Program Plan

2002

National Radio Astronomy Observatory

A facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

NRAO

NATIONAL RADIO ASTRONOMY OBSERVATORY

FY2002 PROGRAM PLAN

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I. Mission Statement

The mission of the National Radio Astronomy Observatory (NRAO) is to design, build, and operate large radio telescope facilities for use by the scientific community; to develop the electronics, software, and other technology systems that enable new astronomical science; to support the reduction, analysis, and dissemination of the results of observations made by the telescope users; to support the development of a society that is both scientifically and technically literate through educational programs and public outreach; and to support a program of staff scientific research that enables leadership and quality in all these areas.

II. Introduction

In 2002, the National Radio Astronomy Observatory (NRAO) Program Plan emphasizes an increased in commitments to the NRAO community of users and to the wider community of students, scientists, and citizens. These commitments involve provision for new facilities, new opportunities for access to NRAO instruments and archival data, and the support of new services for scholars and the public. Specific initiatives in 2002 include the following:

New Observing Facilities

- Complete the ALMA design and development and, if approved to do so, begin the construction phase of the ALMA Project;
- Begin the construction phase of the EVLA;
- Promote the initial science operations of the GBT.

New Opportunities for Scientific Access

- Complete the installation of the 3 mm wavelength observing system on the Very Long Baseline Array (VLBA) and enhance the program to make the VLBA more accessible to a wider user community;
- Initiate the end-2-end project in Data Management and start participation in the National Virtual Observatory, while expanding support of users, internal and external, of NRAO data reduction software;

Expanded Support Services

- Construct and begin implementation of an Education and Public Outreach Strategy;
- Continue to expand the program of user support by establishing a GBT data analysis grants program and working with university-based groups in developing new instrumentation.

The year 2002 will be the final year of the design and development phase of the Atacama Large Millimeter Array (ALMA). Indeed, there is a possibility that ALMA will begin construction in 2002, although the start of construction will be uncertain until the conclusion of the appropriation process. Therefore, this Program Plan is written to the budget as requested of the Congress—$9,000,000 for another year of design and development. We note that the principal deliverables of the design and development phase are already available, with substantial progress having been made toward final agreement on the international arrangements for a joint project and for the site. ALMA has received top-level endorsements from the astronomy and astrophysics survey review committees of all the participating countries. It is internationally recognized as the most important new ground-based facility required to address the research issues of the new century. NSF's oversight committee (MMAOC) has recommended a start of construction in 2002.

The Program Plan for 2002 also anticipates the start of construction for the first phase of the Expansion of the Very Large Array (EVLA). The entire EVLA project, which will improve all the performance specifications of the VLA by a factor of ten, was very highly ranked by the Astronomy and Astrophysics Survey Committee. In FY2002, we plan to install a new wide-band correlator and signal transmission system, new and improved receivers, and an end to end data management system. Later plans call for an improvement to angular resolution by adding antennas at distances intermediate between the VLA A-configuration and the Very Long Baseline Array (VLBA) shortest baselines. Studies leading to the completion of this latter phase of the EVLA will begin in 2002.

The year 2002 will be the year that the Green Bank Telescope (GBT) achieves initial operation at wavelengths of 7 mm and longer. A call for proposals for a program of *early science* was issued in October of 2000. This program will result in a series of results that demonstrate the capability of the GBT and its instrumentation, starting at long wavelengths and proceeding to the millimeter band. After running the first of these observing programs, the telescope was taken from service to conclude a list of final activities by the contractor. At the time of submission of this Program Plan, those activities are complete and the Early Science Program will restart, to be completed by the end of calendar 2001. A second call for proposals has been issued. Meanwhile, long range planning that will lead to a second generation of instrumentation for the GBT has begun. The emphasis of this program will be on array receivers.

The installation of a 3 mm wavelength observing mode for the Very Long Baseline Array (VLBA) will be completed within the resources of this Program Plan. The primary emphasis of the VLBA program in 2002, beyond millimeter observing, will be to make the VLBA more accessible to more of the astronomical community. Studies of potential long-term improvements will also be made, especially in the area of increased signal bandwidth and in understanding the possibilities for transmitting antenna signals to the correlator over high-speed data networks rather than using tape. In that regard, a first step, of using hard disk drives rather than magnetic tape, shows significant promise, and a joint program with Haystack Observatory to develop this system will be supported as part of this year's Program Plan.

In 2002, we will continue to strengthen three activities that cut across all NRAO observing facilities: electronics development in the Central Development Laboratory (CDL), coordination of computing and software development in a central Data Management (DM) group that will also organize new initiatives in data management, and the Observatory program in education and public outreach (EPO). The principal goal for the CDL is to establish the instrumentation infrastructure required for ALMA and EVLA construction. For DM, the principal goal is to begin a new initiative called the End-to-End (e2e) project. It will first provide a data pipeline for the EVLA and eventually for ALMA, the VLBA, and the GBT. It will also serve as the radio archive portal to the National Virtual Observatory (NVO). In the area of EPO, we will construct an Observatory-wide EPO strategy, build the Education Center in Green Bank and strengthen other EPO programs, as noted in this Program Plan.

Finally, a major goal for 2002 is the establishment of better communications with the astronomical community, increased involvement of the community in strategic planning, and increased support for university-based radio astronomy groups. Following the recommendation of the Astronomy and Astrophysics Survey Committee that grants of observing time be accompanied by funds to support observing on new ground-based telescopes, as is done for space missions, we are planning to initiate such a program for all observing programs on the Green Bank Telescope that involve students.

Together, the initiatives of the FY2002 NRAO Program Plan will catalyze the process of binding the NRAO more closely with its community of users and its citizen-supporters.

Green Bank Telescope

The Robert C. Byrd Green Bank Telescope (GBT) will begin regularly scheduled scientific operation in 2002. In 2001, an Early Science Program was initiated in which the community was given access to the GBT during its commissioning period for unique observational projects. This program will conclude in early 2002, and the transition to regularly scheduled programs will begin. By the spring of 2002, the GBT will be operating to a frequency of 50 GHz. Commissioning will continue on a part-time basis throughout 2002 to achieve 100 GHz operation, which is expected by early 2003.

The astronomical community enthusiastically responded to the Early Science call for proposals, which indicated keen interest in the scientific capabilities of the GBT. These include ~8000 m^2 of fully steerable collecting area, an unblocked aperture for high fidelity imaging, a precision structure that will ultimately have three decades of frequency coverage from 100 MHz to 100 GHz, and the telescope's location in the National Radio Quiet Zone. A sampling of the scientific programs and research areas that will be addressed in 2002 follows.

High Redshift Galaxies and the Early Universe

A number of galaxies at very high redshift have been detected in their dust continuum and CO line emission. The look-back time for some of these galaxies is as much as 90 percent of the age of the universe. Virtually all of the galaxies detected so far have had their emission amplified by intervening lensing galaxies along the line of sight. With the sensitivity of the GBT, it is very likely that many unlensed systems can be detected. This will allow a much more thorough study of the early universe. Observers will use the GBT to study J=1-0 CO redshifted to K-band (18-26 GHz), which corresponds to a redshift of ~4. In the near future when the GBT is operating at higher frequencies, it will have sensitive redshift coverage to $z > 10$ using other CO transitions. The GBT will also be used at lower frequencies to study high redshift HI, and OH megamasers. The comparatively good RFI environment in Green Bank will be a great advantage to these low frequency projects, which are often precluded elsewhere.

Cosmology

The high sensitivity, absolute calibration, and low sidelobes of the GBT will make it ideal for studies of cosmology. The GBT will have excellent performance at 1 cm (30 GHz), a preferred window for studies of the cosmic background radiation. It will also have unique capabilities in the 3 mm band, where wide field observations of the Sunyaev-Zel'dovich effect could produce important results on fundamental parameters of the universe. Receivers are planned for the GBT for both the 1 cm and 3 mm bands, and should be available in early 2003.

Planetary Radar

The first scientific project done with the GBT was a successful radar imaging project of Venus and a nearby asteroid, done in collaboration with Arecibo Observatory. Altimetric and spatial resolutions were achieved that were up to 10 times better than those achieved with the Magellan Orbiter in 1990. More projects are planned for imaging planets, moons, comets, and asteroids. This is a powerful research technique will offer fruitful collaboration between the GBT and Arecibo.

HI Spectroscopy

Observations of neutral hydrogen and the hydroxyl radical will benefit greatly from the high fidelity response of the GBT, its location in the Quiet Zone, and the bandwidth and spectral resolution of the GBT Spectrometer. Measurements of accurate, absolutely calibrated Galactic 21cm HI profiles can be done quickly and routinely. Early HI imaging projects on the GBT will seek to determine whether the Milky Way disk has a distinct outer edge, will study the scale height and random velocity of gas in the inner Galaxy, and will test the hypothesis that there is a corotating HI halo about our galaxy.

Pulsars

Pulsar observations will benefit from the GBT's large collecting area, sensitive receivers, excellent sky coverage, and the comparatively low RFI at the site. Initial pulsar search projects on the GBT will seek single, sub-millisecond pulsars, additional double neutron star systems, and X-ray selected objects in the Galactic Center. The GBT will provide a sensitive element for VLBI pulsar parallax measurements. Pulsar timing experiments will be conducted also, including observations of a triple system and an intriguing system with an apparent 11 solar mass companion object.

Astrochemistry

The capabilities of the GBT will make it a powerful instrument for studies of the chemistry in interstellar and circumstellar clouds. The GBT will be used in the search and study of very heavy molecules such as long-chain carbon molecules, and molecules of biological interest such as amino acids and sugars. Initial astrochemistry projects on the GBT will include a search for a simple amino acid and a molecular line survey of the 40-50 GHz frequency range that will provide a factor of ten improvement in sensitivity over previous studies.

Very Long Baseline Interferometry

Many of the most interesting astrophysical problems requiring ultra-high angular resolution, such as probes of active galactic nuclei, require very high sensitivity. The precision collecting area of the GBT can be of enormous benefit to VLBA studies of such objects. In particular, the GBT and VLA will form a very high sensitivity, east-west baseline for inclusion in the VLBA, and possibly the European EVN. The GBT will participate in many VLBI projects in the coming year.

Water masers

One of the most interesting results in radio astronomy in recent years has been the VLBI study of the water masers that are apparently in Keplerian rotation about a central black hole in the galaxy NGC 4258. This study has allowed a very accurate determination of the distance to the galaxy that has modified the cosmological distance scale. Presently, detailed studies of the water masers in extragalactic sources can only be carried out for relatively nearby galaxies because of the faintness of the maser lines. The sensitivity of the GBT may allow detections in more distant galaxies. The discovery and study of additional, distant water masers like the one in NGC 4258 would allow for a direct and precise determination of the size and age of the universe. Searches for extragalactic water masers are planned for the coming year.

Very Large Array

The VLA entered its third decade of full operation with more than 10,000 completed observing projects. The VLA produces more refereed publications per year than any other telescope at any wavelength other than the Hubble Space Telescope. It remains a vital tool at the forefront of many areas of astrophysics, including gamma-ray burst afterglows, black hole X-ray binaries, and studies of stellar evolution. Data from the NRAO VLA Sky Survey (NVSS) and Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey remain a valuable resource for the research community. New and evolving capabilities, including low-frequency (74 MHz) observations, improved high-frequency (22 and 40-50 GHz) receivers, and real-time integration of the VLBA Pie Town station as an element of the VLA, are opening exciting new avenues of investigation for the astronomical community. Demand for VLA observing time is more than twice that available.

Solar System

Using the NVSS, observers have identified radio sources that may be occulted by Saturn's ring system over the next several years. These sources will be observed at higher resolution to improve the knowledge of their positions and structure, to confirm both that they will be occulted and that they are sufficiently point-like to serve as good background sources for occultations. Occultations provide opportunities to quantify the size and spatial distribution of particles in the ring system in the dynamically important 1-10 meter size range.

A number of X-ray and ultraviolet satellites are intensely studying the Sun during the peak of the solar activity cycle. Several VLA programs are under way to make coordinated observations together with these satellites, which include *Yohkoh, SOHO,* and *HESSI.* By combining radio and X-ray imaging, the signatures of nonthermal energy release will be studied, and predictions of flare/micro-flare models will be tested. The populations of electrons in flares will be studied by combining their radio synchrotron emissivity with the X-ray spectral characteristics. The coronal magnetic fields will be measured at the locations where the X-ray bursts occur. Taken together, these studies will provide a much more complete picture of the physics of energetic solar events, and their propagation through the solar corona.

The Galactic Center, Pulsars, Novae, Supernovae, X-ray Binaries, and Other Radio Stars

In 2000, a summer student project revealed the surprising discovery of flaring radio emission from the brown dwarf LP 944-20. Monitoring observations of this source, and observations of other brown dwarfs, will continue in 2002. These observations will be used to determine the frequency and recurrence rates of radio flares in brown dwarfs, and to explore the physics of their magnetic fields.

The VLA has a long history of rapid response to newly-discovered supernovae and outbursts of X-ray binaries. The VLA has contributed multi-frequency radio light curves of both types of objects, providing information vital to deciphering their physics. In addition, VLA observations have revealed the presence of expanding jets in X-ray binary systems, many of which are thought to include black holes as their compact component. Ongoing target-of-opportunity programs will continue these important contributions. Along with the targets of opportunity, specific observations of radio stars will be carried out in coordination with at least three X-ray satellites, *RXTE* (Rossi X-ray Timing Explorer), *XMM* (X-ray Multi-mirror Mission), and *Chandra.* These observations will be used to search for coordinated outbursts, and to model the physics of the X-ray sources by combining radio flux density measurements with simultaneous high-resolution X-ray spectroscopy.

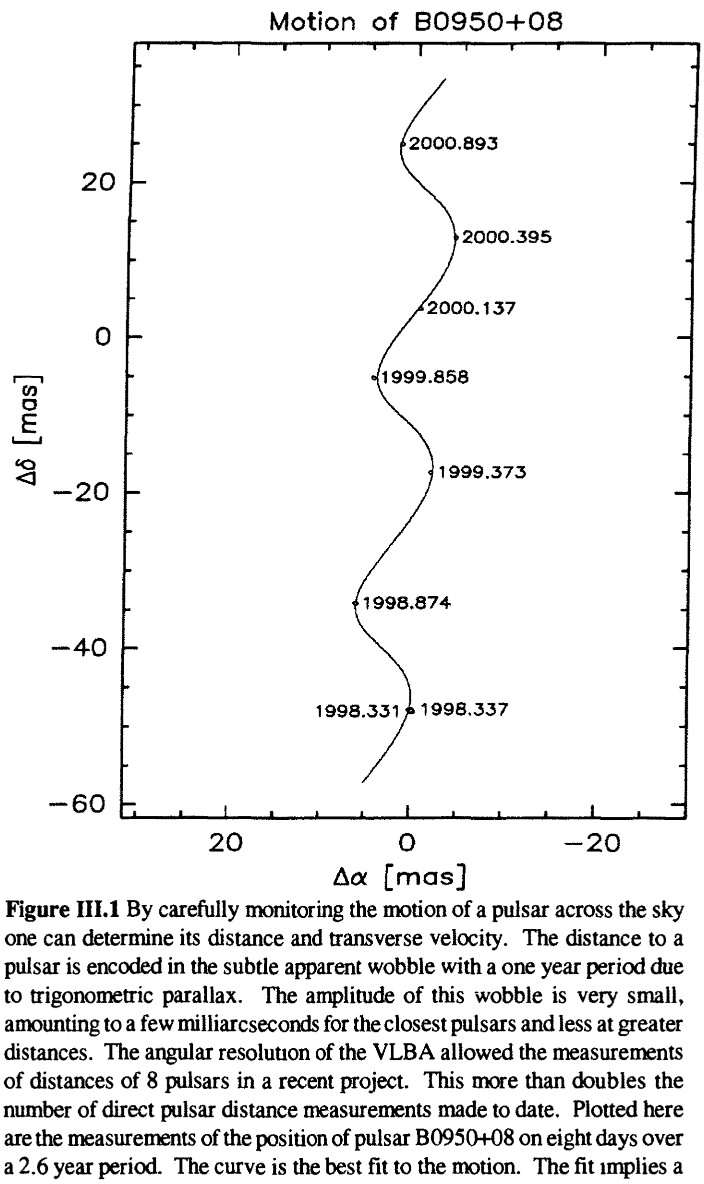


Figure III.1 By carefully monitoring the motion of a pulsar across the sky one can determine its distance and transverse velocity. The distance to a pulsar is encoded in the subtle apparent wobble with a one year period due to trigonometric parallax. The amplitude of this wobble is very small, amounting to a few milliarcseconds for the closest pulsars and less at greater distances. The angular resolution of the VLBA allowed the measurements of distances of 8 pulsars in a recent project. This more than doubles the number of direct pulsar distance measurements made to date. Plotted here are the measurements of the position of pulsar B0950+08 on eight days over a 2.6 year period. The curve is the best fit to the motion. The fit implies a distance of 262 +- 5 parsecs and a transverse velocity of 36.6 +- 0.7 kilometers per second.

Multi-configuration imaging will be carried out of several nebulae surrounding pulsars. The so-called pulsar wind nebula (PWN) candidates are associated with variable X-ray and gamma-ray sources. The PWNs are powered by the pulsars left over after supernova explosions, rather than just "coasting" from the initial impulse of the supernova explosion. If diffuse nebulae are found, the PWNs would be the first class of sources having variable emission above 100 MeV that are known to be associated with the Galaxy (as opposed to being active galaxies, or "blazars").

Two research teams will study supernova remnants to determine their expansion velocities. In G11.2-0.3, the velocity of the shell will be compared to the PWN found inside. In Tycho's supernova, comparison will be made to images of the supernova remnant made with the VLA over the last 20 years in order to provide an accurate measurement of the expansion of the radio-emitting material. This will be combined with a comparison between *ROSAT* (ROentgen SATellite) and *Chandra* imaging taken approximately seven years apart, as well as archival X-ray data stretching back as far as 1979. The 20-year history (5 percent of the time since the supernova explosion) will enable scientists to resolve the discrepancy between previous X-ray and radio measurements of the remnant expansion rate, as well as providing the first measurement of deceleration of the supernova shell as it expands through the interstellar medium.

The Interstellar Medium, Molecular Clouds, Cosmic Masers, Star Formation, and Stellar Evolution

During the first trials of the Pie Town link (which makes the Pie Town VLBA antenna part of the VLA) in 2000/2001, a number of observations were made of regions of recent star formation. SiO maser emission, in two transitions, was imaged in the Orion Nebula's BN/KL star-forming region, in order to determine the physical conditions as a function of location in the Nebula. Continuum observations at 43 GHz were employed to make the first direct detection of an accretion disk around the massive protostar G192.16-3.82. The success of these high frequency observations, and the benefit of the additional factor of two in resolution, will lead to an increased number of similar programs during the Pie Town link session in January-May 2002. Both massive and solar-mass protostars will be imaged in both the 43 GHz continuum and maser transitions to extend the sample of objects in which the details of disk structures and outflows can be imaged, so that the physics of star formation by accretion is better understood. Similar studies will be carried out using the H_2O maser emission at 22 GHz, to study the positions and kinematics of the masers, with the aim of understanding the roles of jets and circumstellar disks in the process of star formation in a variety of environments.

The demonstration in recent years that low-mass protostars are almost never found alone, but rather in groups of three, four, or five stars has produced a challenge to standard models of early stellar evolution. Instead of the slow and gradual process in the standard model, a new model proposes that early stellar evolution is punctuated by the dynamical decay of such small multiple groups. A detailed VLA study of a very active star-forming core will seek to detect orbital motion and evidence for ejection in young systems. The VLA observations will be geared specifically to test the predictions of the alternative model and thus perhaps provide strong support for a radical departure from the standard picture of early stellar evolution.

Normal Galaxies

Researchers plan to observe the nuclear region of M82 to monitor the flux density of 24 compact radio sources, which are presumed to be supernova remnants. This monitoring program—so far detected in two-thirds of these sources—goes back to 1981, so the time base for studying flux-density variation will be extended to more than 20 years.

Most spiral galaxies show flat rotation curves out to large radii, indicating the presence of substantial amounts of mass at large galactic radii. The properties of the matter in the outskirts of such galaxies are not well determined. VLA HI observations will be carried out in several nearby spiral galaxies, and combined with deep H-alpha imaging of the same galaxies, in order to trace the distribution of luminous matter at the large radii. The properties of the gas will be compared to the star-formation activity in order to find the edges of the disks outlined by classical star-formation processes.

Radio Galaxies, Quasars, Active Galaxies, and Gamma-ray Bursts

Research teams will use the VLA in 2002 to observe the brightest cluster galaxies (BCGs) in 46 clusters in order to test the connection between black hole mass and radio emission. These 46 are a subset of a sample of 119 such objects being imaged with the *Hubble Space Telescope* to measure their black hole masses; the other objects have either been detected previously at radio wavelengths, or lie too far south to be observed with the VLA. The radio detection limit for the sample will be reduced by a factor of ~10, and most galaxies are expected to be detected. The nature of the correlation between black hole mass and radio luminosity will be determined, and constraints placed on models of how the black hole characteristics contribute to the production of the radio emission.

The successful target-of-opportunity program to detect and study the radio afterglows of gamma-ray bursts (GRBs) will be continued. The VLA detected the first radio counterpart to a GRB in 1997; as of mid-2001, a total of 20 GRB afterglows have been detected and studied at radio wavelengths. When the VLA makes such detections, the identification and subarcsecond positions are provided to the international, multiwavelength GRB community. Studies of radio afterglows provide unique data on the size, expansion rate and geometry of the GRB fireball and help constrain the physics of the shocks. In addition, the detection of GRB radio afterglows in dusty environments has provided some of the strongest support for the now nearly standard hypernova model for GRBs. In 2002, we will continue the program to monitor GRBs on a nearly daily basis. Since radio afterglows are the only manifestations of the GRBs that can be detected months and years after the initial events, the sensitive VLA observations are the best way to probe the physics of the burst environment, and trace the pre-burst history of the surrounding material.

The FIRST survey will be continued in 2002. This survey, in the B configuration, provides deep, 4 arcsecond resolution radio imaging over large regions of the sky, primarily in the north galactic cap. A considerable amount of overlap exists with the Sloan Digital Sky Survey, so that deep optical imaging (and redshifts) will be available for this substantial population of radio sources, enabling a variety of statistical studies of radio emission from samples of optical quasars and galaxies.

Cosmology, Large Scale Structure, Galaxy Formation, and Gravitational Lensing

The VLBI-determined positions of extragalactic objects defined the International Celestial Reference Frame (ICRF). The Full-sky Astrometric Mapping Explorer (*FAME*) satellite, scheduled for launch in 2004, will provide the positions of 40 million stars within our Galactic neighborhood with an accuracy as much as an order of magnitude greater than the current ICRF. Using the Pie Town link to improve resolution, VLA observers are measuring precisely the positions of some 50 radio stars in order to allow accurate linking of the *FAME* and ICRF reference frames.

The *Chandra* X-ray satellite is observing fields to very low X-ray intensities, with integrations of up to a million seconds (12 days). These deep X-ray images are being complemented by sensitive VLA imaging of the same fields, in order to determine the nature of the faint X-ray sources. The VLA detections (and non-detections) will be used together with the X-ray imaging to address unresolved questions about the natures of distant galaxies and the detailed composition of the point-like X-ray sources that are now known to constitute the bulk of the X-ray background.

Two large surveys, each with hundreds of hours of observing, will take place in 2001 and 2002. One survey will acquire HI imaging data for clusters in a range of redshifts from zero to 0.2. Combined with deep optical multi-color imaging and spectroscopy, this will give the most complete information yet on the evolution of galaxies in the local universe. With a large field of view, researchers will prove both the low-density outer parts of the clusters and the dense cluster cores. The second survey is a deep radio survey of the *SIRTF* (Space InfraRed Telescope Facility) First-look Survey. The *SIRTF* survey at wavelengths between 8 and 70 μm will uncover thousands of galaxies to redshifts of z~1. The far-infrared/radio correlation implies that the VLA observations will detect essentially all the galaxies in the 5-deg^2 field of the *SIRTF* survey, but with much greater positional accuracy than that available with *SIRTF*. Therefore, the VLA observations will be used to identify unambiguously the optical galaxies that are associated with the infrared detections, enabling redshift measurements and detailed follow-up on a large statistical sample of galaxies. This will enable the study of the evolution of starbursts and star formation from the nearby to the distant universe.

The VLA also will be used to carry out a number of programs to study the low-frequency radio emission in the vicinity of clusters of galaxies. The distribution of magnetic fields within the clusters will be imaged by means of Faraday rotation measurements, and the "old" electrons in the cluster halos will be imaged at 74 and 327 MHz. Relic radio sources, both inside and outside clusters, will be studied by similar means. These data will help investigators map out the history of clusters and the galaxy mergers in them, for comparison with the ongoing mergers that are seen in very distant galaxies.

