous data rate and data processing cost. Figure VI-1 shows as an example an on-the-fly map of the CO mission in IC 342 compared with a VLA 327 MHz continuum image of the same galaxy. The procurement and personnel plans below address these problems by proposing a new position for computing and appropriate hardware upgrading.

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 nine years old, and is starting to show its age in terms of reliability and maintenance costs. The plan is to do the design work in 1995, followed by implementation in 1996. The upgrade will be the minimum to keep the VLA operational, but will also provide the foundation needed for the eventual large-scale VLA upgrade.

VLBA Computing

Estimates of the computing requirements for reducing VLBA data were based on a relatively modest model of VLBA observing: detailed images of sources produced from long integration. It now appears that surveys and rapid imaging experiments will be a significant portion of VLBA observing, resulting in up to hundreds of images from a single experiment. VLBA data sets are typically much larger than VLA data sets because of the multiple frequency bands which are used to get wide bandwidth and delays which must be reduced separately for each frequency band. The full impact of VLBA data reduction requirements has not yet been felt, since the VLBA is not yet up to full operational production. The current crop of high-end workstations available at the AOC will be hard pressed to cover VLBA data reduction requirements for the long term. A medium to large VLBA data set will probably require dedicated access to a ~80-100 MIPS machine for several weeks by a single user. There are currently only five such machines available at the AOC, and two in Charlottesville; advance sign-up lists for those machines are two months long.

The AIPS++ Project

The Astronomical Information Processing System (AIPS++) is a software system designed primarily for astronomical data analysis. NRAO's partners in the development of AIPS++ are: Australia National Telescope Facility, Australia; Berkeley-Illinois-Maryland Association, USA; Herzberg Institute for Astronomy/Dominion Radio Astrophysical Observatory, Canada; Netherlands Foundation for Research in Astronomy, the Netherlands; Nuffield Radio Astronomical Laboratory, UK; and the National Center for Radio Astrophysics, India. Inside NRAO, the Project is organized as a construction project of limited duration. The goal is to replace and extend the functionality of the AIPS system within five years. The most pressing short-term goal in the evolution of AIPS++ is to test and validate some of the core infrastructure software by writing two or three trial applications. This, and the probable ensuing consolidation of the infrastructure software, is expected to take one year or more. Subsequently, the capabilities of the system will be expanded to completeness. As the system becomes more and more complete, personnel currently working to support AIPS operations will be transferred over to the operational support of AIPS++.

VII. ELECTRONICS DEVELOPMENT

The NRAO Central Development Laboratory (CDL) is engaged in the design and evaluation of devices that are of potential benefit to the operation or performance of the NRAO telescopes. The CDL works collaboratively with the engineering staff at all the observing sites, and for this reason the range of technical tasks undertaken at any particular time at the NRAO involve work principally done at the sites as well as work physically 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:

- Evaluation of pseudomorphic HFET amplifiers;
- Advanced design and contract fabrication of SIS mixers;
- Prototype and test of 86 GHz HFET-based receivers for the VLBA;
- MMA technology development and demonstration tasks.

HFET Amplifiers

The theoretical performance of small area HFET amplifiers indicates that the performance of such devices should be such as to provide a device noise figure of less than 10 K throughout the centimeter wavelength range. For radio astronomy applications, this will make the HFET's competitive with the best maser receivers. At still higher frequencies, at the long millimeter wavelengths, the HFET amplifiers may be superior to SIS mixers. Figure VII-1 is an illustration of how the best NRAO HFET amplifiers compare with the best NRAO SIS mixer receivers. The crossover point appears to be near 100 GHz.

At the NRAO we are attempting to achieve the expected HFET noise figures at the highest frequencies. By means of a contract with Hughes Research Laboratories, we had fabricated two wafers with nearly 6500 InP HFET devices with gate widths suitable for applications from 1 to 100 GHz. Over the course of the next five years, we expect to incorporate these new devices in receivers for the VLA, VLBA, GBT, and for the 3 mm MMA receiving system.