The VLA has been used at 43 GHz to detect redshifted CO from several distant star-forming galaxies. The line intensities demonstrate that there is sometimes much more molecular material available to form stars than is evident from the higher-order transitions accessible to millimeter interferometers. In 2002, observations of several more conveniently redshifted galaxies will be carried out, both in the 1-0 and 2-1 transitions. These will be used to determine the star formation rates in the distant galaxies, and find whether the excitation temperatures are commonly lower than required to generate strong high-order transitions. Redshifted CO is one of the important targets for the EVLA, so these investigations will improve the quantitative predictions of the scientific return that will be available once the VLA is enhanced.

The VLA will continue its prominent role in searches for and studies of gravitational-lens systems. Candidate radio sources are observed systematically to determine if they are, in fact, gravitational lenses. Known lens systems are observed to determine time delays in brightness variations between components of the lens. In some cases, the time delays between lens components are quite small, requiring routine monitoring observations with good aperture plane coverage in regular observing sessions no more than 1-2 hours in length. The measured time delays between the images of a gravitationally lensed source, when combined with source and lens redshifts and a mass model for the deflector, can yield the angular diameter distances in the lens system and thus help calibrate the Hubble Constant.

Very Long Baseline Array

The VLBA remains a valuable and popular tool for a wide range of astrophysical inquiries because it has the routine capability to produce images with milliarcsecond resolution. Newer capabilities such as pulsar gating and the growing suite of 86 GHz (3 mm) receivers are expanding the value of the VLBA as a scientific tool. The VLBA also has proven itself in routine operation as a ground array for the *HALCA* radio-astronomy satellite, an ability that will pave the way for future space radio-astronomy efforts.

The Galactic Center, Pulsars, Novae, Supernovae, X-ray Binaries, and Other Radio Stars

VLBI measurements of the size of the Galactic Center source Sgr A* generally have shown a linear relation between the source size and the square of the wavelength, which is attributed to interstellar scattering along the line of sight to the radio source. At 43 GHz frequency, there is controversy over whether an intrinsic size has been measured for Sgr A*, and previous 86 GHz observations have had inadequate north-south spacings to make definitive statements about the source size. The power of the VLBA—with 8-9 receivers at 86 GHz, plus dynamic scheduling to take advantage of the best weather—provides the opportunity to settle this question in 2002. Either a clear size measurement or a strong upper limit to the intrinsic size of the source will be of considerable theoretical interest, and will constrain models of the radio emission—is it dominated by a compact jet or by an advection-dominated accretion flow? The available resolution of ~100 microarcseconds is only 8 times the diameter of the event horizon of the 2.6-million solar mass black hole at the Galactic Center.

Researchers have used infrared observations to study stellar motions and infer the mass of the Milky Way's central black hole. A number of SiO maser sources are present in evolved stars within 40 arcseconds of the Galactic Center; the positions of these stars relative to Sgr A* will be measured at multiple epochs with phase-referenced VLBI. Using relative position measurements accurate to 50 microarcseconds, the 3-dimensional motion of the stars will be obtained, and used to help interpret the infrared observations of the accelerating motions of the stars within the central star cluster of the Milky Way.

The resolving power of the VLBA will allow observers to measure parallaxes and proper motions of several strong pulsars. Part of an ongoing program to measure pulsar velocities and distances, this project seeks to measure the velocity distribution of neutron star populations, constrain models of core collapse processes in supernovae and of binary evolution, and refine models relating Galactic dispersion measure and distance.

The VLBA has produced an impressive time-lapse movie showing the dynamics of SiO maser spots in the envelope of the Mira variable TX Cam over the course of an entire stellar pulsation period. This was the first such movie of gas dynamics ever made for a star other than the Sun. This observational triumph has led to theoretical work attempting to explain the physics of this emission. TX Cam, along with another, closer Mira variable, R Cas, will be observed at specific phases of their pulsation in order to resolve still-outstanding questions about the nature of the pumping mechanism—radiative or collisional—for these circumstellar masers.

The circumstellar envelopes of asymptotic giant branch (AGB) stars contain SiO maser emission at both 43 and 86 GHz, including a variety of vibration/rotation transitions as well as transitions from isotopomers such as ^{29}SiO. Quasi-simultaneous imaging of the various maser transitions in both bands, both in total intensity and in polarization, can provide the relative positions and intensities of the different masers. The polarization yields measurements of the underlying magnetic fields and the mechanism of magnetic-field generation, while the relative positions of the masers provide important constraints on the models for the SiO maser pumping. Such studies of multiple transitions, together with the "time-lapse" imaging described above, have the potential to revolutionize the theories of turbulence and mass loss in the circumstellar envelopes.

The Interstellar Medium, Molecular Clouds, Cosmic Masers, Star Formation, and Stellar Evolution

Observations of cosmic masers in a variety of star-formation regions will provide details of a number of processes that can be imaged only with the high resolution and fidelity of the VLBA. Several such investigations are taking place in 2002, and are described below.

The accretion disk around the massive protostar G192.16-3.82, mentioned in the discussion of VLA scientific programs, may be outlined by maser emission in a manner similar to the rotating disks seen in the nuclei of some active galaxies. Observers are using the VLBA to image the H_2O maser emission around this protostar at three epochs, with VLA monitoring observations used to determine when the masers are strong enough to image. The maser emission will be used to trace the detailed kinematics and structure of the maser disk, to provide quantitative evidence for the presence of an inner accretion disk around the protostar. This program typifies the complementarity science that is being enabled by the VLA and the VLBA. The Pie Town link was used to infer the presence of the accretion disk, and now the VLA is being used to monitor the maser strengths in order to determine when VLBA imaging is feasible.

It is generally recognized that magnetic fields play an important part in star formation. The VLBI can measure these magnetic fields by imaging the polarized emission of SiO masers with VLBI, but the strength of the fields depends on the mechanism by which the polarization is produced. This mechanism can only be deduced by comparing polarized structures generated by different rotation transitions of SiO. The Orion-BN/KL region will be imaged by the VLBA in both the 86 GHz (J=2-1) and 43 GHz (J=1-0) transitions in order to discriminate between competing models of polarization generation, and hence to derive magnetic field values. The measure of the turbulent magnetic field will be used to study the entrainment process in the outflows from the Orion star-forming region.

The H_2O maser emission from the massive star-forming region W3(OH) appears to undergo systematic motion relative to an angularly nearby phase-reference source. In 2001 and 2002, researchers will monitor the H_2O masers regularly, with a time interval of two months between the successive observations. An accuracy of a few tens-of-microarcseconds is expected for position measurements of the masers relative to the phase-reference source, and will be used to determine the proper motions of the masers as well as the annual parallax due to the Earth's motion around the Sun. This will provide an unambiguous measure of the distance to W3(OH) and of its kinematics, for use in models of the evolution of massive star-forming regions.

A statistical sample of eight nearby ultra-compact HII regions will be studied using the radiation from the OH maser sources in those regions. The full polarization images of these masers will provide valuable information on the structure of the magnetic fields. The images will serve as first-epoch observations for OH maser proper motion studies, which will show details of the kinematics of the star-forming regions. Together, the kinematic and polarization information will be used to guide theories of high-mass star formation.

Radio Galaxies, Quasars, Active Galaxies, and Gamma-ray Bursts

The nearby elliptical galaxy M87 contains a black hole of several billion solar masses— the largest angular size of any massive black hole except the one at the Galactic Center. Previous VLBA observations at 43 GHz show a jet with a broad opening angle flaring outward in the innermost part of the galaxy. The jet was quickly collimated into the narrow jet seen on much larger scales. Imaging of the inner 0.1 pc of M87 with the new 86 GHz capability of the VLBA will be used to confirm this picture of the formation and collimation of the radio jet, and to test for the presence of extra spectral components related to the accretion disk surrounding the black hole. The sought-after direct measurement of the initial jet collimation will be a critical input to all models of the formation and energetics of jets in a wide range of radio sources. High-frequency (43 and 86 GHz) imaging of three other active galaxies is also scheduled for 2002 in order to image the initial jet collimation in additional objects with relatively large black-hole event horizons. Confirmation of the apparent M87 result in other galaxies will provide a crucial test of the applicability of jet-formation models that are derived from M87.

The high resolution of the VLBA provides a unique capability to investigate the ubiquitous phenomena associated with the central engines of quasars and active galactic nuclei. Time-lapse movies show direct evidence for highly collimated relativistic motion in quasars and active galactic nuclei with apparent velocity typically 5 to 10 times the speed of light. In a number of BL Lacertae objects (quasar-like objects that are thought to have relativistic jets pointed almost directly at us), the highest frequency observations sometimes show apparent speeds significantly higher than those seen with poorer resolution at lower frequencies. Therefore, there is some possibility that the jets decelerate significantly soon after their formation and collimation. VLBA imaging at frequencies as high as 43 GHz will be carried out for four BL Lac objects in order to investigate the reality of this acceleration.

A high-frequency multi-epoch polarization study will carry out observations on ten currently active radio sources that show strong and rapidly variable polarization during outbursts. The imaging data will be compared with radiative transfer models that allow for a range of shock orientations

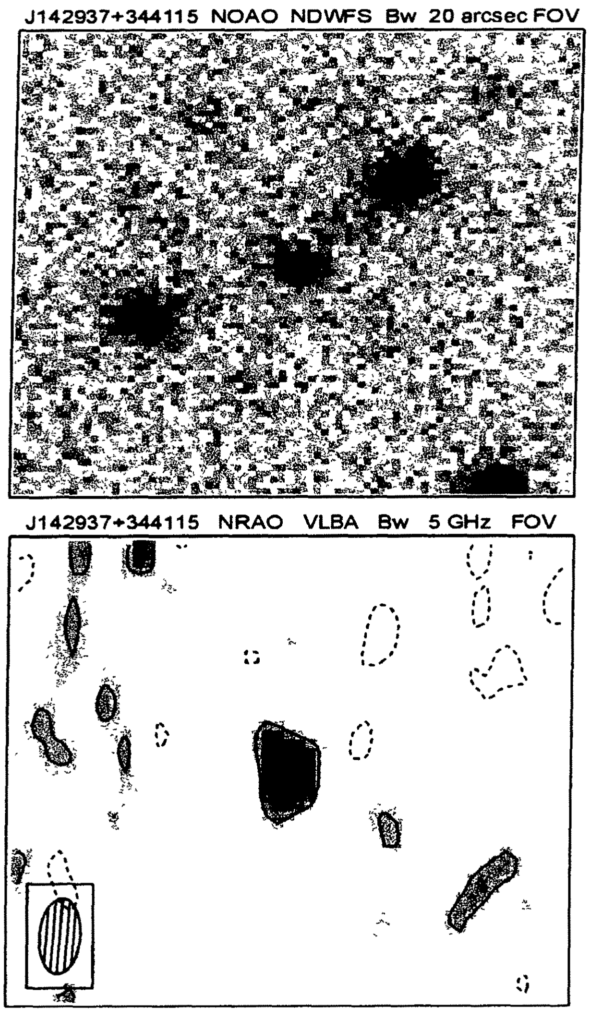


Figure III.2 NOAO and NRAO data for the FIRST source J142937.566+344115.69. The NOAO images each span 20 arcsec and are from date release 1.0 of the NOAO Deep Wide-Field Survey (NDWFS) to a limiting AB magnitude of 26 (Jannuzi & Dey 1999, ASP Conf. Series, 191, 111). The NRAO image spans 20 milliarcsec and is from a VLBA phase-referenced survey of 27 FIRST sources in the NDWFS. This VLBA detection has a flux density of 1.6 mJy, a diameter of less than 1.5 milliarcsec, and a positional uncertainty of less than 2 milliarcsec. The contour interval in the VLBA image is twice the rms noise of 0.25 mJy per beam area. This VLBA source is hosted by a red galaxy of unknown redshift. Four other FIRST sources were detected above the VLBA threshold of 1.5 mJy. Each of the five VLBA detections has a brightness temperature greater than 10 million K and must therefore be an AGN.

relative to the jet flow. The results will provide a direct test of the importance of oblique shocks in the relativistic flows of active galactic nuclei. Other observations will investigate the magnetic field in the AGN environment using high angular resolution multifrequency polarimetry to map the Faraday rotation on parsec scales. These observations will give new insight into the creation of magnetic fields in AGN and their role in the acceleration and collimation of relativistic jets.

Data acquired in 1997 with three VLBA antennas and the 12 Meter Telescope at Kitt Peak were used to make the first 86 GHz VLBI total intensity and polarization images have been made, using Future polarimetry of galaxies at this frequency generally will be unaffected by Faraday rotation, and the high resolution can be used to study magnetic field reversals on small scales near the galaxy cores. The nearly fully equipped VLBA will carry out a pilot program to perform polarimetry on several of the strongest active galaxies, both to study the physics of the magnetic fields and to explore the possible need for new polarimetric algorithms to enhance calibration of the new data. Another observation will test the technique of fast-frequency switching between 86 GHz and lower frequencies in order to image the much weaker continuum nucleus in M81; this technique could increase substantially the number of sources accessible to the VLBA at 86 GHz.

A body of evidence is mounting that nearly every galaxy contains a black hole. In fact, many such massive black holes are thought to be the result of galaxy mergers, so that there should be binary black holes present for significant periods of time; the predicted separation of the black holes is such that they may be resolvable at the highest frequencies of the VLBA. However, it is not known whether the black holes will coalesce on fairly short time scales (well under a billion years), or will "stall" in a binary orbit after all the stars in the vicinity have been ejected from the nucleus of the merged galaxy. In 2001, a VLA 43 GHz finding survey on a sample of nearby E and S0 galaxies determined which galaxies had sufficient flux for VLBA imaging at the same frequency in order to search for binary black holes. Assuming that sufficient candidates are found, VLBA imaging will be carried out to determine (or limit) the fraction of objects with binary black holes at the current epoch, which will constrain the models of their post-merger evolution.

Cosmology, Large Scale Structure, Galaxy Formation, and Gravitational Lensing

The gravitational lens source PKS 1830-211 has recently undergone an outburst, resulting in the creation of a new jet component in the lensed active galaxy. Currently, with an accurate time delay measurement having been obtained over the last several years, the largest remaining contribution to the uncertainty in Hubble's constant is the model of the mass distribution in the lens, which must be able to account for the unusual milliarcsecond structure seen in the northeast image of the active galaxy. The recent outburst provides a valuable opportunity to better determine the properties of the lens by monitoring the evolution of the new jet component. Therefore, multi-epoch VLBA monitoring of 1830-211 is being carried out in 2001 and in 2002 in order to better constrain the lensing model, and thereby derive a more accurate value for the fundamental scaling parameter of the universe.

A variety of planned astrometric and geodetic studies will become part of an international geodetic database used by researchers around the world to establish fundamental reference frames for geodesy and astronomy. The database also will enable researchers to study a variety of geophysical phenomena including plate tectonic motion, Earth rotation rate and orientation, and the interaction between the Earth and its atmosphere.

Green Bank Telescope

The GBT is among the most advanced and versatile telescopes, featuring an unblocked aperture design, an active surface, a laser metrology system for closed-loop surface and pointing control, a rotating receiver turret for fast selection of receivers, and a wide bandwidth spectrometer with up to 256k spectral channels. The frequency coverage of the telescope will be ~100 MHz to ~100 GHz. The combination of all these features in a 100 m diameter telescope will give the GBT unprecedented sensitivity and performance, and the capability to address projects involving low frequency radio phenomena to high frequency molecular line and dust emission. The attributes of the GBT that will make it a uniquely powerful scientific instrument are summarized below.

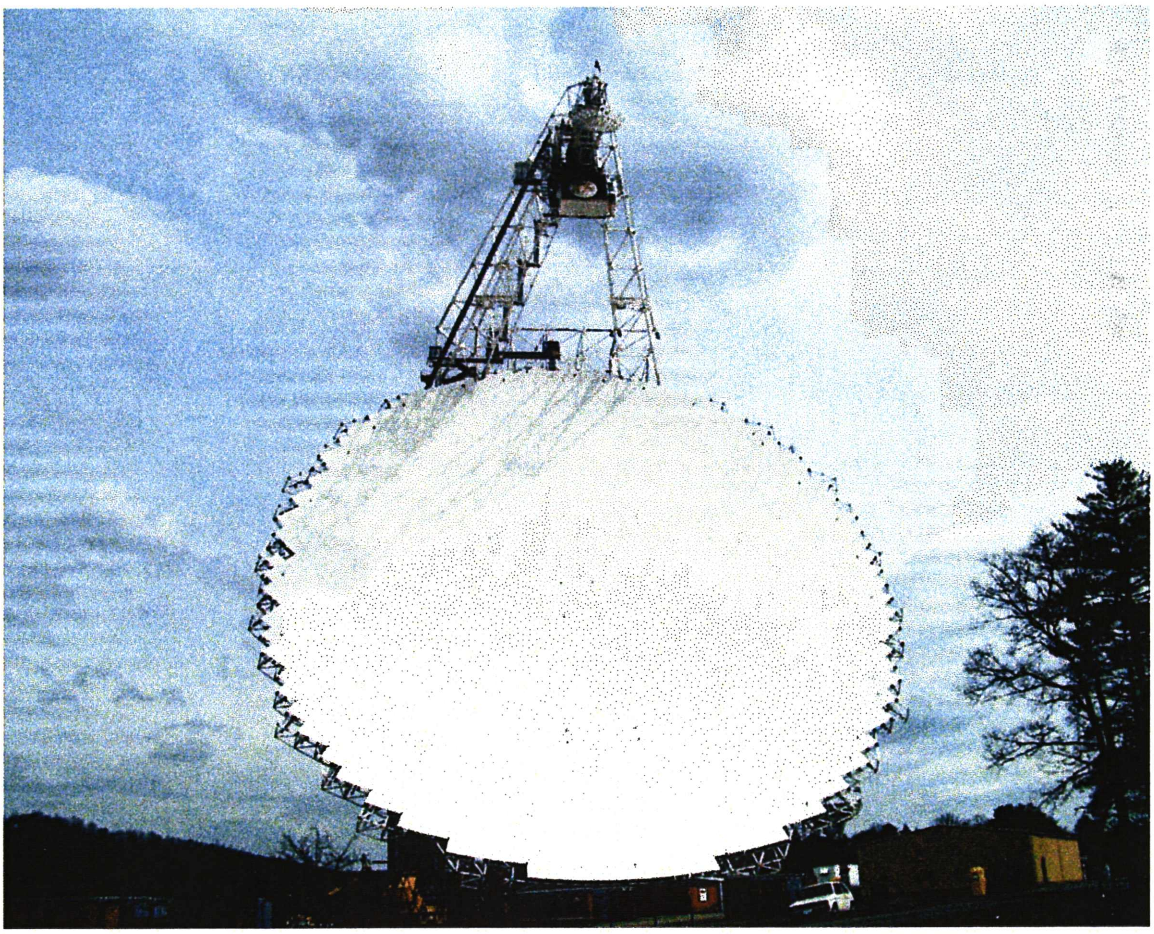


Figure IV. 1 The new Green Bank Telescope positioned to point near the horizon. During 2002, the GBT will be used for an increasingly large fraction of time for scientific research.

Point Source Sensitivity

The GBT will be the largest fully-steerable radio telescope in the world, with a Gain / T_{sys} ratio comparable to that of the VLA and the future ALMA. This will be a powerful asset at all observing frequencies, from 250 MHz to more than 100 GHz. In the frequency range between 20 and 100 GHz, the GBT will be truly preeminent, having point-source sensitivity significantly higher than any other telescope.

High Fidelity Response

The GBT's clear aperture will yield a much reduced response to emission outside the main diffraction beam compared with a conventional antenna. The design minimizes scattering sidelobes, which will reduce astronomical and terrestrial confusion from stray radiation from the sky and human radio frequency interference. For extended line sources, the GBT's clean beam will give the theoretical resolution of the half-power beamwidth, rarely achieved in the past. Data from the GBT will have excellent absolute calibration. The GBT will be an important source of short spacing data for combination with interferometer images. The optics design will also greatly reduce spectral standing waves, which are often the ultimate limitation in the detection of weak, broad lines, such as those from high-redshift galaxies. Spectral baseline effects caused by sidelobe response to solar radiation will also be greatly reduced.

Versatility, Frequency Range, and Agility

The GBT is designed to address a broad range of astrophysical problems. Its active surface and metrology system will maintain high sensitivity and excellent pointing through the 3 mm wavelength band. It has a wide field of view at the Gregorian focus that will give it excellent imaging properties and the ability to accommodate large, focal-plane arrays. The receiver turret in the Gregorian cabin allows quick changes between receivers. The GBT spectrometer is the most versatile spectral line back-end yet constructed. Its resolution and bandwidth will be a very powerful tool to wideband spectroscopy. The telescope will be equipped with back-ends for spectroscopy, continuum, pulsars, and VLBI.

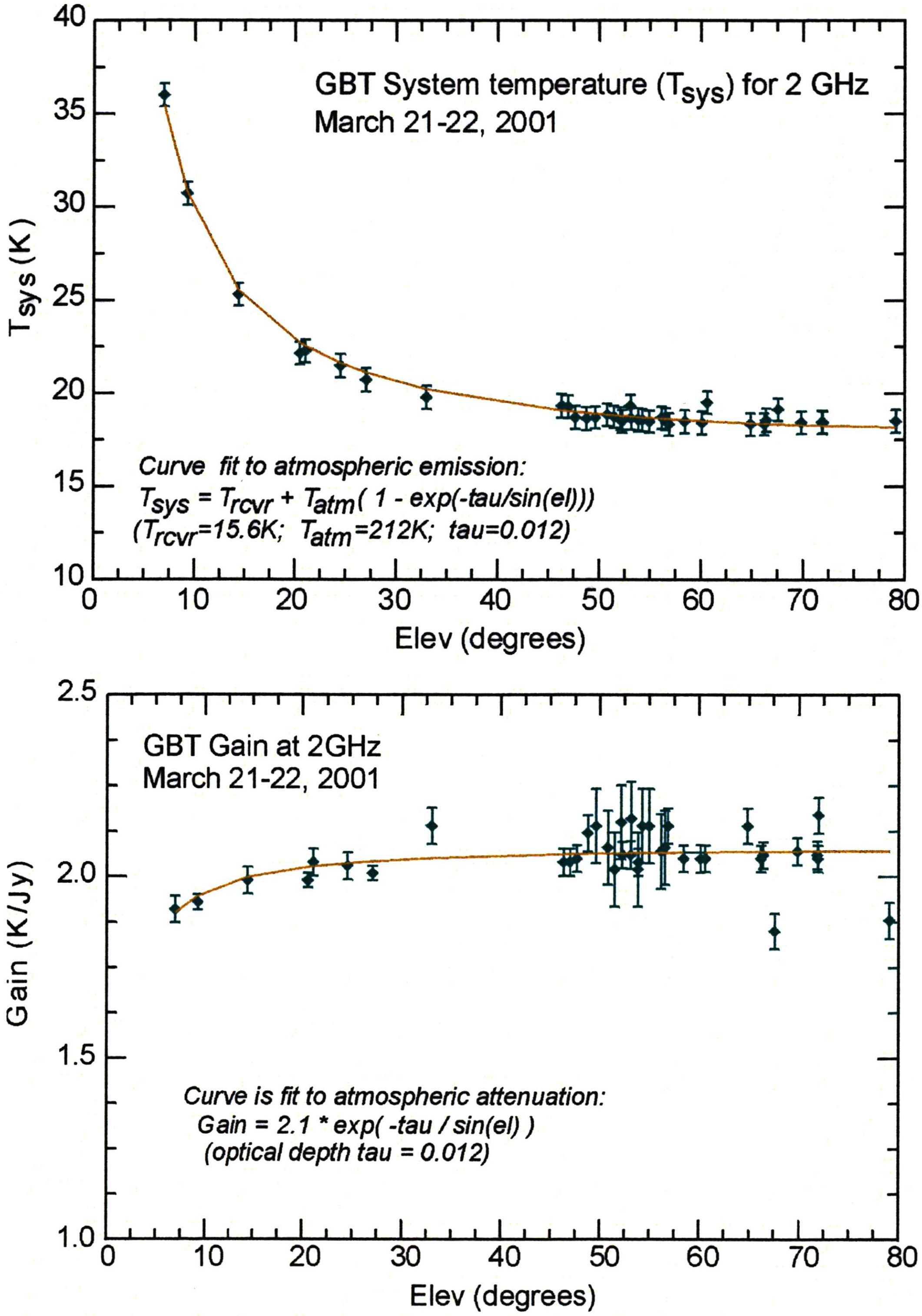


Figure IV.2 Gain is about 2.0 Kelvin per Jansky at 2.0 GHz. The decrease in gain at low elevations is due to atmospheric attenuation. The corresponding aperture efficiency is about 70%. The increase of Tsys with lower elevation is explainable by atmospheric emission. The gain, or G/T, is about 0.1 (per Jy).

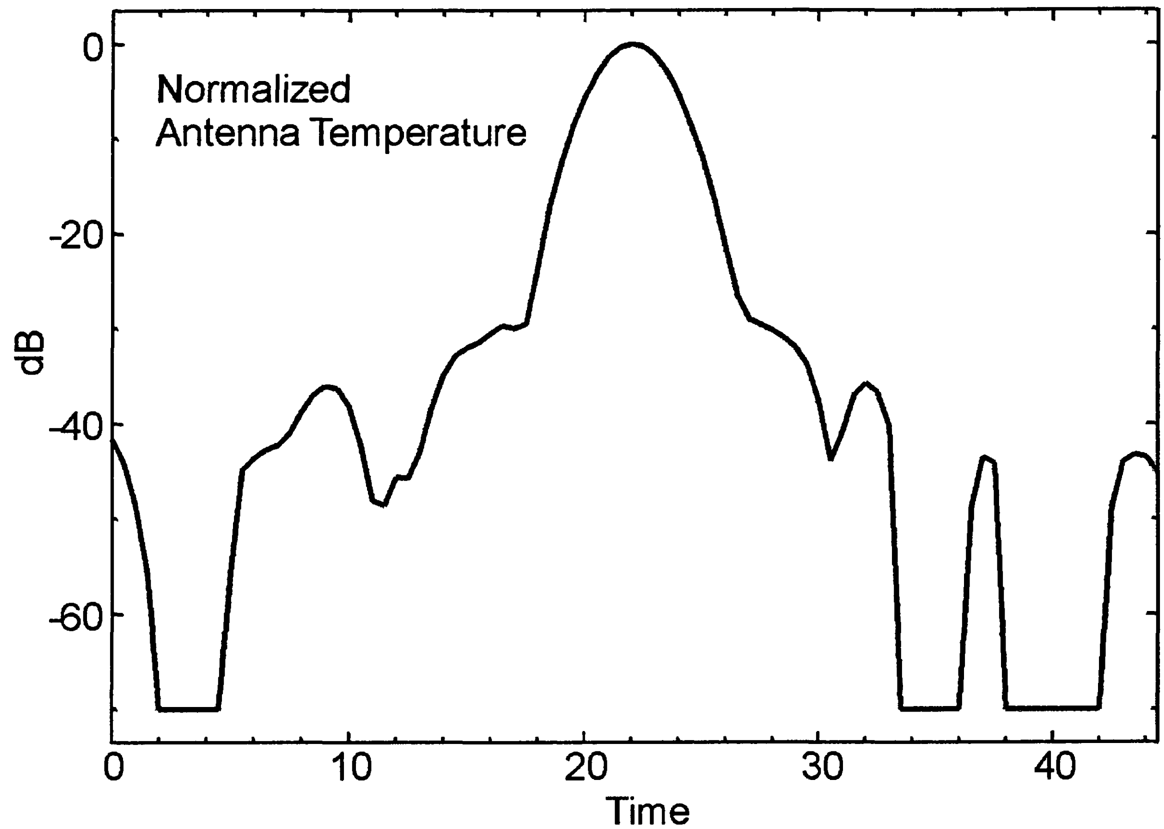


Figure IV.3 The near sidelobes are over 30 db down from the peak. This is about a factor of 10 better than other filled aperture radio telescopes.

Location in the Quiet Zone

Green Bank is situated in a 13,000 sq. mile region known as the National Radio Quiet Zone. By Federal regulation, no transmitters can be erected in the Quiet Zone unless their emitted power falls below proscribed limits at the Green Bank Telescope site. The NRAO is responsible for administering the Quiet Zone, which also protects the U.S. Naval post at Sugar Grove, West Virginia. Together with local geographical features, the Quiet Zone makes Green Bank the best site in the continental United States with respect to low levels of radio frequency interference. As such, the Quiet Zone is a unique national and scientific resource whose protection is a significant responsibility of the NRAO. In particular, protection of the Quiet Zone is absolutely essential to the success of the Green Bank Telescope. The Quiet Zone is experiencing an increasing number of serious challenges and will require continued vigilance by the NRAO during 2002 and the years beyond.

Complementarity with the VLA, VLBA, and ALMA

The attributes of the GBT will give the NRAO a powerful, comprehensive observing capability. The GBT will provide wide-field images that can be combined with VLA images through 50 GHz, and ALMA images through 115 GHz. For many projects, this capability will be invaluable for initial detection observations, for setting the astrophysical context on a broader angular scale, and in specific cases for supplying short-spacing information for the synthesis images. The GBT can be combined into the VLBA to greatly improve sensitivity for certain projects. The complementary capabilities of the GBT offer the possibility of unified observing projects in which a single proposal could request time on two or more NRAO instruments.

These attributes will provide observers with the capability to undertake projects and make observations never before possible. Some projects may be facilitated by only one of the above attributes, whereas many projects may make use of a combination of all of them.

Status and Commissioning Schedule

The NRAO received the antenna from the contractor in late 2000, certified the completion of tasks on the contractor's "punch list" in mid 2001, and is in the process of commissioning it for operation as a radio astronomy observatory. The commissioning and the introduction of visitor observing are being done in planned stages. The foremost goal of the commissioning plan is to develop systems that will allow efficient operation to ~ 50 GHz as quickly as possible. Progression to ~ 100 GHz operation will proceed from this point as expeditiously as possible.

Telescope commissioning is divided into three phases. Significant astronomical capabilities will become available during each phase, and observing projects will be scheduled throughout this commissioning process. Phase I of commissioning will be completed by October 1, 2001, and will provide operation to 15 GHz. It will be achieved without use of the active surface. Phase II will be completed by March 2002 and will provide operation to 50 GHz. This phase requires use of the active surface in "open loop" mode using look-up tables. Phase III will provide operation into the 100 GHz range and requires full, closed loop operation of the laser metrology system with the active surface and telescope positioning system. This phase will be available within a year after Phase II is achieved.

Major commissioning milestones for the GBT are listed in the table below. Other information on the GBT is available on the NRAO web pages at http://www.nrao.edu/GBT.

Table IV.1 Milestones for Commissioning and Early Operations of the GBT

Milestone	Date
Phase I commissioning complete	2001 October 4
Phase II pointing/focus tracking	2001 December 3
Open-loop active surface control	2002 January 30
Ku, K, Q-band receivers commissioned	2002 January 15
Spectrometer pulsar modes available	2002 March 30
Phase II commissioning complete	2002 March 30
Phase III commissioning complete	2003 March 30

GBT High Frequency and Focal Plane Array Programs

The GBT has an excellent initial suite of instrumentation. This includes twelve receivers covering most of the frequency bands from 250 MHz to 50 GHz, the GBT spectrometer (a very versatile instrument with 256k spectral channels, multiple IF, bandwidth, and spectral resolution modes, and a pulsar mode), a digital continuum back-end, VLBA terminal, user-built pulsar back-ends, and ancillary equipment. The Monitor and Control system is flexible and will allow a wide range of observing modes for spectroscopy, continuum, pulsar, and VLBI projects.

This suite of instruments should adequately meet the initial needs of the users. Nevertheless, the scientific potential of the GBT is enormous and instrument technology advances quickly. Consequently, there are a number of major opportunities that require a continuing program of instrument development. In particular, two primary areas exist in which advanced instrument development could have a dramatic payoff: high frequency receivers and imaging systems.

For frequencies above 30 GHz, and particularly for frequencies above 70 GHz, the GBT will be without peer in sensitivity. In the 3 mm wavelength (~100 GHz) band, the GBT will have 10-50 times the sensitivity of existing millimeter-wave telescopes. This will open up an enormous range of scientific problems that can be addressed. For example, only a handful of galaxies has been detected in radio line emission at redshifts greater than the z~1. Virtually all of these are lensed systems and represent only the tip of the iceberg of distant galaxies. The GBT will have the capability of detecting a vast number of unlensed systems which should greatly increase our understanding of galaxy and star formation in the early universe. The GBT will be sensitive to dust emission in the 3 mm band, and will be the most sensitive instrument in existence for highly redshifted dust observations. The GBT will also be a very sensitive tool for Sunyaev-Zel'dovich observations in the 3 mm band.

Development of 3 mm receiving systems is thus a very high priority for the GBT. A plan has been developed for a family of instrument systems for the 3 mm band. The first system to be built is a 68-115 GHz, dual-beam, dual-polarization system, divided into two frequency bands, 68-95 GHz and 90-115 GHz. The low band module (68-95 GHz) will be a correlation-type receiver with excellent continuum and spectroscopic performance. Work on the low band module has begun and construction is to be complete by early 2003. The high band module will eventually be incorporated into the same cryostat, but will be a total power receiver aimed at spectroscopy.

Astronomical imaging at several important wavelengths is another area in which the GBT can make unique contributions. The single and dual-beam systems already constructed will give significant imaging capability, but the speed of imaging can be greatly increased with a focal plane array (multi-beam) system. At the Gregorian focus, the field-of-view of the GBT is large and can accommodate large-format focal plane arrays. The speed of imaging is directly proportional to the number of beams in the array. Rapid imaging can be of benefit to almost all projects observing extended sources. This is also an area in which the GBT can complement the VLA and ALMA by providing high-sensitivity images of a larger region for which the interferometers may be examining specific points at high angular resolution. Working together, the instruments can examine both large- and small-scale structure with comparable flux sensitivity.

The 3 mm working group recommended that imaging systems be developed for the GBT for both spectral line and continuum work in the 3 mm band. Especially exciting is the possibility of placing a large-format bolometer camera on the GBT of up to several thousand pixels, which is now possible. The unparalleled sensitivity of the GBT in the 3 mm band will allow continuum emission from a variety of mechanisms including dust, free-free, synchrotron, and the S-Z effect. A technical feasibility study for the development of a large-format camera was begun in 2001 and will continue into 2003. This effort includes investigations into cryogenics and optical coupling of the camera, and support of bolometer array development at an external laboratory. Options for a 3 mm spectroscopic imaging system consisting of 32 beams are also being examined.

A program is also underway to develop beam-forming arrays for the lower frequencies. These systems have small feeds that fully sample the electric field in the focal plane. The outputs of the feeds are correlated to form beams on the sky. The beams can be shaped electronically to correct for low-order optical aberrations or, possibly, to suppress response to radio frequency interference in a constant direction. The beams can be placed arbitrarily close on the sky, and in particular, can allow full-sampling of sky within the coverage pattern. A prototype beam-forming array has been tested successfully. A two-year R&D program was begun in 2001 to attack the most challenging engineering problems that must be solved to produce a beam-forming array with competitive sensitivity. Once these engineering issues are in hand, a production L-band (21 cm) array with seven or more beams on the sky will be begun.

Multi-year project budgets and long-range spending profiles for the GBT instrument development projects are given in Table IV.2.

Table IV.2 GBT Development Project Spend Profiles

Project	CY2001	CY2002	CY2003	CY2004	CY2005	CY2006	2001-06 Total
Q-Band Tertiary Mirror		30	10				40
RFI Excision MRI Project							0
RFI Mitigation	10	80	25	25	25	25	190
Beam-Forming Array (L Band Prototype)	30	80	130	60			300
3 mm Rx	50	80	60				190
3CAM Bolometer Array		200	500	500	1000	1000	3200
3 mm Focal Plane Array			50	400	100	50	600
Spectrometer / IF Upgrades					250	250	500
Wideband, multi-input spectrometer				250	100	50	400
Rx Upgrades & Misc. Equipment	230	100	50	25	25	25	455
K-Band, Beam-Forming Array					150	250	400
External / User-built Projects		320	280	200			800
Totals:	**$320**	**$890**	**$1,105**	**$1,460**	**$1,650**	**$1,650**	**$7,075**

User Data Analysis Grants Program

The NRAO is instituting a program of grants to users of the Green Bank Telescope to support the analysis of data taken during scheduled observing sessions on the GBT. The primary intent of this program to facilitate the analysis and publication of GBT data. There is a focus on the support of student research, both undergraduate and graduate. The tentative conditions for an award and the application process are as follows.

Funding proposals will be accepted from investigators at universities and other non-profit research institutions, private for-profit institutions, Federally-funded research and development centers, and from unaffiliated scientists. Only applicants at U.S. institutions, whether principal or co-investigators, are eligible to propose. Investigators employed by NRAO are ineligible to receive funding; their participation in an observing program does not affect the eligibility of other investigators or co-investigators. Preliminary Funding Proposals must accompany Observing Proposals. Funding will be awarded based on rankings from the referees and NRAO review, and is subject to the availability of funds. Investigators who have requested funding will receive notification from the telescope allocation committee concerning the status of their funding requests. If funding is awarded, a Final Funding Proposal, with a detailed budget and budget justification, must be received by the NRAO User Grants Administrator within 30 days of the date when allocated observations begin. The detailed budget must be consistent with the Preliminary Funding Proposal. Funding will be awarded for a period of one year, commencing 30 days after the allocated observations begin. One request for a six-month no-cost extension may be made to the NRAO User Grants Administrator. Final Reports to the NRAO User Grants Administrator must be submitted within six months of expiration of the grant. Funding will be awarded under the conditions contained in the document "General User Grant Provisions of the NRAO," which specifies those terms and conditions in the Cooperative Agreement for the operation of the NRAO between the NSF and AUI which apply to User Grants. The funding cap for a User Grant is $25,000 to be divided between support for students, either undergraduate or graduate, travel, and equipment. Indirect costs are not allowed. The minimum grant is $10,000. Recipients of User Grants remain eligible for the standard NRAO user support: travel to NRAO for observing and data reduction, and page charges.

We are planning on a budget of $500,000 for these grants in 2002, providing 20 such grants at the funding cap or more than 20 in the mix of budgets we expect to receive to receive.

Very Large Array

The VLA is the premier centimeter radio telescope in the world today. More than 600 scientists will use the VLA for their research work in 2001 and a similar or larger number will do so in 2002. Demand for the VLA arises both from the multiwavelength nature of contemporary astronomical research and from the flexibility of the telescope. Indeed, in recent studies of publication rates from various astronomical instruments, the VLA is second to only the *Hubble Space Telescope* in the number of refereed papers produced per year. It is widely recognized that radio observations provide unique insight into a variety of astronomical objects that may be used to complement the information gained with telescopes operating at visible, infrared, gamma-ray, or X-ray wavelengths; conversely, radio observations often provide a research focus with data complementary to observations at other wavelengths. The angular resolution, sensitivity and field of view of the VLA are generally similar or superior to those achievable with modern detectors at other wavelengths, allowing multi-wavelength observations to be merged with little ambiguity.

Present Instrumentation

The VLA consists of twenty-seven, 25 meter antennas arranged in a "Y" configuration, with nine antennas on each 20 km arm of the "Y." The antennas are transportable along a double rail track and may be positioned at any of 72 possible stations. In practice, the antennas are rotated among four standard configurations, which provide maximum baselines of 1, 3, 11, and 36 km. Additional "hybrid" configurations with a long northern arm are used to provide optimal sampling of sources in the south. Reconfigurability provides the VLA with variable resolution at fixed frequency or fixed resolution at variable frequency.

The VLA supports eight frequency bands which, generally, can be remotely changed by means of subreflector rotation. (The 74 MHz system consists of dipoles that are mounted periodically for short campaigns, then removed, due to minor impact on the aperture efficiency at some of the other frequencies.) The following table summarizes the current parameters of the VLA receiver system. The VLA has full polarization capability in all continuum and spectroscopic bandwidths ranging from 50 MHz to 195 kHz. Within certain total bandwidth limitations, 512-channel spectroscopy is supported in all bands.

Table IV.3 VLA Receiving Systems

Frequency (GHz)			T_{sys} (K)	Amplifier
0.070	to	0.075	1000[1]	Bi-Polar Transistors
0.308	to	0.343	150	GaAsFET
1.34	to	1.73	33	Cryogenic HFET
4.5	to	5.0	45	Cryogenic HFET
8.0	to	8.8	31	Cryogenic HFET
14.4	to	15.4	108	Cryogenic GaAsFET
22.0	to	24.0	55[2]	Cryogenic HFET
40.0	to	50.0	95[3]	Cryogenic HFET

[1] T_{sys} includes galactic background.
[2] Nine antennas still have systems with T_{sys}(K) = 160K at end of 2001.
[3] Twenty-five antennas equipped at end of 2001.

Ongoing Initiatives

High Frequency Systems

During 2000-2001, a significant number of antennas were instrumented with new receivers at 22 GHz and 43 GHz. Twenty-five antennas now have 43 GHz systems, up from 13 at the end of 1998, thanks to MRI funding from the NSF and additional funds from the Max Planck Institut für Radioastronomie. In addition, a number of antennas have new 22 GHz systems, with T_{sys} of 55 K vs. ~160 K for the older receivers. This number was 18 at the end of 2001, and operations funding has been allocated to bring the total number of new systems up to 23 by the end of 2002. Both the 22 GHz and 43 GHz systems will be completed in 2002 and 2003 as part of the beginning of the EVLA Phase I Program.

Pie Town Link

The VLBA Pie Town antenna has been connected as a real-time active element of the VLA under funding through an MRI proposal to NSF, with matching funds from AUI. This real-time link doubles the maximum baseline of the VLA, improving the highest resolution to approximately 20 milliarcseconds for 43 GHz observations. The incorporation of Pie Town into the VLA makes use of a fiber optic connection completed by the Western New Mexico Telephone Company. During 2000, the Pie Town link capability was opened up for proposals. The Pie Town link proved very popular during the A configuration session from October 2000 through January 2001; a total of 18 programs consisting of 33 observation segments were scheduled, using 251 hours of telescope time (approximately 14 percent of the scientific usage of the VLA).

In 2001, work was carried out to make the Pie Town link more robust. This was done by modifying some electronics modules and testing a capability to monitor and correct for the optical pathlength changes on the 105 km fiber optic path from the VLA to Pie Town. The availability of the Pie Town link has been announced again, for the A configuration session covering the first trimester of 2002. We anticipate that the fraction of scientific observing time granted will be at least comparable to, and perhaps greater than, the amount used in the 2000/2001 observing session.

70-MHz Bandwidth

Starting in 2000, the VLA received new filters and correlator sampling capabilities in order to observe with a 70 MHz continuum bandwidth at each intermediate frequency (IF), up from the value of 50 MHz (effective bandwidth of 46 MHz) that has been in place since the VLA's inception. This capability provides a 20 percent increase in sensitivity for continuum observations of weak sources, thus producing a significant improvement for detection experiments. In 2001, the VLA was tested to bring the 70 MHz bandwidth up to operational readiness, and it should be available to users in 2002. This is only a minor improvement compared to the eight 2 GHz IFs that will be available with the EVLA, but it does provide a useful addition to the VLA in the interim.

Water Vapor Radiometry

In 2001, the NRAO made a significant effort to test and improve the linearity of the prototype water vapor radiometers developed for installation on the new VLA 22 GHz receivers. The lack of availability of engineering resources has hampered this work. The ultimate goal of the task is to use the radiometers in real time to correct the phase of the incoming signals, thus reducing phase fluctuations due to the troposphere by more than a factor of two. This would significantly improve the fraction of time in which observations can be scheduled at 22 and 43 GHz, reduce the time lost due to conducting high-frequency observations in poor weather conditions, and will be crucial for the expected demand on the high frequencies in the EVLA. If the linearity of the re-designed systems proves adequate in late 2001 and early 2002, it would be possible to procure and install water vapor radiometers on all VLA antennas. The estimated cost of $400,000 for hardware (split between two years), plus the cost of the two technicians needed to build and install the units, cannot be funded within the President's budget.

Software

JObserve—a new program for scheduling VLA observations—is a Java-based replacement for the OBSERVE program that has been used at the VLA for many years. It incorporates a more modern user interface, as well as the features necessary to schedule the VLA-Pie Town link; JObserve was used to schedule all the Pie Town link observations in 2000/2001. In 2001, JObserve was modified to incorporate the new 70 MHz VLA bandwidth. Also, a new users guide/cookbook was produced. The software then will support a number of new VLA capabilities that are not present in OBSERVE, and it will be the default program for scheduling most VLA observations in 2002.

Work has proceeded on the re-design of the VLA on-line computing system, whose primary goal is to enable the replacement of obsolete real-time hardware with more advanced computing equipment. This re-design takes into account the numerous requirements for the EVLA, and therefore is more than just a simple replacement of the current system. In late 2001, the failure rate on the real-time hardware increased significantly, so the decision was made to purchase less obsolete hardware as a stopgap, during the transition period to the EVLA. This hardware will be installed in late 2001, and is expected to be in place to perform all monitor and control tasks for the VLA in 2002.

Infrastructure

Additional funding during 2001 enabled significant infrastructure developments; those carried out in 2001 and planned for 2002 include:

- The VLA calibrator manual was improved substantially in 2000 and 2001. Emphasis has been on increasing the density of calibrators available for 43 GHz observations, where both the time and distance of antenna slews from calibrator to source are critical. Data have been added for several hundred sources at 43 GHz, and we expect at least 200 more to be added with observations that take place in late 2001 and in 2002. The effort is scheduled for completion in 2002.
- In recent years, observing in the 1610-1612 MHz OH observing band has been impossible due to the impact of the Motorola IRIDIUM communication satellites. Prototype filters that would permit a correct on-line system temperature correction were procured in 2000. Testing of those filters took place in 2001, with a decision to be made in late 2001 about whether procurement and installation of a full set of filters will take place in 2002.
- Improvements to the pointing performance of the VLA antennas. The six arcsecond pointing performance of one VLA antenna has spurred interest in improving pointing performance throughout the array. A prototype encoder electronics system has been built and tested, and proves to eliminate the cyclic pointing errors and periodic oscillations of the old encoders. Outfitting of VLA antennas with the new encoders began in July 2001.
- Difficulty in identifying the sources of pointing errors has prompted the design of an optical telescope test instrument, which will be used as an aid in isolating causes of antenna pointing errors. First tests of this system were carried out during the middle of 2001, with evaluation of the results still in progress. Tests will continue in 2002, with possible remedial action depending on the results of the tests.
- There are three remaining telescopes with bad azimuth bearings (see VLA test memo 195). Infrastructure funding in 2001 was used to purchase the necessary replacement and refurbished bearings, with the work on bearing replacement to be finished in 2002.
- Panel adjustments based on holographic observations at 22 GHz were completed in 2000, while adjustments based on 43 GHz measurements have been ongoing in 2000 and 2001. The pace of the work is dependent on having the right combination of array configuration and weather, but all 25 antennas with 43 GHz systems will have initial 43 GHz adjustments made by the end of 2001. During 2002, tests of the results of the initial adjustments will be carried out, and a second round of adjustments will be made as required. In addition, the last few antennas getting 43 GHz systems will be tested in late 2002, if available. By the end of 2002, almost all VLA antennas should have 30-40 percent aperture efficiency at 43 GHz.
- Railroad improvements. In 1998, an internal inspection of the VLA track system found one-third of the railroad ties to be past their service life. The required program of 5000 tie

replacements per year did not take place in 2000, due to lack of funding. However, infrastructure funding in 2001 enabled the purchase of a three-year supply of ties and ballast (approximately one ton of ballast is required for every tie replaced). During 2002, with the assistance of temporary summer labor, we will continue the required program of replacing 5000 ties per year, and performing the necessary track-leveling operations.

- Antenna painting. All quadrupod support legs on the VLA antennas have now been painted and five antennas were completely painted in 2001 bringing the total number of antennas completed to 24. Painting VLA antennas was initiated in 1993, beginning with antennas most obviously stained with rust; we expect completion of the repainting of all 28 VLA antennas by the end of 2002.
- Improved safety. Several safety initiatives have been undertaken in recent years in order to protect our workforce: (i) A workable fall arrest system was designed and developed to provide access to the antenna apex in accordance with OSHA regulation, and was installed on all VLA antennas by July 2001. (ii) A guardrail system also was designed to protect employees working at the antenna apex. Guardrail installations began January 2000 and were completed in 2001. (iii) A telescoping grab bar was designed and is being installed on each antenna during the three-year overhaul cycle, in order to make hatch access to the antenna dish safer. Installation of these bars will be ongoing during 2002, and is expected to be completed by 2004.

Expanded Very Large Array

The Very Large Array is the most productive radio telescope ever built. Because of its combination of sensitivity and flexibility, it has been used by thousands of astronomers from every continent for research that spans the entire breadth of modern astronomy. Yet the VLA is limited in its ability to address the key questions of twenty-first century astrophysics. The antennas, site, array layout, and infrastructure—the most expensive components of any array—are fundamentally sound, and will remain so for as long as the array is maintained. But the electronics on which the data transmission and processing are based, the heart of the instrument, has not been changed since the array's commissioning 25 years ago. Implementing modern data transmission and signal processing technologies will increase the observational capabilities of the telescope by an order of magnitude or more, providing the power demanded by the scientific requirements.

The VLA Expansion Project's key goal is to improve the array's observational capabilities by an order of magnitude or more. This would be done by: (a) adding new frequency bands, (b) upgrading or replacing current receivers, (c) replacing the data transmission system and correlator, and, (d) connecting VLBA antennas to the array and incorporating new antennas at locations between the VLA and the VLBA. In addition to these, new and more powerful on-line computing will enable better access to the array's data products, and will give a much improved interface with users.