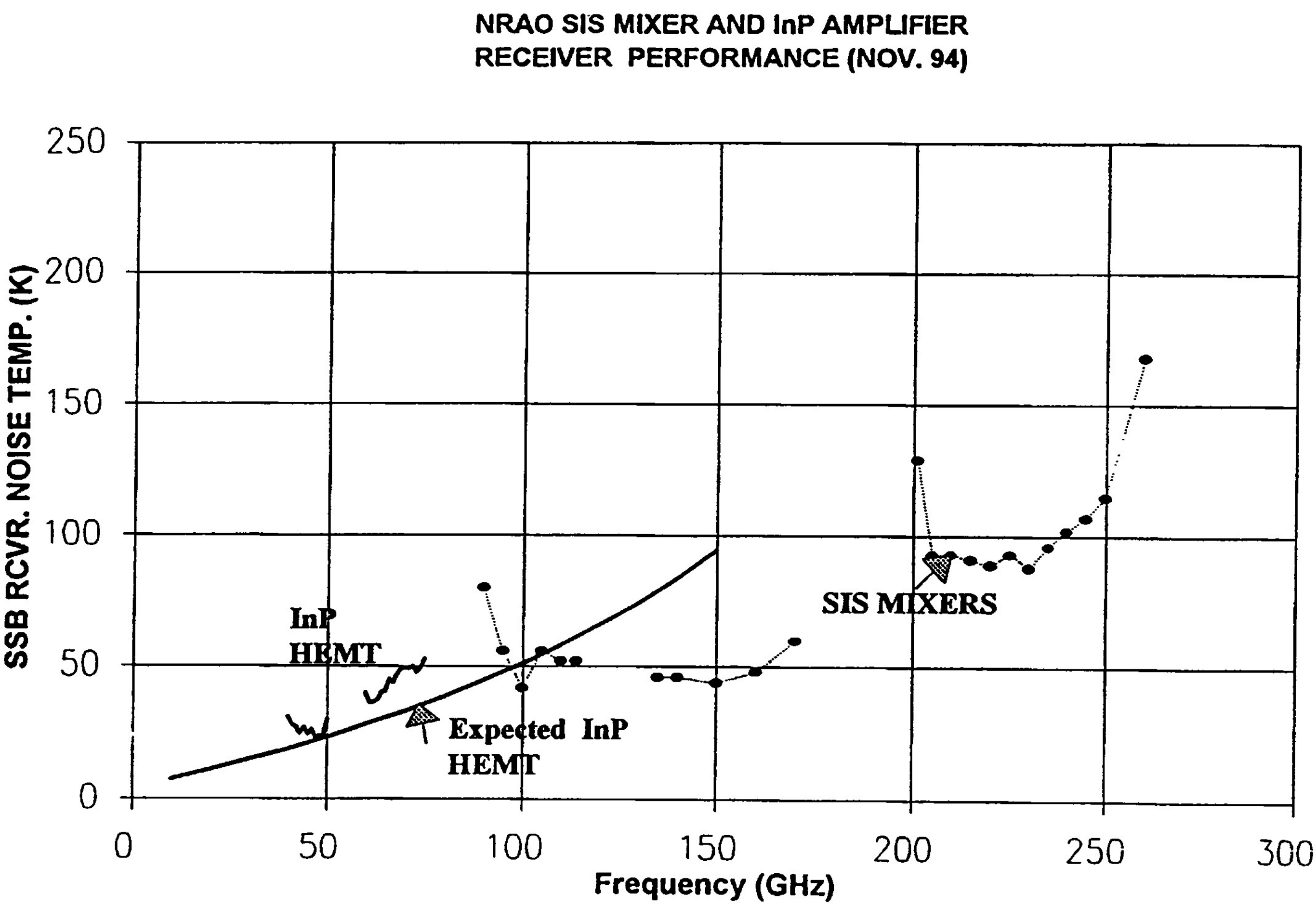

Figure VII-1. NRAO receiver performance.