The effect of these planned improvements and enhancements on the array's capabilities are enormous, as listed below:

- The continuum sensitivity will increase an order of magnitude or more in several bands.
- Continuous frequency coverage from 300 MHz to 50 GHz will be obtained.
- The bandwidth that is transmitted from the antennas, and processed by the correlator, will increase by a factor of 80.
- The maximum number of spectral channels available, and the maximum frequency resolution, will increase by a factor of over 500.
- The resolving power will increase tenfold.
- The new instrument, when cross-linked with the VLBA and with new antennas located about 50-300 km from the VLA, will greatly enhance the VLBA's dynamic range, field of view, and frequency scalability.

The impact on astrophysics of returning the VLA to the state-of-the-art will be profound. Many severe limitations now constraining VLA observations will be removed or greatly relaxed.

A short selection of unique experiments made possible includes:

- Measuring the three-dimensional structure of the magnetic field of the Sun.
- Using the scattering of radio waves to map the changing structure of the dynamic heliosphere.
- Measuring the rotation speeds of asteroids.
- Observing ambipolar diffusion and thermal jet motions in young stellar objects.
- Measuring three-dimensional motions of ionized gas and stars in the center of the Galaxy.
- Mapping out the magnetic fields in individual galaxy clusters.
- Conducting unbiased searches for redshifted atomic and molecular absorption lines.
- Looking through the enshrouding dust to image the formation of high-redshift galaxies.
- Disentangling starburst from black hole activity in the early universe.
- Providing direct size and expansion estimates for up to 100 gamma-ray bursts every year.

The expanded VLA will open a vast area of "discovery space," which is currently inaccessible to any instrument. We can expect that, as with the original VLA, it is likely that the most important discoveries to be made will be those that cannot now be anticipated.

The VLA Expansion Project comprises two major components:

The "Ultrasensitive Array"

This phase of the project concentrates on improvements to sensitivity, frequency availability, spectral capabilities, and improved on-line computing. The major components are:

- A new correlator, able to support 32 to 40 stations, to process broadband signals and to provide vastly improved resolution and flexibility for spectral line work.
- A fiber optic data transmission system to transmit the broadband signals and monitor data from the antennas to the control building, replacing the original waveguide.
- New on-line computers, operating software, and archiving, to enable more powerful and flexible interaction between the telescope and the operators and observers.
- Improved receivers with lower noise temperatures and much wider bandwidth performance (up to 8 GHz in each polarization channel) in existing bands; addition of 2.4 GHz and 33 GHz bands at the Cassegrain focus; completion of the outfitting for the 45 GHz band; extension of the 1.4 GHz band to ~1 GHz. The goal is to provide continuous frequency coverage from ~1 GHz to 50 GHz, in eight frequency bands, from the Cassegrain focus.

In May 2000, the NRAO submitted to the NSF a proposal to fund Phase I of the VLA Expansion Project. This phase of the project would last nine years, at a total cost of $76M, of which $50M would be new funding from the NSF. The remainder will come from expected operations funds that would be re-directed to support the project, and from contributions from foreign partners. The Phase I proposal was reviewed by an NSF Review Panel and on December 14-15, 2000, a Site Visit was made by an NSF appointed committee. As a result of the Site Visit the NSF requested more information on various aspects of Phase I; NRAO provided this information in a document "VLA Expansion Project: Response to NSF Request for Additional Information," on February 21, 2001. The NSF provided $3M in the NRAO budget for 2001 to allow the planning and development of Phase I to begin and a Project Manager for EVLA was appointed on May 2, 2001. Detailed planning and design of the project began at that time.

The "New Mexico Array"

This phase of the project will expand the resolution of the array by a factor of 10 by:

- Adding additional new stations at distances of up to 300 km from the array center, to provide now unavailable baselines between those in the VLA and those in the VLBA.

- Adding fiber optic links between the VLA and the inner VLBA antennas, and between the VLA and the additional new stations.

In addition, other enhancements may include:

- Possible implementation of an improved low frequency capability, which will provide frequency coverage from ~300 MHz to 1 GHz.
- Stations for a compact E-configuration with baselines less than ~300 meters, to be used for imaging low-surface-brightness objects.

A decision on whether to include these additional improvements will await further study of their scientific viability and cost.

Phase I Program

Antenna and Receiver Improvements

At the antennas, the project involves improving receivers at the existing observing bands, adding receivers to support new observing bands, adding fiber optic LO and IF links, and modifying the antenna structure for improved operation.

Improvements to Existing Frequency Bands

The VLA receivers have been upgraded gradually since the early 1980s. Initially, better low-noise amplifiers were used in existing receivers. More recent systems have used the VLBA receiver design, in which the receiver is attached directly to the feed and the polarizer is cooled in the cryogenic dewar. This design reduces the noise contribution from the polarizer and eliminates long, ambient temperature waveguide runs that add to the system temperature.

The VLBA-style receivers are now used in the 1.4, 8.4, and 45 GHz bands. These receivers will remain with perhaps only minor modifications. The greatest improvement in system temperature can be made in the 5, 15, and 22 GHz bands using the VLBA-style receivers and modern HFET amplifiers. Completely new receivers will be built for these bands, and should reduce the system temperatures as much as a factor of three. The new receivers also will provide up to 8 GHz bandwidth per polarization channel (needed for continuum sensitivity) and will tune over a wider frequency range (to include spectral lines, such as methanol, whose astrophysical significance was unknown when the VLA was built).

Two components of these receiver improvements were begun in 1999: (a) completion of the 45 GHz system, using funds granted the NRAO by the NSF through the MRI program with assistance from the MPIfR in Germany; (b) retrofitting the 23 GHz system with a modern receiver/polarizer. These two projects will be completed as part of Phase I of the EVLA.

New Observing Bands at the Cassegrain Focus

Two new receiver systems will be added at the Cassegrain focus: 2.4 GHz and 33 GHz. The 2.4 GHz system is optimal for study of objects with a normal synchrotron spectrum, will provide an outstanding capability for studies using Faraday rotation, and will allow the VLA to participate in bistatic planetary radar observations with the Arecibo Observatory. The 33 GHz band is optimal for study of objects with a thermal spectrum, and will allow imaging of many interesting molecular lines, including redshifted CO and O_2. Table IV.4 summarizes the proposed new and upgraded VLA Cassegrain observing bands.

Table IV.4 EVLA Cassegrain Observing Bands

Band Code	Freq. Range (GHz)	Bandwidth (GHz)	Bandwidth Ratio	Status
L	1.0-2.0	1.0	2.0	Upgrade
S	2.0-4.0	2.0	2.0	New
C	4.0-8.0	4.0	2.0	Upgrade
X	8.0-12.0	4.0	1.5	Upgrade
Ku	12.0-18.0	6.0	1.5	Upgrade
K	18.0-26.5	9.0	1.5	Upgrade
Ka	26.5-40.0	13.0	1.5	New
Q	40.0-50.0	10.0	1.25	Complete

Sensitivity Goals

Table IV.5 compares the continuum sensitivity of the current instrument with the expected performance of the VLA Expansion. We assume a maximum usable bandwidth with RFI excision at the lower frequencies, and add an atmospheric contribution where relevant. The number under δS refers to the continuum sensitivity in μJy/beam achieved in 12 hours of integration, summing over two orthogonal polarizations with the listed instantaneous bandwidths, and with natural weighting.

Table IV.5 EVLA Point-Source Continuum Sensitivity

Wavelength (cm)	Effective BW (GHz)	Expanded VLA		Current VLA (2000)	
		T_{sys} (K)	δS (μJy)	T_{sys} (K)	ΔS (μJy)
90	0.05	80-135	20.0	150	170
50	0.1	55-90	12.0	-	-
30	0.25	30-32	3.0	-	-
20	0.5	26	1.9	32	5.0
11	1.5	29	1.1	-	-
6.0	3.0	31	0.82	42	6.4
3.6	3.0	34	0.95	35	5.3
2.0	4.0	39	1.0	110	20
1.3	6.0	55-70	1.2	55	12
0.9	8.0	45	1.1	-	-
0.7	5.0	66	2.4	90	60
0.6	3.0	120	6.0	150	150

New LO/IF Transmission System

To transmit up to 16 GHz of bandwidth from each antenna, we will use optical fiber links to all of the VLA stations, to the nearby VLBA antennas, and to additional new antennas located between the VLA and the present VLBA stations. Separate fibers will carry the LO reference signal and the digital IF signals. Between four and six single mode fibers will run to each antenna station. Although low temperature coefficient fiber will be used on runs exposed to ambient temperature, a round-trip phase correction system probably will still be needed.

A New Correlator

The new correlator should be able to process data from at least 40 antennas and have enough delay capability to accommodate baselines as large as 500 km. It could then process any combination of the twenty-seven VLA antennas, two or three of the innermost VLBA antennas (those at Pie Town, Los Alamos, and Fort Davis), and up to eight new antennas on baselines between those in the VLA and in the VLBA.

The Herzberg Institute of Astrophysics (HIA) Canadian correlator design group at the Dominion Radio Astrophysical Observatory (DRAO) prepared a proposal to fund and build the Expanded VLA correlator. A preliminary proposal was reviewed by the NRAO and was revised to incorporate suggestions by NRAO staff. A Memorandum of Understanding between the NRAO and HIA concerning the design and construction of the EVLA correlator by the HIA group was drafted in June 2001. At that time the HIA was in the process of applying for funds to build the correlator with a goal of starting work by the end of 2001.

Anticipated Activity for 2002

The Preliminary Design Review (PDR) for the top-level system design of the EVLA will be held in December 2001. PDR's for all major subsystems will also be held early in 2002. Major subsystems include Feeds and Support Structure, Receivers, Local Oscillator System, Intermediate Frequency (IF) System, Fiber Optics System, Correlator, Monitor and Control System and Data Management System. Following each PDR, design and construction of prototypes for each subsystem will commence. The long distance runs of fiber optic cable will be purchased and installation of this cable along the arms of the VLA will begin in the third quarter of 2002. For the Receiver subsystem, as well as the prototyping work on the new receivers for the other bands, construction of the final production receivers for the 22 GHz and 45 GHz bands will begin.

Very Long Baseline Array

Present Instrumentation

The VLBA is a dedicated instrument for very long baseline interferometry (VLBI), with ten antennas distributed throughout the United States in a configuration that optimizes the distribution of baseline lengths and orientations. Baselines between 200 and 9000 km are covered, which provides resolution as fine as 0.1 milliarcseconds at 86 GHz. The shorter baselines, and hence the highest concentration of antennas, are near the VLA for optimal joint observations and to allow for the VLA Expansion Project to fill the VLA-VLBA gap in the range of accessible baselines. 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. Table IV.6 summarizes the performance of the 10 frequency bands for which the VLBA is outfitted, all with dual circularly polarized receivers. The antennas are operated remotely from the Socorro Array Operations Center; local intervention is required only for tape changes, routine maintenance, and troubleshooting.

VLBI requires highly accurate frequency standards and a wide-bandwidth recording system at each site, which includes the presence of one hydrogen maser and two longitudinal instrumentation tape recorders at each site. The recorders allow more than 20 hours of recording at 128 Mbits per second without tape changes, or correspondingly less time when recording at 256 or 512 Mbits per second. The VLBA correlator is located at the Array Operations Center (AOC), and is able to correlate as many as eight input data channels from each of 20 antennas simultaneously. For most modes, the correlator can provide 1,024 points per baseband channel, and up to a maximum 2,048 spectral channels per station or baseline can be provided for each recorded signal.

Table IV.6 VLBA Receiving Systems

Frequency Range (GHz)			Typical Zenith SEFD[1] (Jy)	Typical Zenith Gain (K Jy)
0.312	to	0.342	2217	0.097
0.596	to	0.626	2218	0.090
1.35	to	1.75	295	0.093
2.15	to	2.35	325	0.094
2.15	to	2.35[2]	344	0.089
4.60	to	5.1	289	0.132
8.0	to	8.8	299	0.118
8.0	to	8.8[2]	391	0.111
12.0	to	15.4	543	0.112
21.7	to	24.1	976	0.104
41.0	to	45.0	1526	0.078
80.0	to	96.0	3500	0.030

[1]System equivalent flux density

[2] With dichroic.

[3] All except Brewster and St. Croix installed.

Ongoing Initiatives

High Frequency Systems

The major new capabilities expected for the VLBA in 2002 are in the area of high-frequency performance. Specifically, the NRAO outfitted six antennas at 86 GHz by the end of 2000, enabling a stand-alone observing capability for the VLBA at this high frequency. Researchers conducted the first scheduled observations between February and May 2001. It is anticipated that an additional two antennas, for a total of eight, will be outfitted in Fiscal Year 2001, with a ninth antenna (Brewster) scheduled for December 2001, leaving only the site at St. Croix without an 86 GHz receiver. (It is possible that the ninth system may be used to replace the unique prototype system at Pie Town, because of the scientific benefit of having the greatly improved performance over a range of short and intermediate baselines.) Funding from the Max Planck Institut für

Radioastronomie made possible the purchase of hardware for systems 5 through 8, while the implementation took place with operations funding. The NRAO is procuring the ninth system with operations funding.

In 2001, retrofitting continued on some of the early receivers (2 through 4) in order to improve their radio-frequency performance. This retrofit, which will be completed in 2002, reduced the receiver noise temperature of the Kitt Peak system by roughly 80 K, and has also proven to smooth out large ripples through the bandpass. In addition, pending the availability of the amplifiers designed for MAP, the frequency coverage of the first systems will be expanded to cover the range between 80 and 96 GHz rather than 80 to 90 GHz, enhancing both the continuum and spectral-line coverage (systems 5 through 8 have covered the range up to 96 GHz since their inception).

All stations have implemented improvements in pointing performance in order to take full advantage of the 86 GHz observing capability. This was done by application of the offsets caused by the azimuth rail heights before solving for the rest of the pointing terms. In 2001, pointing tests revealed periodic oscillations as a function of encoder position in the VLBA antennas—a problem similar to that found previously on the VLA. An assessment of this effect, and a plan for remedying it, will be developed in 2002.

During 2001, the NRAO undertook a major effort on a local holographic system to improve the antenna surfaces and the 86 GHz aperture efficiency to 25-30 percent. The first measurements on the Pie Town antenna took place between April and June 2001. Results are being assessed to determine whether the main reflector's panel setting or the subreflector accuracy is the dominant cause of the relatively poor (~15 percent) average aperture efficiency of the VLBA antennas. It is likely that the different antennas, in fact, have different relative contributions due to these two effects. In late 2001, the assessment of the Pie Town results will be completed. The first half of 2002 will be devoted to measuring several other antennas and developing a plan of attack to improve the aperture efficiency. Options currently under consideration include (1) re-setting the panels; (2) re-machining the subreflectors (probably an expensive and undesirable approach); or (3) designing a wavefront-correcting lens to place in front of the 86 GHz feeds.

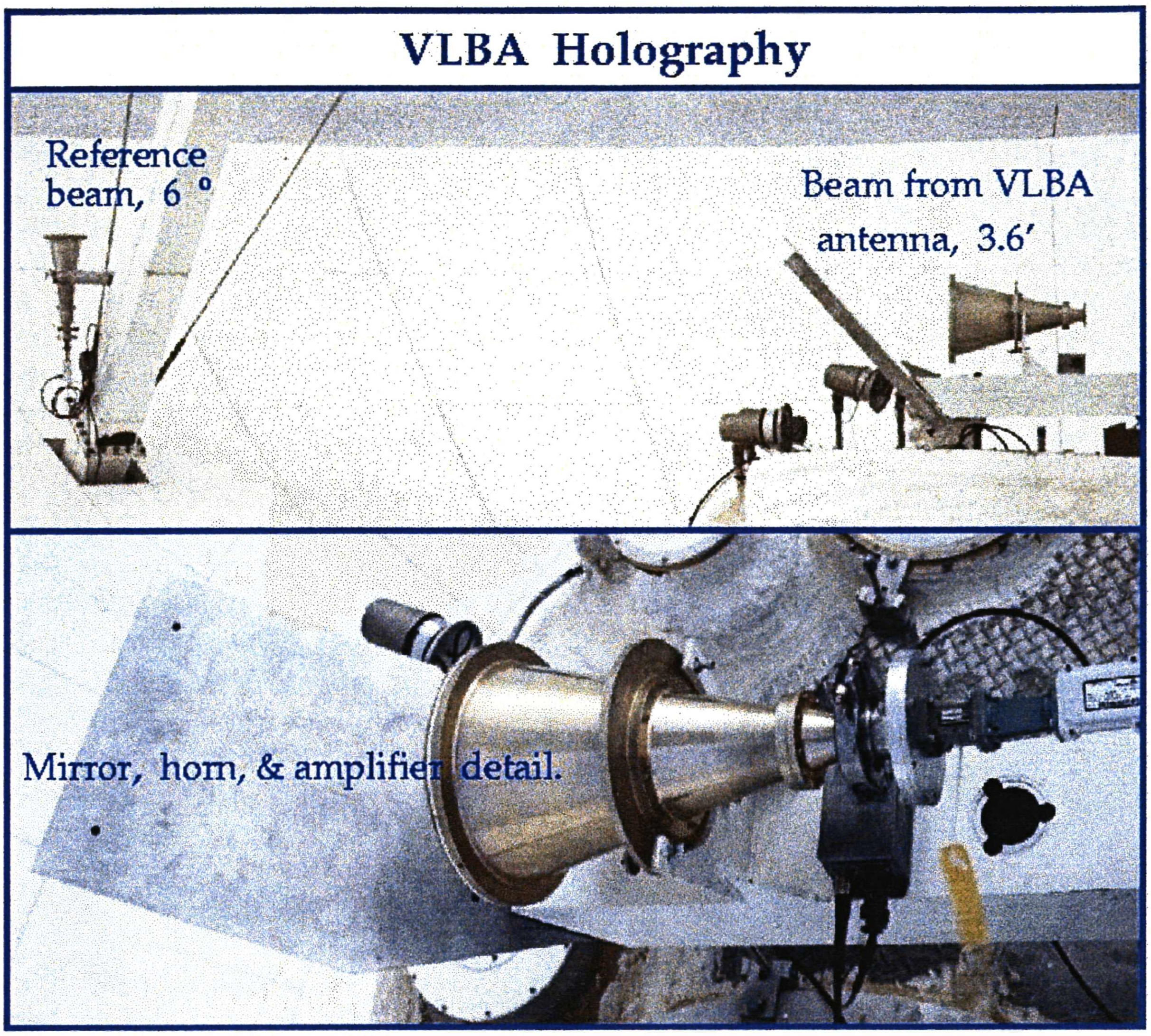


Figure IV.4 Overview of the VLBA holography hardware by scanning an antenna's beam over a raster around an unresolved radio source, and using another antenna pointing at the same source as a reference, information is obtained about the amplitude and phase distributions of the signal reflected from the antenna surface. These distributions are used to specify corrections for the focus and alignment of the feeds or of the positions of individual panels in the reflector. The small reference horn at left receives the beacon from a geostationary satellite at 12GHz. The horn and mirror combination at right (lower image) is positioned over the regular VLBA receiver suite, and gets the same signal after it has reflected off the VLBA antenna. The two signals are down-converted by the regular VLBA electronics, digitized in a PC-based data acquisition system and then correlated in the PC. The resulting beam pattern is recorded on the disk. Fourier transformation of the complex beam then recovers the image (Figure IV.5) of the surface errors on the main- and sub-reflectors.

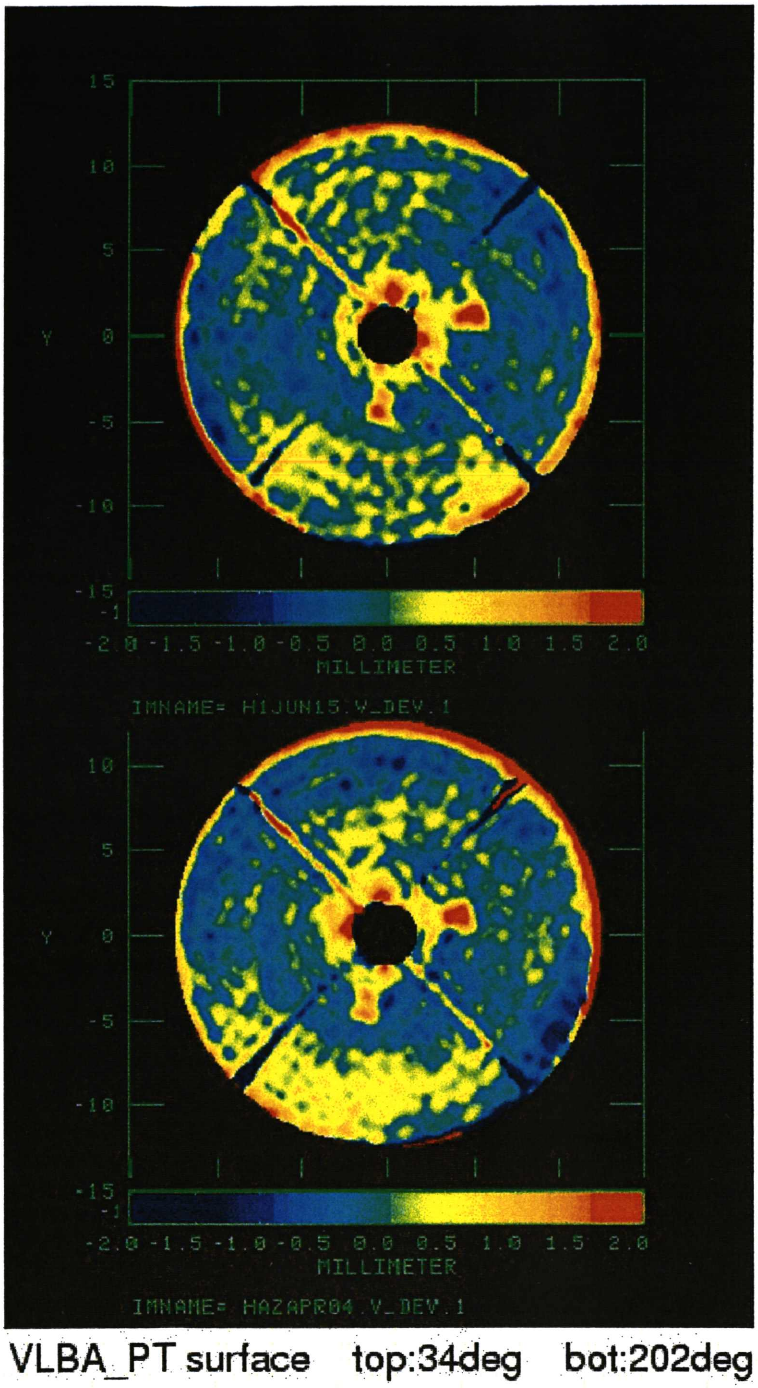


Figure IV.5 Surface errors corresponding to two positions of the subreflector rotation.

Dynamic Scheduling

Dynamic scheduling has progressed well, with about 40 percent of VLBA observing time now scheduled with a lead time of less than two days. In 2001, the lead time was shortened as much as possible in order to provide the highest probability that 86 GHz observing would be scheduled during the best weather conditions. In 2002, we anticipate the termination of the VLBI Space Observatory Program (VSOP), which has relied on fixed allocations of VLBA time in order to observe in conjunction with an orbiting satellite. Therefore, we expect the fraction of VLBA time that is dynamically scheduled to exceed 50 percent by the end of 2002.

Wideband Recording

All VLBA stations (as well as the VLA and the Green Bank Telescope) were equipped with a 512 Mbits-per-second observing capability in mid 2001. This feature will be useful at all frequencies, but especially at 86 GHz, where continuum observations are typically sensitivity-limited. Operational (tape-changing) constraints, however, limit the full use of the 512 Mbits per second mode. In 2002, we will use the new mode as much as possible within the limits of staffing at the remote VLBA sites. In addition, we will explore the pros and cons of implementation of a video cassette-based system (under development at York University in Canada) and a removable-disk system (being assessed at Haystack Observatory) for the next generation of recording that has the potential to increase the VLBA data rate to 1-4 Gbit per second. By the end of 2002, we expect to have a cost estimate for implementing these systems on the VLBA.

User Support

In 2001, we completed work on an initial suite of VLBA data-reduction procedures in AIPS. These procedures are distributed with the regularly available 31DEC01 version of the AIPS package. During 2002, we will test a data-calibration service for all U.S.-based users with relatively straightforward continuum observations.

Infrastructure

Significant infrastructure developments during 2001 and planned for 2002 include:

- The astrometric analysis of the VLBA calibrator survey was carried out in 2001, in conjunction with the geodetic group at NASA's Goddard Space Flight Center. The positional accuracy for the VLBA calibrators is now at 1 milliarcsecond or better, compared to the 12-55 milliarcsecond accuracy that was available from VLA observations. This will enable significantly improved phase-referencing in 2002, an important advance since close to 50 percent of all VLBA programs use the phase-referencing technique. In 2001 and 2002, we also are carrying out observations of additional potential calibrator sources in the galactic plane, especially in the southern sky, where the density of known calibrators is lower than desired. This effort is scheduled for completion in 2002.
- A VLA program to monitor potential VLBA polarization position angle calibrators was continued in 2001, and tests confirmed that it had significant benefit for VLBA users. The program will be continued in 2002, and the well-developed scripts for its routine data reduction will be translated into AIPS++.
- Antenna painting will continue in 2002 with a focus on sites with the highest rainfall. St. Croix will continue to get special attention in this regard.
- In 1998, an azimuth wheel drive assembly was replaced at Brewster after the discovery of deteriorated bearings in the drive assembly due to a design flaw. Almost one year later, the replacement antenna drive axle suffered a fatigue failure. A new axle was designed, fabricated and installed at Brewster in late October 1999. Another wheel assembly with the redesigned axle was installed at St. Croix in January 2000. We are prepared to install similar assemblies at other sites as failures with the original drive assemblies occur. We conduct

bearing inspections with every major maintenance visit. In 2002, a wheel assembly replacement will be done during the major maintenance visit to Hancock.

- Fall arrest and apex guardrail protection will be added to VLBA antennas to protect our workers while performing maintenance tasks on subreflector focus/rotation mounts. Three VLBA telescopes were retrofitted in 2001, and three more will have the protection added during major maintenance visits in 2002.

Central Development Laboratory

Cooled HFET Development

The NRAO has worked on the development of heterostructure field-effect transistor (HFET) amplifiers for many years and is the recognized leader of cooled HFET amplifier development for radio astronomy. The highest frequency amplifiers cover the band 68-116 GHz with noise performance comparable to SIS mixers and much wider instantaneous bandwidth.

The NRAO has produced hundreds of advanced HFET amplifiers for use on NRAO telescopes and for others in the radio astronomy community and other research areas. These range from low-frequency amplifiers (for < 1 GHz) used in fundamental particle physics and magnetic resonance imaging development to the highest attainable frequencies for cosmic microwave background experiments. At the lowest frequencies, special balanced amplifiers have been developed that largely eliminate the need for bulky isolators and have better immunity to the effects of interference.

The current total production rate for all amplifiers of all types is approximately 100 per year; this rate is expected to be sustained in 2002.

Two new InP amplifiers developed for the bands 3-13 and 8-18 GHz have now been produced in quantity. These provide noise temperatures of about 5-6 K over these bands using devices from NRAO wafers, and less than 3K using experimental devices (which also provide even more gain). They are useful for both front end and first IF use. In 2002, we plan to extend this series in InP down to 1 GHz; we will then have modern amplifiers for all useful frequencies up to 116 GHz.

In 2001, the development of an integrated IF amplifier with an SIS mixer, covering a 4-12 GHz IF band, was successful, resulting in an SIS mixer with 8 GHz bandwidth and good noise temperature. This large instantaneous bandwidth is required for maximum continuum sensitivity by ALMA. This development work will be continued in 2002.

A variant of the highest frequency amplifier design was produced in quantity in 2001 which has been optimized for the band 80-96 GHz for use by the VLBA. This has been used to improve the performance at 86 GHz on VLBA antennas. A second variant that is useful up to 116 GHz has been produced for ALMA evaluation receiver use. A third variant optimized for 68-90 GHz will be produced in 2002 for the first module of the GBT W-band receiver.

We plan in 2002 to continue production of InP 40-50 GHz amplifiers for eventual use in retrofitting the very first Q-band receivers installed on the VLA.

Continued production of InP 18-26 GHz amplifiers in 2002 will enable completion of the upgrade of the VLA at K-band.

InP amplifiers for 26-40 GHz will be produced in 2002 for the Ka-band receiver for the GBT. Additional amplifiers will be produced as time permits for eventual use on the VLA.

Low-frequency balanced amplifiers for frequencies up to 1.2 GHz have now been developed that have octave bandwidths. For example, amplifiers for 500-1000 MHz and 600-1200 MHz with about 3 K noise temperature are now incorporated into GBT receivers. A newly designed 1-2 GHz balanced amplifier with only a single stage has been designed that will allow RFI mitigation by installation of a filter between amplifiers, increasing the dynamic range and linearity of the receiver.

As a direct result of our development program, the use of cryogenic low noise balanced amplifiers has extended beyond the realm of conventional radio astronomy applications. A group of researchers at MIT and Lawrence Livermore National Laboratory has utilized our balanced amplifiers in their large scale microwave cavity search for dark matter axions. Our balanced amplifier is also a key enabling technology in the development of DC-SQUID amplifiers and Single Electron Transistor (SET) devices. Using our cryogenic balanced amplifier as a second stage, a team at UC Berkeley demonstrated, for the first time, a low noise DC-SQUID amplifier operating above 500 MHz with a noise temperature on the order of 250 mK, and a group at Yale demonstrated the SET as the world's most sensitive electrometer. Advances in both SET and SQUID devices will help make large scale bolometer arrays practical in the near future. Amplifiers are supplied to outside groups at cost when there is no commercial source.

Other Hardware Developments

The search for the ultimate vacuum window, required for cryogenic receivers, inevitably results in a compromise between leak rate and electrical loss. We have developed and produced in quantity broadband vacuum windows for the 75-110 GHz band using crystalline quartz for the VLBA W-band receivers. Work on higher frequency windows is will continue.

A new harmonic comb generator for injection of phase calibration signals into receiver front-ends is under development. The present comb generator works well up to a frequency of about 25 GHz. With the use of RF components capable of working to higher frequencies, it is planned to extend this coverage to at least 720 GHz. This will be of use in both SIS mixer testing and LO multiplier development.

Spectrum Protection and Radio Frequency Interference

Radio frequency interference is an increasing problem for radio astronomy. Probably the single most destructive source of RFI is increasing satellite traffic, with downward pointing beams which we cannot escape even by going to remote sites. Our strategy for preserving observing capability which will last well into the 21st century is to participate in the regulatory process and negotiate with operators of space-borne transmitters to minimize RFI effects on our observations. To this end, the NRAO will continue to participate in regulatory committee deliberations and publicize the need to preserve spectrum space for astronomical research. This has led recently led to great success in reserving spectrum above 70 GHz for radio astronomy, but vigilance cannot be diminished. We will also pursue technological improvements, such as the use of balanced amplifiers in the crowded low-frequency spectrum, the use of HFET amplifiers instead of the more RFI-susceptible SIS mixers at frequencies below 100 GHz, and beam-nulling correlation techniques.

Adaptive Interference Excision

We received funding from the NSF MRI program to develop fundamental techniques for the protection of radio astronomy and eco-biology search instruments from the effects of interference from ground-based and satellite transmissions. The title of the project is "Development of Interference Countermeasures for High-Sensitivity Radio Astronomy," and the goal was for $270,000, nominally for October 1, 2000-2002. Adaptive signal canceling and null-steering methods will be analyzed and applied to system-noise-limited measurements of very weak cosmic signals. Signal processing hardware and software will be developed for use on the GBT and at Arecibo to cancel interference at frequencies below 1.7 GHz for the study of highly redshifted neutral hydrogen in external galaxies, and for the study of the OH molecule in our own and external galaxies.

The MRI Program provided the $270,000 for the two-year period, the SETI Institute is supplying $144,000 in matching funds to be spent on supporting half time of two postdocs in California, and a consultant.

An adaptive filter noise-canceling system prototype was developed in 1998 and a new version is being developed to improve upon the analog filtering, create a more robust interface between the adaptive system and the spectral processor, and increase the effectiveness of RF shielding within the adaptive system. The number of reference channels will be increased to four. The improved and enhanced adaptive system will be set up in Green Bank for extended field studies. The polarization and other properties of the interference signals, as well as the response of the adaptive technique to signal polarization, will be investigated. The measurements will be compared with the results from ongoing simulations.

Fully Sampled, Focal Plane Array Receiver

At present, single-dish radio astronomy systems with multiple beams on the sky use multiple conventional channels, each with its independent feed and receiver. Due to feed interactions, it is difficult to place the individual beams closer together than about 2.5 beamwidths. Thus, for mapping radio sources that are only slightly extended, a multiple-beam receiver does not achieve a significant speedup in observing compared to a single receiver. We have developed a prototype of an array feed receiver that packs planar feeds close together and achieves multiple beam synthesis by weighted combination of multiple feed outputs. This system was tested on the 140 Foot and showed that multiple beams with good beam shape and efficiency can be synthesized from appropriately phased linear combinations of the basic feed elements. An advanced version of the receiver was developed and tested in 1999; its noise temperature was higher than expected. It has been determined that this is due to the feeds used; modified versions of the feeds are being investigated with the intention of curing this problem and resuming tests.

In May 2000, the NRAO launched an initiative to improve the data services and products offered to users of NRAO telescopes. This initiative was combined with a restructuring of existing Observatory-wide computing activities to form a new organizational component in the NRAO: Data Management. In this section, we discuss the mission of Data Management, and the budget required to support those missions.

Mission and Structure of Data Management

The primary mission of Data Management (DM) is to plan for an improvement in and oversee the provision of data services and products offered to users of NRAO telescopes. DM sets policies and standards in these areas, and coordinates relevant activities across the Observatory. DM, therefore, augments the computing divisions at the various NRAO sites and telescopes, rather than replacing them. The key roles of DM are in aiding coordination and collaboration and in setting common policies and priorities. A key mechanism has been the Data Management Executive Committee, consisting of the heads of computing at the various NRAO sites, and heads of the major software projects. Scientific input is provided by a Scientific Working Group composed of NRAO scientists from all sites and projects.

The organizational structure of computing support in the NRAO remains as it was before Data Management. The sites and projects (GB, AOC, Tucson, ALMA) each have a computing division, charged with providing local support, that reports to the local site director or project manager, as appropriate. Operational funding is through the sites or projects, whereas developmental research-related funding is via Data Management.

Organizationally, DM is split into four divisions, each with a well-defined area of responsibility contributing to the overall mission of Data Management.

Division	*Responsibility*
End-to-End Project (e2e)	*Provide end-to-end processing for data from all NRAO telescopes using shared tools and resources.*
Computing Software and Hardware Development; User Support	*Develop software and hardware solutions for NRAO computing activities, including AIPS++; software system user support.*
Telescope Computing	*Ensure coordination and cooperation between monitor and control computing for NRAO telescopes*

Division	Responsibility
Central Computing Services	*Manage shared, central computing services such as security, communications, information infrastructure, major hardware purchases, etc., and the disposition of funding for computing activities.*

Data Management Plans for 2002

End-to-End: The End-to-End project was started in July 2001. The motivations behind the End-to-End project (see the web site http://www.nrao.edu/e2e) are to ease and simplify the use of NRAO telescopes, and to ensure wider use and circulation of scientific data from NRAO telescopes, via dedicated radio astronomical archives and, for example, the planned National Virtual Observatory. The e2e project will bring NRAO into parity with other modern observatories such as the Space Telescope Science Institute. More specifically, e2e has the following goals and commitments to our users:

- To provide coordinated, end-to-end management of observing from initial proposal to final scientifically useful data products.
- To ensure uniformity of interfaces to all NRAO telescopes.
- The NRAO must take responsibility for the initial quality of data and images delivered to users. The NRAO must deliver an improved scientific data product to users.
- The NRAO must provide easy (web-based) access to archives of contemporary and historical images, surveys, catalogs, etc. for all NRAO telescopes.
- This NRAO must vigorously pursue development and collaboration with the university community and other observatories in areas relevant to observer access and use of radio telescopes.

Our proposal for funding from the NSF CISE/ITR program was funded at 10% of the proposed level. Hence according to the current budget, we can pursue the e2e project only with reduced scope. Funding is based on internal resources: the core DM group, the AIPS++ group, and "contracts" with EVLA, ALMA, GBT, and VLBA. The total effort available is about 65 FTE-years, spread over the next nine years. The e2e goals for 2002 are mainly planning, design, and some initial steps toward needed capabilities:

- Complete initial planning and design for e2e on NRAO telescopes. Preliminary Design Reviews will be held for all components of the End-to-End system.

- Develop and deploy an archive for the GBT telescope. We expect to outsource the development of the core archive engine, and NRAO staff will do the adaptation to radio astronomy.
- Continue development of software-based pipelines for processing VLA data.
- Initiate development of next generation proposal handling and scheduling tools (including dynamic scheduling).

Computing Software and Hardware Development: The transition from our existing data analysis packages, AIPS and Unipops, to the AIPS++ package will continue in 2002. AIPS++ has been under development by a consortium of radio observatories. AIPS++ is the prime data reduction and analysis package in use at the GBT, replacing Unipops. AIPS++ has been used throughout the GBT construction for various engineering purposes, is being used during the commissioning phase, and will be used for subsequent scientific observations.

In the second half of 2000, and in 2001, the AIPS++ software reached the stage where it required a significant increase in testing of the scientific capabilities and completeness of the package. An enhanced effort by the scientific staff and the AIPS++ group is bringing the software to the stage where it will be capable of analyzing a substantial fraction of VLA observations. We expect this highly collaborative effort between the AIPS++ Project and the other NRAO scientific staff ("the AIPS++ User Outreach Initiative") to be the centerpiece of AIPS++ activities in 2002, and to be a key component in obtaining widespread acceptance and use of AIPS++ by the radio astronomical community. This initiative includes:

- Interactive user training and tutorials, at sites within the community and at centralized workshops organized at NRAO.
- Continuation of the successful testing program by internal NRAO scientific users.
- Detailed monitoring of the performance of the scientific reduction capabilities at the scientific user level.
- Improvements to the existing high-level scientific user documentation, as recommended and aided by NRAO scientific users.

We will also continue the parallelization initiative, conducted in collaboration with the National Center for Supercomputer Applications, is proceeding well, resulting last year in a parallelized application for wide-field imaging as needed for EVLA. In 2002, we expect this to be followed by a similar parallelized application for mosaicing observations, such as those planned for EVLA and ALMA.

As AIPS++ approaches full capability, the NRAO will continue to support the large user base of the AIPS package. Work in AIPS will concentrate on supporting existing users, and on tracking key changes in the capabilities of NRAO telescopes.

Telescope Computing: This part of DM plays a key role in uniting the efforts of the Telescope Control and Monitor groups at the NRAO telescopes. Although post-processing of NRAO telescope data by choice will use the same software package (AIPS++), such a choice is neither possible nor totally appropriate for telescope control and monitor where the demands on the software can be quite different. Nevertheless, coordination and collaboration is useful. Our main activity in FY 2002 will be a repeat of the very successful meeting of NRAO real-time programmers that was held in 2001.

Central Computing Services: CCS is split into five subdivisions:

CCS subdivision	***Responsibility***
Management and Coordination	*Manage and coordinate shared computing activities across the Observatory*
Information Infrastructure	*Maintain and develop centralized information services, including web servers, email gateways, mailing lists, directory services, and some archive services.*
Security	*Establish, enforce, and monitor policies and procedures for the protection and correct use of NRAO computing facilities*
Communications	*Manage both the Internet presence and the Intranet across the Observatory, including router configuration, setup, network monitoring, and support.*
HQ computing	*Support computing needs of the Director's Office, Public Outreach, Business and Personnel offices, and the CDL.*

Each of these has its own goals in 2002.

CCS subdivision	*Goals in 2002*
Management and Coordination	• *Develop and deploy Common Computing Environment at all NRAO sites for both Windows and Unix*
Information Infrastructure	• *Consolidate web presence onto small number of servers* • *Initiate a common directory access protocol across the observatory computing resources* • *Investigate Knowledge Management solutions*
Security	• *Improved control over remote access* • *Deploy Virtual Private Networking for NRAO staff on travel* • *Improved intrusion detection* • *Improve email filtering for viruses, etc.*
Communications	• *Completion of video-conferencing system* • *Investigate change of contract for Intranet* • *Evaluate alternatives for long-distance* • *Investigate real-time VLBA connectivity*
HQ computing	• *Deploy test-bed Network Attached Storage system*

Funding and Resources for DM

Effects of Change in Fiscal Year: The change in Fiscal year yielded a one-time infusion of $1,000,000 in 2001. These funds allowed a number of expenditures that considerably helped the state of computing within the Observatory. The funds enabled the following actions:

- Issuance of an RFP for an archive system, software and some hardware, for the e2e work described above.
- We purchased a small test-bed system for the development of pipeline processing for the Very Large Array.
- The VLA real-time system Modcomp computers were upgraded to systems that can be maintained until the EVLA Control and Monitor System is deployed.
- We purchased a high-end computational server for reduction of GBT observations.
- Four crucial but ageing file servers were replaced throughout the Observatory.

- We were able to upgrade additional public (4) and scientist (17) computers.
- The video-conferencing system was augmented to allow inclusion of the VLA site and the auditorium in Socorro, Green Bank, and Charlottesville.

Impact of the Request Level Budget:

The proposed budget is inadequate to pursue the goals for Data Management outlined in the NRAO Long Range Plan for 2002 - 2006. To come up to the staffing in the Long Range Plan, we would need 6 new positions:

- **e2e Project:** Three new developer positions are needed. These are vital to restore the original scope of the project.
- **AIPS++:** Two new positions are needed: one to replace Cornwell who moved to e2e, and one FTE in user support.
- **CCS/Information Infrastructure:** A Web architect is needed.

The DM/CCS M&S allocation must cover virtually all upgrades computing hardware such as staff desktop workstations, visiting observer data reduction systems, and associated peripherals. As detailed in the Long Range Plan, approximately $300K extra is needed for these recurring costs.

These needs are to be considered along with the needs of other Observatory activities in the allocation of uncommitted carryover funds in FY2002. Filling new positions in 2002 would create a long-term need for funds that would require an increase in the NRAO base program.

VII. Education and Public Outreach

The NRAO is recognized nationally and internationally as a world-class leader in radio astronomy research and development. The discoveries made and advances in technology conducted at NRAO facilities continue to draw the attention and imagination of the public, key decision makers, and scientists within the global astronomy community. Augmenting the primary mission of the NRAO is a comprehensive Education and Public Outreach (EPO) program that strives to improve awareness and understanding of astronomy. These outreach efforts also demonstrate the value of NRAO to the wider community that supports us, to attract and train students in radio astronomy, and to advertise the capabilities of our facilities to the astronomical and scientific community.

Recent highlights of the observatory's EPO program are summarized here, and our plans and ongoing developments described.

Education

Green Bank

Courses for College Teachers/College Support

Beginning in 1988, Green Bank has hosted three-day workshops each spring for science faculty of undergraduate colleges. Approximately 450 college teachers from around the country have participated in an NRAO-GB Chautauqua Short Course. In FY2001, two Chautauqua programs were held. The program has resulted in greatly increased contact with undergraduate students, including the annual weeklong Penn State Educational Research in Radio Astronomy program. In its eleventh year, the program involves high school and college students in an ambitious suite of projects using the 40 Foot Telescope.

Directed-Study Courses for Secondary Teachers

The Science Teachers Institute is a program funded through competitive grant awards by the NSF Education Directorate. K-12 teachers visit Green Bank for a two-week intensive course in astronomy and the "scientific method." In one form or another, the program has been in operation since 1987; nearly 800 teachers and college students have participated in it. The cornerstone of the experience is a set of open-ended research projects that groups of teachers must perform on the 40 Foot Telescope. Working closely with observatory scientists, teachers gain concrete experience in science research. They then develop research projects for their classroom students. Participants also train other teachers to develop inquiry-based projects for their students. Through reporting from our participants, NRAO estimates that more than 5,000 teachers have been impacted through the program. Our current NSF-funded teacher enhancement program adds a second year Technology Institute, which trains teachers in the use of astronomy data reduction software, specifically *the*

Hands-on Universe (HOU) image-processing program. HOU, a nationally recognized program in its own right, gives teachers software tools to use in creating astronomy research projects with their students. The current NSF-funded teacher program will continue through 2003.

Teachers who are graduates of our programs are encouraged to bring groups of their students to Green Bank to use the 40 Foot Telescope, and many do so each year. NRAO staff collaborates with interested teachers to tailor an extended visit to the specific group of students. The 40 Foot Telescope remains the focal point of the education efforts in Green Bank, and minor repairs and upgrading of the instrument were performed in FY2001.

Programs for Students

In FY2001, the observatory continued its partnership with Green Bank Middle School. Through a grant award from Apple Computers Inc., observatory staff, collaborating with middle school teachers, has developed an innovative multi-disciplinary astronomy project for seventh grade students. In "Our Place in the Universe," all seventh-grade students work in teams to conduct an in-depth investigation of a constellation. As part of their project, the students conduct observations with the 40 Foot Telescope and interview staff scientists. At the conclusion of their work, NRAO hosts a colloquium at which student teams present their results to their peers, parents, and observatory staff. This project will continue in 2002. In addition, NRAO-GB has partnered with the local school system to offer incentives to county middle school students who wish to go to college. The Observatory hosted an overnight camp for these students in 2001, and we plan to continue our involvement in this program in 2002.

Organizations ranging from the National Youth Science Camp to college astronomy clubs make extended visits to use the 40 Foot Telescope. Extended visits range in duration from half-day visits to overnight stays. This year, NRAO hosted Girl Scout and Boy Scout "Astronomy badge" days where scouts completed activities and earned their astronomy badges. NRAO also organized several overnight events for youth camps. More than 1150 children and adults have participated in extended visits since January 2001.

In 2001, NRAO was again successful in attracting NSF funding from the "Research Experiences for Teachers" program. Funds over a two-year period will allow four high-school teachers to work with scientists at Green Bank and Socorro. All RET teachers are expected to present posters at the January AAS meetings.

In addition, NRAO-GB applied to the NSF sponsored MPS Intern program in 2001. This program, if funded, will hire four teachers each summer (2002 -2003) to create educational kits for loan to classrooms.

Community Programs

NRAO-GB conducted several outreach programs in 2001. They include:

- Mentor programs for about half a dozen students from area high schools who spend part of each week on site working on scientific and engineering projects for their senior theses.
- Career awareness tours for the Pocahontas County High School freshman class.
- After-school "science-for-fun" program for local elementary school children.
- The Regional Science Bowl for high school students continues to be held at NRAO.
- A monthly radio show featuring astronomy and the observatory.
- An NRAO-GB education web site to promote our educational programs.
- Presentations at the State and National Education and Tourism Conferences
- Business Partner to local elementary and middle schools, and the county high school.
- AAS sponsored Shapley lectures to undergraduates at colleges in the mid-Atlantic region.

New Mexico

Courses for College Teachers/College Support

In cooperation with the University of Dayton, NRAO conducted the fourth Socorro short course for college teachers in 2001, and plans to continue the annual course in 2002. The course, "Interferometry in Radio Astronomy: The VLA and VLBA," was first offered in 1998. The short course includes lectures on the theory and practice of interferometry and aperture synthesis, as well as several areas of astronomical research at the VLA and VLBA. The course also included detailed technical tours of the Array Operations Center and the VLA. This course has been extremely well received by the participants, and we have made this a permanent part of the Socorro educational program.

Small but useful amounts of VLA observing time are regularly given to astronomy professors for educational exercises. Harvard University, Agnes Scott College, Haverford/Bryn Mawr, and other institutions have thus used the VLA to provide hands-on exercises with real observational data. In 2001, the Haverford/Bryn Mawr group was one of the first groups in several years to actually come to Socorro and the VLA for their observations. The general availability of this program has now been announced in the NRAO Newsletter, and we anticipate increased demand in 2002.

Linking Astronomers with Teachers

NRAO is a member of the Southern New Mexico Project ASTRO coalition, which serves schools in the southern half of the state. Project ASTRO is an educational program of the Astronomical Society of the Pacific, and is funded in part by the National Science Foundation. This program links professional and amateur astronomers with elementary and middle school teachers to bring astronomy into the classroom. NRAO staff members serve as team members with local schoolteachers, and we also support Project ASTRO by providing educational materials, information, and class tours for teachers in this program.

Community Programs

- Science Fairs and Science Olympiad: NRAO provides financial support and prizes for science fairs in Socorro County, the state Science Fair, and the New Mexico Science Olympiad. NRAO also provides numerous staff members as judges and officials for these events. Both the New Mexico State Science Fair and the state Science Olympiad are held every year in Socorro, and the NRAO schedules a special, guided VLA tour for participants of both.
- Southwest Consortium of Observatories for Public Education (SCOPE): NRAO is a member of this consortium, which also includes Kitt Peak National Observatory, Whipple Observatory, McDonald Observatory, Apache Point Observatory, and the National Solar Observatory. SCOPE is an effective vehicle for cooperation and information exchange about public-education programs among the participating observatories. In addition, this organization has raised funds from both public and private sources to produce educational materials about astronomy. These materials have been distributed at no charge to tourists at the VLA Visitor Center, to visitors at other regional tourist attractions, and to area schools. A SCOPE-produced educational poster on solar science was included as a centerfold insert in the September 2000 issue of "Science & Children," the journal of the National Science Teachers Association. A poster on the Sloan Digital Sky Survey is being distributed in late 2001 and early 2002.
- STARTEC – State of the Art Telescope Educational Consortium: Begun in 2001, STARTEC is a global version of SCOPE. By sharing resources and expertise, the members of STARTEC (including NRAO) will enhance the individual education and public outreach activities and better carry the excitement of astronomy to a wider audience throughout the world.