SIS Mixers

The long-standing collaboration between the NRAO and the University of Virginia Semiconductor Devices Laboratory is once again yielding high quality Nb SIS devices. We use the devices in receivers for the 12 Meter Telescope covering 68-300 GHz, and we are experimenting with radical new tunerless designs capable of meeting the demanding MMA specifications for sensitivity and wide bandwidth. Increasingly, it is work preparatory to the MMA that is the focus of the NRAO SIS design effort. Three of the important goals in this respect are:

- Evaluation of the feasibility of building single sideband SIS mixers with no active mechanical tuning or rejection elements. If successful, such mixers will enhance the sensitivity of the signal sideband by eliminating the sky noise contribution from the unwanted sideband;
- Develop balanced SIS mixers to separate local oscillator and signal paths;
- Develop an integrated SIS mixer and IF amplifier for wider IF bandwidth. A secondary goal of this project is to simplify the manufacture of SIS mixers for greater reproducibility and easier maintainability.

86 GHz VLBA Receiver

At an observing frequency of 86 GHz, the VLBA has an angular resolution twenty times better than that at 5 GHz and better even, by a factor of two or three, than the resolution of the current generation of space VLBI missions, VSOP and Radioastron, at their *workhorse* frequency of 5 GHz. With the 86 GHz 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. This is the right resolution at the right frequency.

Two prototype 86 GHz receivers for the VLBA are under construction now. They incorporate the Hughes InP HFET amplifiers and are both dual polarization receivers. In 1996 the receivers will be installed on two of the VLBA antennas for tests. If successful, the entire VLBA will be equipped with similar receivers on an incremental basis over the next four years.

MMA Development Tasks

Much of the SIS emphasis and a significant fraction of the effort on high frequency HFET amplifiers is done in the expectation of the needs of the MMA. The MMA focus on multiples of forty of all the key components of a radio telescope brings to the fore the need to design simple devices that are easy to build, replicate, and maintain. While these design parameters have always been important in other NRAO applications, they become foremost for an instrument as complex as the MMA and one likely to be located on a very remote site. The need for MMA design simplification extends also to the need for a simple multiplier design and a straightforward calibration system.

In collaboration with the University of Michigan, we are engaged in design work on a 60-90 GHz monolithic multiplier that, if successful, may be appropriate for the MMA local oscillator multiplier. A second collaboration, this time with both the University of Michigan and the University of Virginia, is working to develop a calibration system for the MMA. The problem is that tunnel diode noise sources that are currently used successfully at centimeter wavelengths do not give sufficient signal power above 25 GHz and hence are inadequate for the MMA. In the course of this long range plan we will jointly explore use of resonant tunnel diode structures as calibration noise sources. If the design and tests go well, MMA fabrication facilities will be developed at one of the participating universities.

VIII. BUDGET AND PERSONNEL PROJECTIONS

(NSF Funds, $ in Thousands)

	1996	1997	1998	1999	2000	2001
OPERATIONS (Div. Astron. Sci.)						
Base Operations	$31,600[1]	32,115	33,400	34,735	36,120	37,565
Research & Oper. Equip.	980	1,200	1,400	1,400	1,500	1,700
NSF Operations	$32,580	$33,315	$34,800	$36,135	$37,620	$39,265
NEW INITIATIVES (Major Res. Equip.)						
MMA Design & Dev.[2]	--	9,600	9,800	6,735	--	--
MMA Construction[2]	--	--	--	5,000	25,000	25,000
VLA Upgrade	--	--	--	--	1500	3000
Total New Initiatives	--	$ 9,600	$ 9,800	$11,735	$26,500	$28,000

Personnel Projection (Full-Time – Year End Ceiling)

Operations	425	415	417	417	419	419
MMA Design & Dev.	--	44	48	--	--	--
MMA Construction	--	--	--	49	55	55
Non-NSF Research	10	10	10	10	10	10
Personnel Totals	435	469	475	476	484	484

[1] Includes $1M MMA funding

[2] In 1994 dollars