Observatory-wide Programs

Undergraduate Research Program

The NRAO has sponsored a summer student program for undergraduates and graduates since 1959. For a decade, much of the funding for this program has come from the NSF Research Experience for Undergraduates (REU) program, which typically has supported 15 students per year for approximately 12 weeks in-residence at one of the NRAO sites. Additional students are funded out of NRAO operations. In 2001, there were 27 summer students working on both scientific and technical projects. This program is slowly expanding as interest in using radio astronomy to excite the imagination of students grows.

During their stay, the students are treated as part of the organization and are expected to take part in observatory activities, including preparing talks, giving tours, attending colloquia, etc. Their focus is their research project, and they are granted access to the library and computing facilities. A course of lectures in radio astronomy is prepared by NRAO staff and presented over the summer. The students are expected to contribute materially to the research they are assigned, and these contributions are often reflected in co-authorship on the resulting papers. The summer REU program is a valuable introduction to scientific research for the students and provides NRAO staff contact with what we hope will be the professionals of the future. A highlight of the summer 2000 REU program was the surprise discovery of radio emissions from a Brown Dwarf, which challenged conventional wisdom of these objects. The student's discovery was widely publicized and even appeared in *The New York Times*.

In addition to the summer REU program, we fund a number of cooperative student positions in New Mexico and Green Bank from our NSF Cooperative Agreement, involving engineering students from nearby colleges who work on technical projects in support of the instruments as part of their college requirements.

Graduate Education

Professional astrophysics is now a multi-wavelength, problem-oriented discipline. Students entering the field need a wider range of skills than most college courses can provide. To rectify this situation, and to train students in the techniques of radio astronomy specifically required for the individual student's research, NRAO staff scientists collaborate with university astronomers in the supervision of Ph.D. thesis projects. Awards are made to graduate students to take up residence at the appropriate NRAO site taking data, reducing it and writing their thesis, all under NRAO guidance. During 2001, there were six such students in residence. This program is highly valued by faculty in universities unable to support this kind of position otherwise, and by NRAO staff for the excellent student interaction it generates.

In addition to the resident students, over 150 Ph.D. theses a year include data taken with NRAO facilities. Short stays of one to three weeks at the site, travel reimbursement, and computing facilities are provided to assist any students using NRAO facilities.

Postdoctoral Education

Postdoctoral appointees are given Jansky Research Associate positions with a term of two years that may be extended for a third year. In the selection process, recent graduates are given preference to those applying for a second postdoctoral position. Jansky Research Associates are available not only to radio astronomy students but also to recent Ph.D. recipients in Engineering and Computer Science.

Research Associates at the NRAO are encouraged to define their own research program; they are not asked to serve as apprentices to NRAO staff scientists. The purpose of the program is to provide an opportunity for young scientists to establish their research credentials so that they may more effectively compete for permanent positions in astronomy. In 2001, there were 16 Jansky Research Associates in residence.

Public Relations

Visitor Centers

Across the nation, it is estimated that more people visit museums every year than attend professional sporting events. The visual impact of our instruments and the educational value of self-directed exploration around our sites make visiting the NRAO instruments an enjoyable and enriching experience for more than a hundred thousand people per year. Over the next few years, we plan to improve and expand the visitor centers at Green Bank and the VLA, as described below.

Green Bank Visitor Center

In Green Bank, the NRAO is on track to open a new astronomy education and visitor center in spring 2003. This center will provide year-round educational programs for the general public and students. In 1999, SEM Architects Inc. was selected to design the astronomy education center. The design work is complete (Fig. VII.1), and we put the project out for bid in June. Bids have been received and negotiations are underway for a projected construction start-up in September. The learning center will contain exhibit space, classrooms, auditorium, gift shop, offices and astronomical observing instruments. Funds in the amount of $7.65 million have been secured through a NASA appropriation for construction.

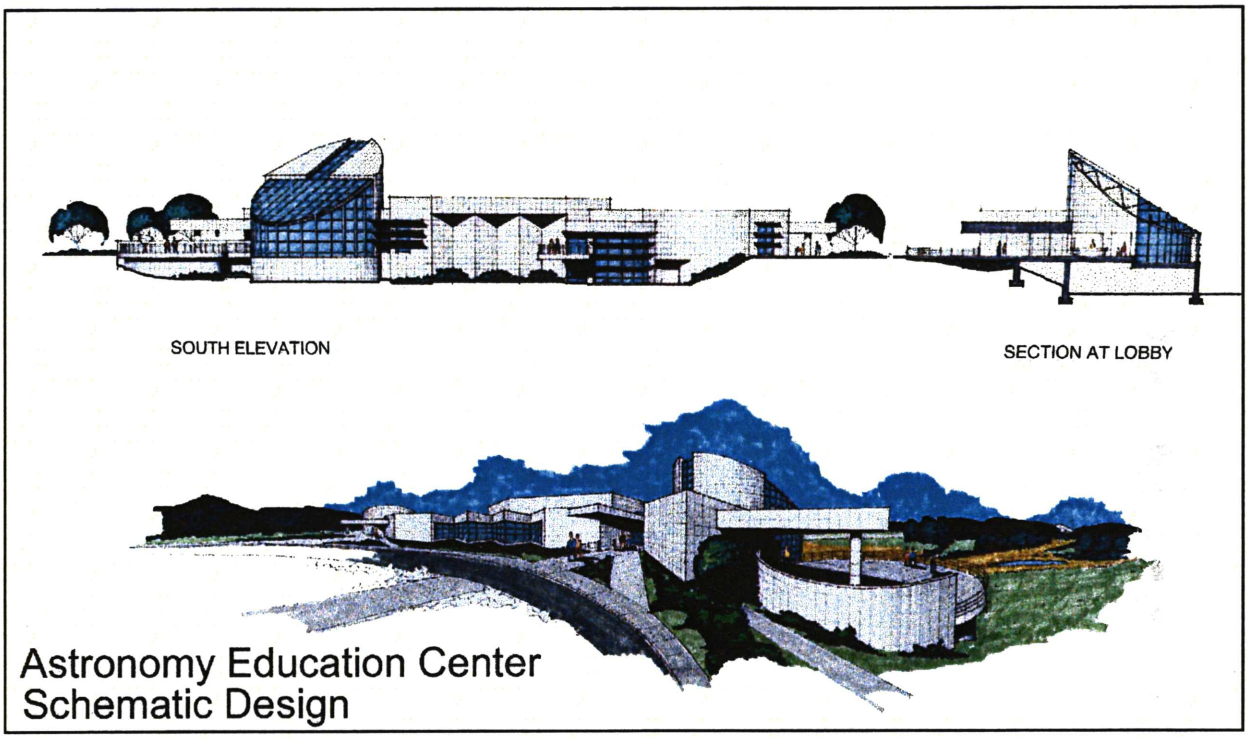


Fig. VII.1. Green Bank Astronomy Education and Visitor Center (SEM)

In concert with the construction of the Education Center, plans for building a new dormitory are underway. The new dorm, or bunkhouse, as we call it, will provide inexpensive overnight quarters for school groups visiting the new center.

The NSF-funded exhibit project, entitled *Catching the Wave*, has made substantial progress in 2001, culminating in an outside evaluation of exhibit prototypes in the fall. Exhibit construction will continue in 2002, with the exhibition ready for installation in the center on its completion. Visitors to the site in 2001 have been excited by the chance to interact with hands-on exhibits – even in prototype form.

The goal of the Green Bank public tour program is to give visitors a better understanding of, and appreciation for, astronomy and the work done at the NRAO in Green Bank. The public is encouraged to visit the site. Hourly guided tours, directed by local college students, are given each day from Memorial Day Weekend through Labor Day, and on weekends in September and October. Group tours can be arranged at any time of the year. Our tourism records, which are direct tally, show 30,000 visitors to the observatory in 2000 – a 17 percent increase over 1999. Visitation to the site in the first half of this year indicates that the 2001 total will be even higher. One reason for this increase is the GBT, which has been featured in newspaper articles and radio stories in 2001. Another is increased outreach to tourism outlets around the state and county. NRAO-GB received a small grant from the local tourism commission in 2001, enabling us to place signs throughout the county. In addition, NRAO tourism brochures have been placed in all of the highway welcome centers around the state, and at Convention and Visitors Bureaus.

During the 2001 summer tour season, special programs were once again offered each Wednesday evening to give smaller groups a more in-depth experience at the observatory. Tour staff offered programs ranging from star parties, to in-depth technical tours, to image processing sessions. Over 150 visitors participated in these events. A portable planetarium (StarLab) was purchased in 1999, and has been used in the special program series this year. Teachers were trained in the use of the StarLab in 2000 and 2001; NRAO makes it available to schools at no charge. In 2001, elementary and middle schools throughout Pocahontas County, W.Va., and the local region used StarLab, impacting over 1200 students and parents.

VLA Visitor Center

The VLA Visitor Center remains a popular destination for tourists. More than 20,000 visitors annually sign an unattended guest book, and tourism experts contend that the actual number of visitors, including those who do not sign the book, is as much as three times higher. The VLA Visitor Center thus may be serving 50,000-70,000 tourists annually. In a typical year, these tourists come from all 50 states and some 40 foreign countries.

The visitor center features an automated video presentation, displays on the history of radio astronomy, the operation of the VLA and VLBA, and information on scientific results from both instruments. It is the starting point for a self-guided walking tour that provides visitors a close-up look at a VLA antenna and, from an observation deck on the control building, views of the electronic equipment, the control room, and the array itself. A free brochure guides visitors through the walking tour, and informational signs at strategic points on the tour explain the workings of the instrument. The VLA Visitor Center was built in 1983, and the last significant upgrade to its exhibits was made in 1989. At 1,500 square feet, it is small in comparison to many other observatory visitor centers. To bring the VLA back to the state of the art in public outreach, the NRAO plans to build a new VLA Visitor Center that will serve as a far more effective tool for attracting and educating tourists about astronomy and NRAO research. The center also will become the centerpiece for a wide range of new educational outreach programs. The effort to build a new Visitor Center is being led by a full-time education officer appointed in 2001, and the long-time public information officer in NRAO-New Mexico.

Though the VLA Visitor Center is designed to provide a self-guided educational experience for tourists, NRAO also provides a number of guided tours. In the summer months, NRAO offers regularly scheduled weekend tours, often involving our REU summer students as guides. Throughout the year, by appointment, NRAO conducts guided tours for educational and scientific groups. These include school and university classes, amateur astronomy clubs, engineering societies, and others. Typically there have been more than 60 of these special tours per year, serving more than 1,500 people. The presence of the newly appointed education officer has already made a difference in the number of tours that can be given, and we expect the number of tours to be closer to 80-100 in 2002.

In the past year, we provided guided tours to elementary and secondary school groups from several states. The University of New Mexico, New Mexico State University, New Mexico Tech, and Los Alamos National Laboratory regularly schedule guided VLA tours for classes and summer student programs. Science camps for youths also have taken advantage of our programs. We distribute a booklet entitled "Bringing Your Class to the VLA," which provides teachers with background information and tips on maximizing the educational value of a class visit through prior preparation and follow-up activities.

In the interim period before a new Visitor Center can be funded and constructed, an effort is under way to improve the current facility at the VLA. The present building will be remodeled in 2002 in order to provide space for a small gift shop, which will enable funding of a full-time employee at the VLA site to conduct tours and answer questions. New interactive exhibits are being designed, and a more up-to-date video presentation is under development. (The current video presentation was produced in 1992.)

In November 2001, a retreat will be held at NRAO-Green Bank to develop a comprehensive education and public outreach strategy for the entire observatory. At this event long-term plans for the VLA Visitor Center will be further expanded. We anticipate a final vision for the new Visitor Center to be completed in 2002, with fund-raising efforts to begin shortly thereafter. Guided by the expertise of professional educators and museum specialists, these efforts will support planning a building that will provide space for, among other things, a new suite of thematic, interactive displays focusing on radio astronomy, the VLA and the EVLA, the VLBA, and some natural/cultural history of the VLA site. The building also will provide facilities for formal and informal science education programs for schools and the general public. These detailed plans will form the groundwork for implementing a solid education and outreach program targeting New Mexico students and teachers and reaching out to the general public.

To further assist in this endeavor, the VLA Visitor Center has sought and been admitted to membership in the Association of Science-Technology Centers. Through a variety of programs and services, ASTC provides professional development for the science center field, promotes best practices, supports effective communication, strengthens the positions of science centers within the community at large, and fosters the creation of successful partnerships and collaborations. Using the expertise, collaborations, and publications provided by this organization, the VLA visitor center committee will broaden its base of knowledge for designing a state-of-the-art Visitor Center.

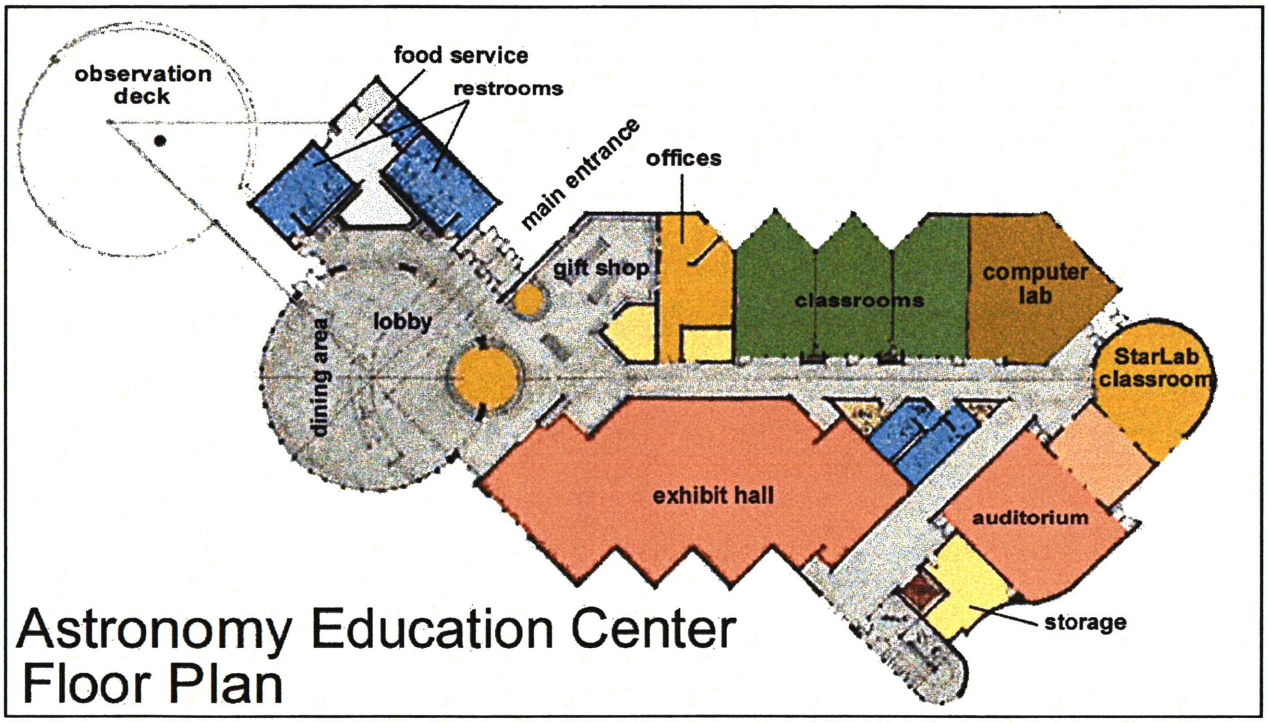


Fig. VII.2. AEC floor plan (SEM) for VLA Visitor Center.

Conference Displays

The NRAO continues to maintain and enhance its high visibility at scientific and professional meetings. This is an important way for the observatory to advertise the capabilities of our organization and instruments, and to establish our credentials as a world-leading scientific organization with a history of serving the astronomy community. NRAO traditionally operates booths at the winter and summer meetings of the American Astronomical Society (AAS). During 2001, NRAO presented displays at both AAS meetings (San Diego and Pasadena). At the Pasadena AAS, the main NRAO booth was devoted to presenting a summary of the user services, some of them new, for the NRAO telescopes. Additional booths highlighting EVLA, ALMA, GBT, and AIPS++ flanked the central NRAO display. The complete unified set of new scientific brochures describing each of the NRAO instruments was available for astronomers at this meeting.

In New Mexico, NRAO provides a display and staffing for career days at area schools, a particularly important function in a region where there are large numbers of minority and disadvantaged children who need to be made aware of the possibility of scientific or technical careers. In cooperation with the National Solar Observatory and Apache Point Observatory, we provide and staff a display at the New Mexico State Fair, an event that in a typical year draws about 400,000 attendees. We provide a display and staffing for the Albuquerque Astronomical Society's annual Astronomy Day event at New Mexico's largest shopping mall. More than 40,000 people usually visit that mall during the Astronomy Day exhibition.

World Wide Web

The NRAO is working to keep pace with the every-growing public and consumer demand for Internet services and content. The NRAO homepage on the Internet *www.nrao.edu* is the primary point of contact with the scientific community and the general public. The NRAO web system provides information about our facilities and recent scientific results, and is also used as an integral part of the operation of our instruments.

Currently, the NRAO website contains rich information about radio astronomy, our instruments, press releases, data products, and general contact information. Plans continue to develop a mirroring system around the four main NRAO sites, which would enable rapid access to our site internally and from anywhere in the United States. The new central server for this system is in Charlottesville, and our IT staff is working to bring it on line.

Our most recent addition to the website is an Image Gallery, which features results from our instruments, professional photography of the various NRAO telescopes, and other images of interest. Our policy, which is based on the Cooperative Agreement, is that images are available freely to the public for noncommercial purposes. The Image Gallery is in its first stages and will be expanded significantly in 2002 to include a comprehensive repository of images.

We currently are testing a "Radio Science Depository," where interesting images and other results can be stored and indexed for access by researchers and the general public. Other potential projects for our website include real-time displays of our instruments (previously available for the 12 Meter Telescope, and in planning for the GBT). Green Bank and Charlottesville staff are consulting with a computer graphics team in Chicago to create a virtual tour of the Green Bank site and the GBT, include still, 360-degree, and video images.

Media Relations

NRAO's public-education efforts, through visitor centers, teacher workshops, class tours and other programs, reach tens of thousands of people annually. However, news stories about the NRAO and the research done on NRAO telescopes can reach many millions of readers and viewers in a single day. Wide dissemination of NRAO research results through the mass media contributes significantly to fulfilling the Observatory's mission of building a scientifically literate society. In addition, by thus allowing the taxpayers to share in the excitement of new astronomical discoveries, we help ensure continued public support for astronomy.

Press Releases

The public information officers write and issue press releases, working closely with the researchers involved, NRAO management and the NSF Office of Legislative and Public Affairs. These releases routinely generate news coverage in major newspapers such as *The New York Times* and *The Washington Post*, as well as coverage on cable and broadcast outlets and networks. Wire-service stories resulting from NRAO press releases can appear in hundreds of subscribing news outlets.

Press releases feature the work of NRAO staff scientists and investigators from other institutions who use NRAO's telescopes. When the investigators are from other institutions, we often work collaboratively with the press officers of those institutions to produce either a release that is issued jointly or simultaneous individual releases focusing on the aspects of the research most pertinent to the different institutions. In the process of preparing to issue a release, the public information officers provide assistance and guidance to the researchers with respect to the news-embargo policies of journals such as *Nature* and *Science*.

Press releases are distributed by electronic mail to major news organizations directly, and, through the American Astronomical Society, to more than 1,400 science journalists around the world. The releases and associated images also are available on the Observatory's World Wide Web site. Frequently, Web-based news organizations, such as Space.com, will link directly from their news stories to the NRAO press release and images.

In addition to stories about research results, state and regional publications often run stories about NRAO facilities as tourist destinations. Both Green Bank and the VLA are widely cited in tourist publications.

AAS Press Room

The American Astronomical Society meetings receive some of the best news coverage of any scientific organization. The AAS press room operation frequently is cited as an example for other scientific societies to follow. This operation, while organized by the AAS Press Officer and his deputies, relies on continual staffing and assistance by press officers of observatories and other research institutions.

NRAO has supported this effort for nearly a decade by providing public information officers to staff the AAS press room. AAS meetings draw a corps of science reporters that account for the majority of astronomical stories in the U.S. media and a significant fraction of astronomical news coverage worldwide. Press-room service by NRAO public information officers has allowed us to build long-term working relationships with many of these reporters, resulting in enhanced media visibility for the observatory.

Research results from NRAO instruments presented at AAS meetings frequently are featured in press releases we distribute at the meeting. In addition, many of these research results have been the topics of AAS-sponsored press conferences at the meetings. A result highlighted in a press conference at an AAS meeting is virtually guaranteed to receive significant media coverage.

Media Inquiries

Throughout the year, the public information officers receive a large number of inquiries about NRAO and radio astronomy from journalists, book authors and screen writers. Such inquiries can range from general questions about astronomical phenomena such as eclipses and meteor showers to detailed questions aimed at providing background for a book. Authors of works not only on science and engineering but also business, art, and history have called in the past for information. The inquiries come from authors of fiction as well as of non-fiction, all of whom look to NRAO to help ensure some level of technical accuracy in their works.

The public information officers routinely provide tours of NRAO facilities to journalists and authors.

Filming Coordination

Radio telescopes have a constant appeal to film makers, commercial photographers and producers of commercials and advertisements. Such interest often runs in spurts, and at times can become quite time-consuming. The NRAO has established policies that seek to ensure reasonable access to commercial film makers and photographers while at the same time protecting the operation and reputation of the observatory. Implementing industry-standard access fees and reimbursement policies has ensured that taxpayer funds are not expended for commercial uses and also has generated funds that are earmarked for the observatory's Education and Public Outreach activities.

Publications

The NRAO continues to work with the graphic design and consulting firm, Gotham Graphix, to design a suite of promotional literature. These documents represent an overarching image for the observatory and have helped to use consistent imagery on all of our outreach materials.

For each of the NRAO instruments, the designers produced two documents—one for scientific audiences and one for the general public. These brochures are intended for distribution through visitors' centers, tourism promotion outlets, to educators, and at AAS and other scientific meetings. In 2001, the design of these brochures won an award of honorable mention from the American Marketing Association.

The redesign of NRAO brochures will continue into 2002, with a new public brochure for the VLBA, a new overall General Information Brochure for the NRAO, and a remake of the brochure "New Technologies Fostered by Radio Astronomy."

To celebrate two recent important milestones at the Observatory (the VLA 20th anniversary and the GBT dedication) commemorative posters were produced using professional photographers. In the coming year, we plan to produce a suite of striking posters highlighting all of our sites/projects to be distributed at official events, professional meetings, schools, etc. We also plan to produce another NRAO calendar, which was a very successful product in 1999.

Amateur Astronomers

Amateur astronomers are a proven resource for public education, many of them showing great enthusiasm for bringing astronomical information to the public and to schools. NRAO has forged close ties with New Mexico's extensive amateur astronomy community. We regularly provide lectures and tours for amateur groups. In addition, NRAO provides staff assistance, VLA tours and lecturers for the annual Enchanted Skies Star Party, an event that draws amateur astronomers to Socorro from across the United States and several foreign countries. Participants at this event have commented that the VLA tour and the opportunity to interact with professional astronomers have been the highlight of their visit.

The addition of General Public and Education pages on both the VLA and VLBA websites has increased our visibility globally. Virtual tours of antennas and antenna sites, visual explorations of how radio astronomy works, and descriptions of current projects being observed at the VLA and VLBA telescopes are the bases of these websites. Image galleries, real-time webcam images of the telescopes, descriptions of works performed on site (job and career information) are planned for the future.

Amateur Radio Astronomers

The NRAO is ideally positioned to use the amateur radio community, with more than 600,000 licensed operators in the United States, as a force multiplier for public education efforts. As expected, many of our staff members are licensed radio amateurs and are involved in local and national radio organizations. Staff also present lectures to amateur radio organizations, and the NRAO provides displays and information about radio astronomy at amateur radio events.

In Green Bank, the Society of Amateur Radio Astronomy (SARA) once again met for their annual conference. SARA members are active supporters of radio astronomy outreach. For example, using castoff Primestar satellite dishes and electronics, they have developed low-cost demonstration radio telescopes. These demo telescopes, capable of detecting the Moon, Sun and thermal emission from people, have been donated to museums and classrooms around the country. NRAO-GB will be the recipient of one of these systems in 2002. We plan to use this telescope in the new education center.

Staffing

The NRAO is expanding the staffing of its public relations, media relations, and education functions. Efforts are being made to hire a director for education and public outreach who will oversee and coordinate all of NRAO's communications activities. During 2001, a new public information officer was hired in Charlottesville to help with outreach for ALMA and the GBT, in addition to general outreach for NRAO headquarters. These additions will augment public information and public education staff at Socorro and Green Bank, who currently oversee the media relations and education activities at the respective sites. It is planned that over the next year, a dedicated person to oversee Web development will be brought on board to ensure NRAO is able to take full advantage of Internet outreach to enhance its overall service to astronomers and the public.

Strategy Planning

With this expansion and focus on education and public outreach, the NRAO has planned an EPO summit in November in Green Bank. Staff from the various sites and invited guests from other scientific and education organizations will meet for two days to audit our current activities, place them in context of our goals and objectives, and craft a strategic EPO plan for the coming years.

Project Overview

The Atacama Large Millimeter/Submillimeter Array (ALMA) is a collaborative venture of the U.S. National Science Foundation, a coalition of European institutes represented by the European Southern Observatory (ESO), and potentially the National Astronomical Observatory of Japan (NAOJ). The NSF, as the U.S. partner in ALMA, also represents minority participation by the National Research Council of Canada (NRC) so that the NSF is properly the *North American* partner in ALMA. The three ALMA partners are working toward a project that embraces equality of effort and contribution from, and benefit to, the partners. As we begin the NRAO FY2002 Program Year a signed ALMA partnership agreement exists among North America and Europe (only) for an initial Design and Development project phase. Events during the program year are expected to produce a signed ALMA partnership agreement between North America and Europe, and perhaps Japan, for the construction phase of the project to begin in FY2003, and possibly in FY2002.

The North American participation in ALMA is executed by AUI/NRAO, funded by the NSF through their Cooperative Agreement with AUI for management of the NRAO. The U.S. participation in ALMA grew out of the Millimeter Array (MMA) Project, which was proposed to the NSF in 1990 by AUI and funded for a 3-year Design and Development phase that began in 1998. In 1999, the NSF agreed with the European coalition to merge the MMA with the European Large Southern Array (LSA) project to create the *bilateral* ALMA Project. Subsequently, the NRAO ALMA project management, and the ESO ALMA project management have worked cooperatively on a common design and prototyping effort. This work has led to a jointly agreed work breakdown structure (WBS) for the design phase, and a complete draft of the WBS for the construction phase of the bilateral project that includes a thorough cost estimate and project schedule. With the request of NAOJ that Japan become a third ALMA partner, work has begun to establish the scope, cost, schedule and division of effort for a possible *tri-lateral* project. The results of this work will be presented to the potential partners for their approval early in the 2002 NRAO Program Year.

Thus, a thumbnail overview of ALMA is this:

- ALMA is a joint project being planned by the NSF and ESO, each of these entities representing other participating parties;
- ALMA is engaged in a common design and development program managed cooperatively by the NSF, acting through AUI/NRAO, and ESO;
- A common ALMA construction program WBS, cost, schedule, and division of effort has been developed jointly by AUI/NRAO and ESO for the bilateral project;
- NAOJ has requested to join ALMA as a third partner bringing additional resources, scientific capability and providing a cost savings to the other two partners;

- A common ALMA construction program WBS, cost, schedule and division of effort for the project will be completed and presented to the ALMA partners for their approval in the 2002 NRAO Program Year.

Science Objectives

The ALMA Project will provide scientists with an instrument uniquely capable of producing detailed images of the formation of galaxies, stars, planets and the chemical precursors necessary for life itself.

ALMA is designed to operate at wavelengths of 0.4 to 9 millimeters where the Earth's atmosphere above a high, dry site is partially transparent and where clouds of cold gas as close as the nearest stars and as distant as the observable bounds of the universe all have their characteristic spectral signatures. It will image stars and planets being formed in gas clouds near the sun, and it will observe galaxies in their formative stages at the edge of the universe, which we see as they were nearly ten billion years ago. ALMA provides a window on celestial origins that encompasses fully both space and time.

ALMA will provide an unprecedented combination of sensitivity, angular resolution, and imaging fidelity at the shortest radio wavelengths for which the Earth's atmosphere is transparent. It will provide a wealth of new scientific opportunities. In particular, the scientific specifications for ALMA were chosen to allow astronomers to:

- Image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as $z=10$;
- Trace through molecular and atomic spectroscopic observations the chemical composition of star-forming gas in galaxies throughout the history of the universe;
- Reveal the kinematics of obscured galactic nuclei and quasi-stellar objects on spatial scales smaller than 300 light-years;
- Assess the influence that chemical and isotopic gradients in galactic disks have on the formation of spiral structure;
- Image gas-rich heavily obscured regions that are spawning protostars, protoplanets and pre-planetary disks;
- Determine the temperature of the photosphere of thousands of nearby stars in every part of the Hertzsprung-Russell diagram;
- Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of invisible stellar nuclear processing;

- Obtain unobscured, sub-arcsecond images of cometary nuclei, hundreds of asteroids, *Centaurs,* and Kuiper-belt objects in the solar system along with images of the planets and their satellites—observations that can be done for astrometric or astronomical purposes during daylight or nighttime hours;
- Image solar active regions and investigate the physics of particle acceleration on the surface of the sun.

This list of specific science capabilities leads to a definition of common science requirements that can in turn be used to establish requirements on the technical performance of ALMA. Foremost among those science requirements are precision imaging and sensitivity. Precision imaging and sensitivity enable the entire spectrum of science to be done with ALMA, irrespective of whether the scientist wishes to study solar system objects or galaxies twelve billion light-years away. Quantitatively, the *level 1 Science Requirements* for ALMA are the following:

ALMA Level-1 Science Requirements

- The ability to provide precise images at an angular resolution comparable with that expected from the Next Generation Space Telescope (NGST). Resolution better than 0."1. The term "precise imaging" means images not limited by imaging artifacts at a dynamic range less than 1000:1 over the entire sky visible from the ALMA site;
- The ability to detect CO emission in a normal galaxy like the Milky Way at a redshift z=3 in less than 24 hours of observation. The scientifically related requirement is this: the ability to image the kinematics of such a galaxy using the NII or CII emission line in a single source transit;
- The ability to image the gas kinematics in a solar mass protostar with a protoplanetary disk at the distance of the star-forming clouds in Ophiuchius or Carina Australis.

Technical Objectives

The technical challenge to the ALMA designers is to build a telescope that extends the high-resolution imaging techniques of radio astronomy to millimeter and submillimeter wavelengths.

High Resolution Imaging

High resolution imaging is achieved by making use of the technique of aperture synthesis, which uses many individual antennas to synthesize the imaging performance of a single antenna significantly larger than the individual antennas. Aperture synthesis is the technique used, for instance, by the Very Large Array to image at centimeter and meter wavelengths. ALMA will use

64 individual precision antennas all operating in concert to extend the aperture synthesis technique to observations at millimeter and submillimeter wavelengths. The signals received by the superconducting receivers on each antenna will be digitized and processed in a special purpose computer or signal correlator. Images of astronomical objects and cosmic phenomena will be made using computer algorithms designed to correct for atmospheric propagation effects, and for the fact that the synthesized telescope is in fact made up of individual, separated antenna elements. The image-forming optics of ALMA is a computer.

The objects that a scientist wishes to study often are embedded in larger structures that are physically or causally related to the objects of interest. Examples would include a protoplanetary disk found within the molecular envelope of a protostar, or the active nucleus of a spiral galaxy. In many cases, perhaps most, the physical context in which an object is found illuminates its origin or evolution. For this reason, the scientist will need to image both very small structures (the protoplanetary disk or galactic nucleus) and the much larger embedding structure (the molecular cloud or spiral galaxy). ALMA realizes this capability by means of rearranging the physical layout of the antennas on the site. Such reconfigurability provides ALMA with a zoom-lens capability.

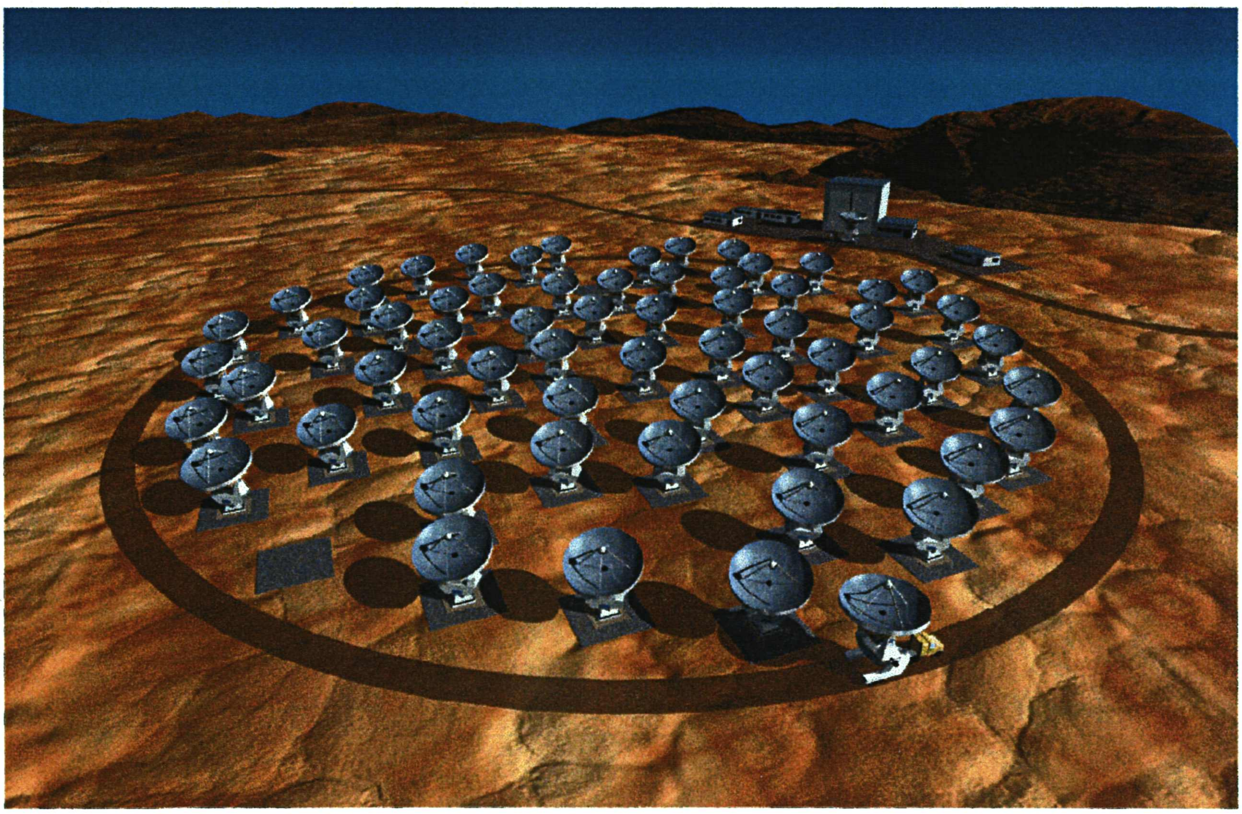


Figure VIII.1

In Figure VIII.1, ALMA's 64 antennas are shown arranged close together for observations of large regions of the sky at low resolution. The antennas may also be arranged in progressively larger oval configurations for higher resolution observations of smaller regions of the sky. In the lower right of this image one of the antennas can be seen being moved from one location to another. Also illustrated in this image are the ALMA control building, maintenance shops and the tall antenna assembly building.

The antennas can be moved into larger configurations using a special forklift-type vehicle, but they must be attached to prepared concrete foundations. ALMA has 250 antenna foundations or "stations" for the five array configurations. Each station is connected to the site electrical power and communication network. An antenna moved from one station to another can be simply connected and it will be ready to resume observations.

The largest array configuration is an oval configuration nearly 14 km in diameter. This large configuration will give images with the highest angular resolution, a resolution as high as 7 milli-arcseconds. As an aid to visualizing the range of array configurations Figures VIII.2 and VIII.3 illustrate how the smallest and largest ALMA array configurations would appear on some familiar Washington, D.C., landmarks.

Figure VIII.2

Figure VIII.3

Operation at Millimeter and Submillimeter Wavelengths

The challenge of engineering the unique ALMA telescope to operate at millimeter and

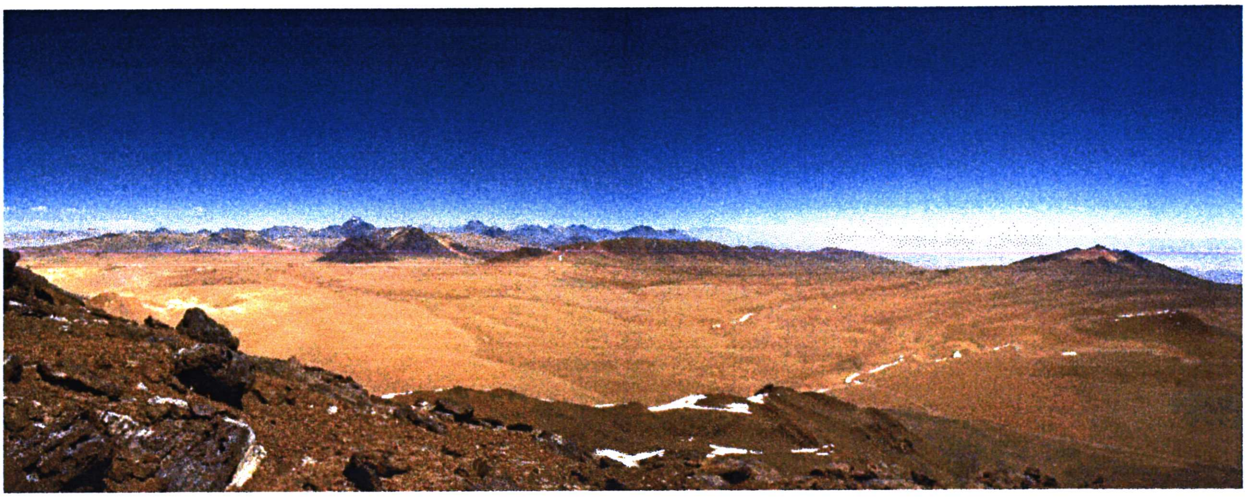


Figure VIII.4

submillimeter wavelengths begins with the telescope site. Water vapor in the Earth's atmosphere strongly absorbs light from cosmic sources at millimeter and submillimeter wavelengths; little of that light may reach the surface of the Earth. The solution is to locate ALMA in the thin, dry air found only at elevations high in the atmosphere. For this reason, ALMA will be sited in the Altiplano of northern Chile at an elevation of 5,000 meters (16, 500 feet) above sea level; this area known as the Llano de Chajnantor is directly east (downwind) from the Atacama desert, the driest desert in the world. A photo of the site is shown as Figure VIII.4. The ALMA site is the highest, permanent astronomical-observing site in the world. As an engineering project, ALMA is 64 precisely tuned mechanical structures each weighing more than 100 tons, superconducting electronics cryogenically cooled to less than 4 degrees above absolute zero, and optical transmission of terabit data rates—all operating together, continuously, on a site more than three miles high in the Andes mountains.

In order to make efficient use of the exceptional atmospheric transparency above the Chajnantor site it is necessary to design the receiving system such that the noise contributed by the receiver is as low as possible, that is the noise is close to the quantum limit. The ALMA receiver noise specification is set with this requirement in mind. In addition, the ALMA synthetic aperture must remain coherent; this sets a specification on the permissible instrumental phase distortion, which in turn sets a specification for many things including the accuracy of the antenna primary mirror surface, the stiffness of the antenna backing structure and quadripod support, and the phase noise resulting from transmission of the local oscillator reference signal in fiber optic cables. All of these requirements serve to define the ALMA technical system, or project scope and specification, as outlined for the bilateral ALMA project in Table VIII.1.

Table VIII.1: Baseline Bilateral ALMA Scope and Specification

Array	
Number of Antennas	64
Total Collecting Area (ND^2)	7238 m^2
Total Collecting Length (ND)	768 m
Angular Resolution	0.2" λ (mm)/Baseline (km)
Array Configurations	
Compact: Filled	150 m
Intermediate (2)	500 m, 1500 m
Precision Imaging	4.5 km
Highest Resolution	12.0 km
Antennas	
Diameter	12 m
Surface Accuracy	20 μm RMS
Pointing	0.6" RSS in 9 m/s wind
Path Length Error	<15 μm (sidereal tracking)
Fast Switch	1.5° in 1.5 seconds
Total Power	Instrumented
Transport	By rubber tired vehicle
Receivers	
91-119 GHz HFET or SIS	T(Rx) <50 K
211-275 GHz SIS	T(Rx) < 6hv/k SSB
275-370 GHz SIS	T(Rx) < 4hv/k DSB
602-720 GHz SIS	T(Rx) < 5hv/k DSB
Dual Polarization	All frequency bands
Intermediate Frequency (IF)	
Bandwidth	8 GHz, each polarization
IF Transmission	Digital Fiber Optic
Correlator	
Correlated baselines	2016
Bandwidth	16 GHz per antenna
Spectral Channels	4096 per IF

Project Status

In both the United States and Europe, ALMA is in a design and development phase. The objectives of this phase of the work are (1) to complete the project description, including scientific and technical requirements, the proposed technical and management approaches, a work breakdown structure and the cost estimate and schedule for the construction phase of the project as derived from the WBS; and (2) to develop the complete ALMA technical specification by means of prototypes and demonstrate through performance measurements on the prototype components that the specifications are being met. Presently, the project description, (1) above, is complete for the bilateral ALMA project and prototype components of the critical technologies are in fabrication and/or test. A summary of that work organized by the level-1 WBS tasks is presented below.

Administration

The principal administrative task involves establishing a thorough management structure for the joint U.S.-European project and implementing that structure within the technical teams. The approach adopted is based on Integrated Product Teams (IPTs) in which the responsibility for each major task is assigned to one partner or the other but the work is executed jointly by the technical teams of both partners. That is, responsibility is assigned but the effort is shared. The goal is to have the IPT structure in place and functioning by the time the ALMA project moves into construction.

Site Development

In the design and development phase of the ALMA project the site development task is limited to development planning. The main issues for which planning is in progress include the following:

- Identifying a location for the Operations Support Facility (OSF) that is near enough to the village of San Pedro de Atacama that general infrastructure support can be made available, but also near enough to the array site that the OSF can function effectively as the center for array operations and instrument maintenance and repair. The elevation of the OSF should not be higher than approximately 3000 meters above sea level so that the OSF staff can carry out their tasks without the need for supplemental oxygen;
- Identifying a route for a road to connect the OSF to the array site. The road would be used to transport equipment and personnel as necessary. That road may be the existing international highway to Argentina known as the Paso de Jama. An alternative route is also being studied;
- Carrying out an environmental impact survey for the array site, the OSF location and the road connecting the two;
- Planning for utilities. In particular, a comparative study is underway to determine whether the cost/benefit ratio is higher for ALMA to use commercial electrical power or whether ALMA should plan to generate its own power from locally supplied natural gas; and,

- Constructing a first draft of a site layout plan for both the array site and the OSF that can be used to guide the efforts of the contract architectural and engineering firm to be hired in the construction phase of the project.

Prior to the approval for ALMA construction by the partners, and permission is obtained from the government of Chile, no funds or effort will be expended on site development in Chile.

Antennas

Two contracts have been let for prototype antennas, one by the U.S. and the other by ESO. The bid packages for the two prototype antennas were written to identical technical specifications; the successful bidders on each side responded with significantly different designs that each meet not only those specifications, but they also satisfy an identical set of detailed Interface Control Documents (ICDs). The ICDs were carefully coordinated to ensure that each antenna will have compatible mechanical, electrical and control interfaces. Prototype antenna testing at the VLA site will be conducted in 2002.

Front-end Subsystem

The front end task has three components. The first is to fabricate two identical dual-channel (3 mm and 1 mm wavelength) front ends specifically to be used for the testing program of the two prototype antennas. These evaluation front-ends will be thoroughly tested in the laboratory to characterize their performance and to ensure that the data acquired from them will provide the basis for a valid comparison of the prototype antennas. These are not ALMA prototype front-ends. The second task is to design and fabricate a receiver to be used for holographic measurements of the surface of the two prototype antennas. This is a prime focus receiver operating at 3 mm that will receive a monochromatic broadcast tone in two channels simultaneously; one signal from one channel includes reflection from the antenna primary mirror and the other is detected directly from the transmitter. The phase difference between the two channels measured while the antenna is scanned over a raster of positions can be fourier inverted to produce a map of the local spatial distortions of the primary reflector. The one holography receiver will be used for both antenna prototypes. The third task is to design the ALMA front-end.

The ALMA front end is a single cryogenic dewar, or vessel, that is designed to accommodate ten frequency band receivers or cartridges. Initially only four cartridges will be built, for the bands at 3 mm, 1 mm, 0.85 mm, and 0.45 mm, respectively. In 2001, a successful preliminary design review (PDR) for the front end subsystem was held. As a result of that PDR the WBS and cost model for the front end task was reassessed, and the delivery schedule was modified. The plan is to develop the ALMA front-end in two stages of prototype—an engineering model to be followed by a fully functional prototype—both to be complete before series production begins. Prototypes of the critical technologies are in fabrication for delivery by the end of calendar 2001.

Local Oscillator Subsystem

The task for the local oscillator subsystem is in fact two tasks, namely, development of the baseline LO system and design experimentation with an alternative photonic system.

The baseline LO system uses a YIG generated microwave source that is multiplied and amplified to 100-122 GHz where it is phase-locked to a reference tone. To reach the higher millimeter and submillimeter wavelengths the 100-122 GHz LO "driver" is multipled in diode semiconductors. Multipliers needed for the LO for all four of the initial ALMA frequency band cartridges are being designed, fabricated, and tested.

The alternative "direct photonic LO" is generated in a fast photodiode detector as the difference frequency between two infrared lasers. The photonic LO is a new technology. The issues to be addressed include design of the photodiodes that are capable of providing sufficient power at high frequencies and an evaluation of whether the phase and amplitude noise on the photonically generated LO will meet the ALMA specifications.

Back-end and Correlator Subsystems

The 16 GHz analog IF output of each ALMA front-end is digitally sampled at the antennas and the digital signal is sent by fiber optic cables to the correlator. Prototype designs of the hardware needed for the sampler and the IF transmission based on a parallelization of commercial components are being fabricated and tested.

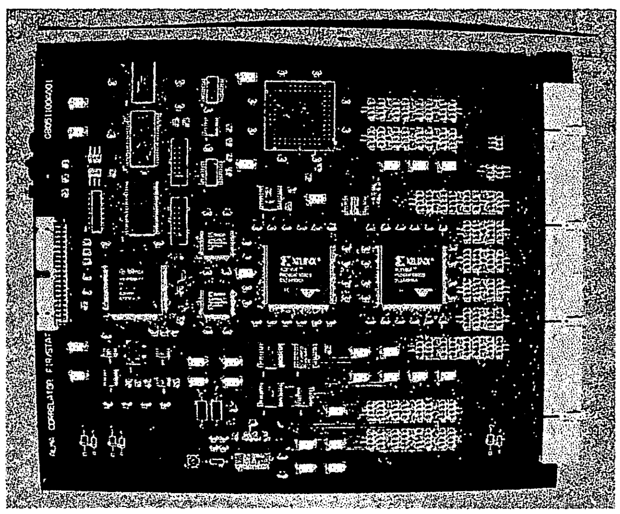


Figure VIII.5

Two correlators are planned for ALMA. The first is a single-baseline "test correlator" specifically built for the test interferometer. It will be used for the evaluation tests of the two prototype antennas. This correlator, and its software, is complete and is ready to be used with the prototype antennas at the VLA site. The second correlator is the ALMA baseline correlator. Its task is to cross-correlate the digital IF signals from all 2,016 pairs of ALMA antennas. Prototype correlator boards have been successfully tested for the long term accumulator and the digital filter; these boards are shown in Figures VIII.5 and VIII.6. The correlator computation is done in a specially designed ASIC chip; the chip design is finished and prototyping is underway.

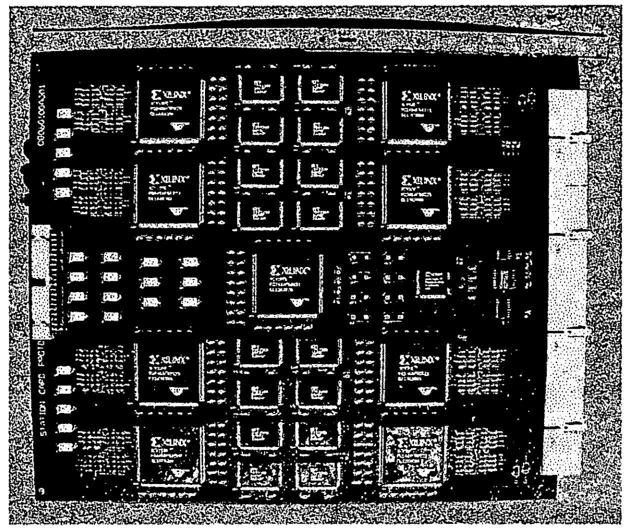


Figure VIII.6

Computing Subsystem

The software system for ALMA also is done in two task steps. First, the software to support testing of the prototype antennas is being adapted from existing software used in other astronomical applications. This includes not only the software needed to drive the antennas, but it also includes the software system by which instruments and controlled and monitored, the software to be used in holographic measurements of the antenna surface, the software for the test correlator, and the software system by which the pointing and astronomical data is analyzed. The second step is to provide for the software needed by ALMA itself. Here the software system design is being developed in concert with the ALMA software group in Europe, design decisions are made (such as the decision to use an AMBSI standard monitor and control bus), and a division of effort for the software task in the construction phase of ALMA is negotiated.

System Engineering and Integration

The test interferometer will also serve not only to test the prototype antennas but also to test the system concepts to be employed for ALMA; hence a substantial effort is directed toward the test interferometer. Site preparations are underway at the VLA site. The antenna foundations are being constructed and the utility and communications cables are being laid. Planning for the antenna testing program is complete in draft form, including the schedule for the tests, and criteria have been established for the competitive antenna evaluation.

Configuration control for the ALMA project is a primary responsibility of the system engineering group. A process to maintain and control the configuration has been established and agreed by the

U.S. and European partners, and a configuration control board is in place to facilitate the process. This is necessary for proper management of the project.

Science and Imaging

Scientific advice is provided to the project through the ALMA Science Advisory Committee (ASAC). The Project Scientists from the U.S. and Europe jointly chair the ASAC and solicit from the ASAC advice on technical questions that have a potential impact on the science performance of ALMA. Current questions under study involve the science priorities to be established for those deferred science capabilities that may become part of the scope of the three-way project (i.e., with Japan).

The science and imaging team has the responsibility to establish the array configuration layout that will maximize the imaging capability of the instrument, and to establish the calibration system necessary. A configuration PDR held in February 2001 led to preliminary agreement for the layout of all 250 antenna stations; this information has been supplied to the site development group. A calibration PDR was held in June 2001 which provided a course of action to be implemented over the next two years.

ALMA Program 2002

The pacing item for the ALMA Project is procurement of the production antennas. Since the production antenna contract is meant to follow a competitive evaluation of the two prototype antennas at the test interferometer, the focus of the ALMA effort in 2002 will be the test interferometer. The plan for the test interferometer in FY2002 includes:

- Completion of the test interferometer site, including provision for temporary office, laboratory and residential space;
- Installation of a tower (50 m high) for the holography transmitter and outfitting of the tower with the transmitter itself together with needed utilities and communication system;
- Delivery of the prototype antennas;
- Delivery of the holography receiver and software system;
- Delivery of the evaluation front-ends (2 units);
- Delivery of the LO system;
- Delivery of the IF system;
- Complete end-to-end laboratory test of the test interferometer instrumentation system, including software system and validation that it meets specifications;
- Delivery of nutating secondary mirrors for the two prototype antennas; and,

- Initiation of the prototype antenna testing program by means of a joint U.S.-European science and technical team.

Although the test interferometer will be the focus of the effort in FY2002, important prototyping tasks will continue directed toward the actual ALMA hardware itself. Most importantly in this regard is work on the front end system. The project deliberately chose to build front-end hardware for the prototype antenna testing that was special purpose, it was not an ALMA prototype front-end. This allows the ALMA front end designers to avoid having to concentrate their attention on two tasks simultaneously (the test interferometer and ALMA itself). Instead, they can work progressively toward delivery of the first production front end subsystem to Chile at the time it is needed when the first production antenna is planned to arrive in Chile. The same can be said of the correlator effort. The correlator needed for the test interferometer was delivered early in 2001, thereby freeing the correlator team to focus their efforts on design and prototyping of hardware needed for the ALMA baseline correlator.

Other ALMA task groups will work to install the actual ALMA prototype hardware on the test interferometer so that it can be tested, incrementally, with the prototype antennas. The IF digital transmission system, including use of the digital filter cards, will be particularly important in this regard. The techniques to be used for system engineering will also get a thorough evaluation at the test interferometer.

Table VIII.2 ALMA FY2002 Major Tasks and Milestones

WBS Level 1	WBS Task	Milestone or Deliverable
1.0	Administration	Establish International Project Office
2.0	Site Development	PDR Site Development Establish GPS coordinates of all antenna stations Identify OSF location and site layout Deliver preliminary layout of array site Deliver assessment of electric power options
3.0	Antennas	Deliver prototype antennas to VLA test site Deliver nutating secondary (2) Install metrology equipment on antennas Install holography tower Initiate antenna engineering evaluation

WBS Level 1	WBS Task	Milestone or Deliverable
4.0	Front-end Subsystem	Deliver holography receiver Deliver evaluation front end (2 units) Deliver holography transmitter & install Deliver ALMA engineering model FE
5.0	Local Oscillator	Deliver 80-240 GHz multiplier LO Deliver prototype 650 GHz multiplier LO Deliver prototype 345 GHz multiplier LO Deliver photonic system noise & power tests ALMA LO decision: multiplier or photonic
6.0	Back-end Subsystem	Deliver digitizer for test interferometer Deliver IF transmission system for test Interf.
7.0	Correlator	Contract for prototype correlator chip Deliver prototype correlator boards
8.0	Computing Subsystem	Deliver software engineering standards Deliver common software design Deliver pipeline software plan Deliver high-level system design Deliver monitor and control system design Deliver holography software
9.0	System Engineering	Deliver antenna evaluation plan Deliver optical pointing telescope Establish antenna evaluation team Initiate scientific antenna evaluation program
10.0	Science and Imaging	Deliver ALMA calibration plan Deliver prioritization of science enhancements CDR antenna configuration

The entire scope of activities planned by both the U.S. and European partners in ALMA are set forth in the ALMA WBS. The milestones table above was abstracted from that WBS.

The ALMA resource plan for FY2002 in Table VIII.3 is written to the President's request of $9M for ALMA in FY2002.

Table VIII.3 ALMA FY2002 Budget by WBS Element ($k)

WBS Element	Labor*	Travel	Contracts	M & S	TOTALS
Administration	846	120	0	450	1416
Site Development					
Antenna	153	75	50	150	428
Front End	1705	60	400	200	2365
Local Oscillator	738	45	100	50	933
Back-end System	767	45	30	160	1002
Correlator	408	25	225	75	733
Computing	776	100	40	110	1026
System Engineering	505	60	25	150	740
Science & Imaging	222	60		75	357
TOTALS	$6120	$590	$870	$1420	$9000

** 69 FTE*

Table IX.1. NSF New Funding by Function
($ k)

Operational Functions	Salaries & Benefits	Materials, Services & Equipment	Travel	Total New NSF Funds Request Level
Observatory Wide Activities	$10,084	$1,748	$433	$12,265
GBT Operations	6,781	1,155	130	8,066
VLA/VLBA Operations	12,677	6,660	417	19,754
CDL Revenue & Common Cost Recovery		(225)		(225)
ALMA (U.S.)	6,120	2,110	590	8,820
Management Fee		990		990
Total NSF	**$35,662**	**$12,438**	**$1,570**	**$49,670**

Source of Funds for Total Budget at NSF Request Level

Operations	*$40,530*
REU	*100*
RET	*40*
ALMA (U.S.)	*9,000*
TOTAL	*$49,670*

Table IX.2. Non-NSF Funding
($ k)

Funding Source	Salaries & Benefits	Materials Services & Equipment	Travel	Total Request Level Budget
Misc. Grants		150		150
NASA OVLBI Space		135	25	160
Total Non-NSF		285	25	310

Table IX.3. NSF Funds by Budget Category
($ k)

	New NSF Funds	Uncommitted Carryover of 2001 Funds	Total Available for Commitment at Request Level	Commitments Carried Over from 2001 Funds	Available for Expenditure at Request Level
Personnel Comp	$26,543		$26,543		$26,543
Personnel Benefits	9,119		9,119		9,119
Travel	1,570		1,570		1,570
Materials & Services†	11,673	7,300	18,973	6,500	25,473
Management Fee	990		990		990
Common Cost Recovery	(100)		(100)		(100)
CDL Device Revenue	(125)		(125)		(125)
Res & Oper Equipment					
Total NSF Operations and ALMA	**$49,670**	**$7,300**	**$56,970**	**$6,500**	**$63,470**
MRI		250	250	0	250
CISE		450	450	0	450
Education (RC & CTW)		320	320	0	320
Total NSF	**$49,670**	**$8,320**	**$57,990**	**$6,500**	**$64,490**

† The uncommitted carryover of $7.3M is a consequence of the shift in fiscal year. It derives from three sources: the planned carryover funds ($4.0M) for future investment after payment of the GBT arbitration judgment, additional carryover ($1.4M) that resulted from an inability within the shortened 2001 fiscal year to fully commit all of the one-time funds received in FY2001 for GB deferred maintenance and infrastructure improvements, and additional carryover ($1.9M) that resulted from the late arrival of funds for the EVLA Project only a few months before the end of the shortened 2001 fiscal year.

		New NSF & Carryover Budget FTE	Totals ($k)	Mission Requirements Budget FTE	Totals ($k)
1	Observatory Administration				
1.1	Director's Office	6.4	931.34	6.4	931.34
1.2	Administration	24.1	2028.82	28.1	2318.82
1.4	Program Planning	0.4	35.00	0.4	35.00
1.5	Spectrum Management	0.8	102.55	1.0	120.55
1.6	Interfer. Countermeasures (MRI carryover)		200.00		200.00
1.7	RE/OE (carryover)		1566.10		1566.10
1.8	Dir Reserve (carryover)		1000.00		1000.00
	Subtotal 1	31.7	5863.81	35.9	6171.81
2	Science/Research				
2.1	Management & Admin	0.5	88.90	0.5	88.90
2.2	Library	2.3	564.22	2.3	564.22
2.3	Science/Research	17.1	2093.30	17.1	2093.30
2.4	Science Trg & Education Progs	12.5	686.49	12.5	686.49
2.5	Observatory Surveys	1.5	143.08	1.5	143.08
2.6	GBT User Grants (carryover)		500.00		500.00
	Subtotal 2	33.9	4075.99	33.9	4075.99
3	Education and Public Outreach				
3.1	Management & Admin	2.1	196.86	3.1	262.02
3.2	Community Relations	1.1	45.35	1.1	45.35
3.3	Media Relations	1.1	93.91	1.1	97.11
3.4	GBT Public Outreach Program	1.7	87.14	2.7	137.3
3.5	VLA/VLBA Public Outreach Program	1.2	111.46	2.2	163.22
3.6	RC and CTW (Education carryover)		320.00		320.00
	Subtotal 3	7.2	854.72	10.2	1025.00

		New NSF & Carryover Budget FTE	New NSF & Carryover Budget Totals ($k)	Mission Requirements Budget FTE	Mission Requirements Budget Totals ($k)
4	GBT and Related GB Opns				
4.1	Management & Admin	34.0	2200.93	34.0	2200.93
4.2	GBT Facilities	42.8	3107.02	43.8	4119.89
4.3	Projects	25.4	1758.17	26.4	2154.69
4.4	Staff Scientific Research	1.6	193.89	3.6	363.33
4.5	Central Instrument Shop	2.3	265.24	2.3	265.24
4.6	Infrastructure (carryover)		1400.00		1400.00
4.7	University Contracted Projects (carryover)		350.00		350.00
	Subtotal 4	106.1	9275.25	110.1	10854.08
5	VLA/VLBA Operations				
5.1	Management & Admin	19.1	3145.41	19.1	3145.41
5.2	VLA/VLBA Facilities	172.1	11988.94	178.7	13013.17
5.3	Projects/Developments	10.15	1073.75	10.6	1139.75
5.4	Staff Scientific Research	6.6	611.51	10.1	898.03
5.6	VLA/VLBA Link (MRI carryover)		50.00		50.00
	Subtotal 5	207.95	16869.61	218.5	18246.36
6	EVLA				
6.1	Project Management	3.3	388.50	3.3	388.50
6.2	System Integration & Testing	3.8	860.40	3.8	860.40
6.3	Civil Construction	1.6	825.40	1.6	825.40
6.4	Antennas	4.2	413.90	4.2	413.90
6.5	Front End Systems	6.2	859.80	6.2	859.80
6.6	Local Oscillator System	5.3	443.50	5.3	443.50
6.7	Fiber Optic System	3.8	1318.60	3.8	1318.60
6.8	Intermediate Frequency System	4.7	756.70	4.7	756.70
6.9	Correlator	5.4	779.90	5.4	779.90

		New NSF & Carryover Budget		Mission Requirements Budget	
		FTE	Totals ($k)	FTE	Totals ($k)
6.10	Monitor & Control System	9.5	1121.80	9.5	1121.80
6.11	Data Management & Computing	2.6	129.40	2.6	129.40
	Contingency (11%)		1185.00		1185.00
	Subtotal	50.4	9082.90	50.4	9082.90
	Redirected Ops Effort	-21.4	-1585.00	-21.4	-1585.00
	Canadian Contribution	-5.0	-749.00	-5.0	-749.00
	AUI Fee (2%)		135.00		135.00
	Subtotal 6 ($5,000 new funds, $1,883.90 carryover)	24	6883.90	24	6883.90
7	Central Development Lab				
7.1	Management & Admin	2.0	262.52	2.0	264.52
7.2	Electronics Development	5.9	498.96	6.9	748.05
7.3	Production	6.2	396.35	6.2	396.35
7.4	Maintenance	1.0	86.04	1.0	86.04
7.5	External Sales	1.5	89.62	3.5	175.78
7.6	ALMA Reimbursed Effort	2.5	146.78	2.5	146.78
	Subtotal 7	19.1	1,480.27	22.1	1817.52
8	Data Management				
8.1	Management & Admin	0.3	66.25	1.3	120.61
8.2	e2e Project	3.2	400.11	5.7	869.52
8.3	Computing Software & Hardware	7.3	747.69	7.3	827.00
8.4	Central Computing Services	8.8	1006.1	9.8	1209.83
8.5	Telescope Computing	2.2	243.23	2.2	256.19
8.6	Staff Scientific Research	1.7	173.07	2.5	251.51
8.7	Archive and Equipment (carryover)		600.00		600.00
8.8	Dual Space Visualization (CISE carryover)		450.00		450.00
	Subtotal 8	23.5	3686.45	28.8	4584.66

		New NSF & Carryover Budget		Mission Requirements Budget	
		FTE	Totals ($k)	FTE	Totals ($k)
9	ALMA				
9.1	Administration	9.4	1416.00	10.9	1572.62
9.2	Antenna	2.8	428.00	3.2	1052.82
9.3	Receiver Systems	18.9	2,364.93	21.9	3296.73
9.4	Local Oscillator	8.2	933.10	9.5	1248.00
9.5	IF System	8.5	1,001.78	9.9	1381.02
9.6	Correlator	4.5	733.06	5.2	1182.11
9.7	Computing	8.6	1,025.94	10.0	1255.65
9.8	System Integration	5.6	740.19	6.5	1016.24
9.9	Calibration & Imaging	2.5	357.00	2.9	494.81
	Subtotal 9	69.0	9,000.00	80.0	$12,500.00
	WBS Total*		57,990.00		$66,159.32

* Includes $49,670 in new funds, $7,300 in operations carryover, and $1,020 in other carryover.

Cosmology, Large Scale Structure, Galaxy Formation, and Gravitational Lensing

Radio observations, which are relatively unaffected by obscuration, are able to probe the most distant regions of space and give new insight into star formation and AGN activity in the early universe as well as the relation between radio, optical, and X-ray emission from quasars and AGN. 21 cm spectroscopy is complementary to optical studies, since it is able to detect gas-rich systems and isolated HI clouds that might otherwise be missed. Star formation and starbursts mold the appearance of galaxies. Apparently, star formation proceeded at much higher levels in the early universe than occurs now. Simulations of the appearance of the deep millimeter/submillimeter sky as viewed by ALMA and by the GBT will continue as part of efforts to design the former and to instrument the latter. The Green Bank Telescope will be used to measure CO emission from a sample of galaxies at intermediate z, taking advantage of its broad spectral coverage and great sensitivity to prove its usefulness as a redshift machine.

The SIRTF First Look Survey (FLS) will be the first science program executed following the launch of SIRTF. It will cover 5 square degrees with 100 times greater sensitivity at 24 μm and 70 μm than preciously achieved. It will detect thousands of galaxies to z~1, enabling study of the evolution of starbursts, assessment of the contribution of dusty AGNs, and possibly the detection of new source populations. A pre-launch 1.4 GHz VLA survey of the FLS area will be made with $5\sigma \sim 75$ μJy sensitivity and 5" resolution. Most far-infrared sources obey the tight far-infrared/radio correlation, so the VLA images will be similar to the FLS images, but with sufficient resolution and position accuracy to make reliable optical identifications with objects as faint as R~ 25.5 mag. The VLA continues to be used for very deep surveys of small selected fields with particular attention to the Chandra Deep X-ray Field South. These observations will probe AGN and star formation in the early universe as well as the relation between star formation and active galactic nuclei.

Deep VLA 20 cm surveys will be used to study the star formation rate in rich clusters of galaxies to redshifts up to z ~ 0.4. The radio estimates are independent of dust obscuration and will be used to estimate the importance of dust and galaxy evolution in clusters. Other deep VLA surveys at 20 cm will be used to study the change in the rate of star-formation in galaxies with epoch. The VLA surveys will reach detection levels (15 μJy) and will sample star-formation-rates as low as 10 solar masses per year at z = 1 and 200 solar masses per year at z = 3. This will be accomplished by combining the VLA data with surveys of the same fields in the optical, near-IR, and submillimeter wavelengths. The redshifts for about 2000 objects will be measured or constrained from the optical-IR spectral energy distributions and/or the ratio of submillimeter/radio flux density.

Sensitive, wide field imaging and pointed observations are being made using the Max Planck Bolometer Array (MAMBO) at the IRAM 30 m telescope. Observations include sensitive (rms = 0.5

mJy) imaging over wide fields (150 arcmin^2), plus pointed observations of selected samples of high redshift objects. The wide field imaging results provide stringent constraints on the millimeter source counts at sensitivities comparable to typical SCUBA surveys, with the advantage of having wide fields to study source clustering properties on megaparsec scales. Sensitive radio images of these fields have also been obtained with the VLA with an rms noise level of 6 microJy at 1.4 GHz. The radio observations are critical to these studies since they facilitate source identification, and provide estimates of source redshifts. In parallel with the observational studies, the radio-through-IR spectral energy distributions of star forming galaxies are being studied in order to refine the radio-to-millimeter photometric redshift technique.

The pointed MAMBO observations have targeted large samples of QSOs at high redshift, including the DPSS and SDSS samples. These observations have more than quadrupled the number of high redshift QSOs detected at 250 GHz, including the most distant dust emitting source known ($z = 5$). The radio continuum and CO emission properties of these sources are being studied to address the question of whether there may be active star formation in the QSO host galaxy co-eval with the AGN activity. Other samples of objects being studied with pointed observations include: extremely red objects, microJansky radio sources with no optical counterparts, and Ly-α dropout galaxies.

Extensive, multi-band observations of high redshift radio galaxies are being made to search for evidence that some of these sources reside in regions of gas and galaxy over-densities indicative of cluster or proto-cluster environments. Evidence includes: (i) clustering of Ly-dropout galaxies, and submillimeter-selected dust and CO emitting massive starburst galaxies, on Mpc scales, (ii) rotating, 100 kpc-scale Ly-α halos and Ly-α absorption, (iii) disturbed radio source morphologies and spectroscopic signatures of kinematic interaction between radio jets and the ambient medium, (iv) extreme values of Faraday rotation, comparable to observed values in low redshift cooling-flow cluster atmospheres, (v) in one case, extended X-ray emission. Drawing an analogy to the recently observed clustering of Ly-dropout galaxies in blind surveys, it appears that some high redshift radio galaxies are beacons to highly biased hierarchical galaxy formation within large scale structure.

Observations with the VLA, the VLBA, and the GBT will be used to study cold gas at high-z, through observations of HI 21 cm absorption, and molecular lines in absorption and emission. An important new field being explored is the observation of CO(1-0) and CO(2-1) emission from high-z galaxies using the VLA at 0.7 and 1.3 cm. These observations constrain the spatial distribution of the emitting gas, the excitation conditions in the molecular gas, and the brightness temperature of the emitting regions. Observations are also being made of molecular and HI 21 cm absorption at intermediate redshifts toward red quasars, including gravitational lenses and AGN in spiral host galaxies, at resolutions down to milliarcseconds using the VLA and VLBA. These data provide exquisitely detailed information on the dense ISM in high-z galaxies, including cloud size and mass estimates and abundances of astrochemically interesting molecules. They can be used to constrain the evolution of the temperature of the microwave background and set the most stringent astronomical limits on the evolution of the fine structure constant. The gravitational lens studies also provide an estimate of the mass of the lensing galaxy independent of lens modeling.

At redshifts greater than one, most of the baryons in the Universe are believed to reside in the space between galaxies, in the so-called Ly-α forest absorption features. Even at low-z, these clouds are believed to contain as many baryons as reside within luminous galaxies. However, the nature of the connection between Ly-α absorption line systems and galaxies is still unknown. Ly-α systems may be totally uncoupled to bright galaxies; or related only in the sense that they move within the same large-scale structures that galaxies themselves populate. Conversely, it has been suggested that Ly-α clouds are intricately related to galaxies, either bound to them within extended halos, or as ejecta expelled during a burst of star formation. Directly investigating the connection between the absorbing systems and galaxies is only possible at the lowest redshifts. Observations of the HI distribution out to a radius of 300 kpc and within 600 km/s of the Ly-α cloud position will explore these connections by mapping the neutral hydrogen environment of a sample of nearby ($z < 0.015$) Ly-α clouds. If it can be proven that Ly-α clouds are not directly-related to galaxies, then their numbers and spatial distribution will place important constraints on large-scale structure formation and cosmological parameters.

The VLA will be used to try to detect dense molecular gas associated with high-redshift, radio-quiet quasars, to investigate whether they are the high-z counterpart to nearby, ultraluminous infrared galaxies. While a few high-z quasars have now been detected in CO emission, it is within the dense molecular material, traced by high-dipole moment molecules such as HCN, that the stars form. A detection of redshifted HCN(1-0) by the VLA will for the first time enable a direct comparison between these two classes of object.

A number of observational programs are designed to investigate the physical conditions within galactic nuclei and lensed systems. By measuring the intensity and extent of a variety of molecular transitions, an accurate measure of these extragalactic environments can be obtained, allowing, among other things, a comparison between the molecular clouds within galactic and extragalactic environments.

The NVSS will be used to study the radio emission from UGC galaxies. For the first time, thousands of nearby "normal" galaxies have been detected at 1.4 GHz. Their well-determined luminosity function will yield an accurate estimate of the current average star-formation rate in the universe.

The VLA and GBT will be used to identify, characterize, and monitor the polarization and total flux density properties of faint radio sources that are foreground contaminants of the Cosmic Microwave Background surveys such as that being carried out by the Cosmic Background Imager. In addition, the VLA and VLBA will be used to carry out follow-up observations of candidate gravitational lens systems discovered in the Cosmic Lens All-Sky Survey (CLASS).

Powerful data analysis techniques with which to analyze interferometric observations of anisotropy in the Cosmic Microwave Background radiation will be developed, building upon the expertise developed as part of design work for ALMA. Computer-based simulations of the growth of structure in the Universe and the formation of galaxies as signaled by the presence of luminous dust-shrouded millimeter-loud galaxies will be carried out, with the goal of guiding the design parameters of ALMA and its data pipeline.

Radio Galaxies, Quasars, Active Galaxies, and Gamma-ray Bursts

The VLA is being used to study radio galaxies embedded in dense X-ray emitting clusters. In addition to the intriguing correlations between the X-ray (as revealed by Chandra) and the radio emission, VLA maps of the Faraday RM distribution can be combined with density profiles derived from the X-ray observations to yield estimates of cluster magnetic field strengths and topologies. New VLA 20 cm observations will be used to confirm and study the diffuse radio emission in luminous X-ray emitting cluster at z = 0.2.

VLA 20 cm observations in the D array will be used to search for low surface brightness jets extending far beyond the established scales for a sample of FR I radio galaxies. One such source, found using the NVSS and confirmed with a deeper VLA integration, extends more than 1 Mpc compared with the 20 kpc characteristic of previous work. This suggests we could be missing an important part of the structures and thus the evolutionary history of such radio jet galaxies. The dynamics and morphology of the inner jets of low power radio galaxies will be studied using the VLBA. This will help in understanding the differences between these objects and high power radio galaxies and quasars. The VLA will be used to obtain sensitive high-resolution imaging and polarimetry of the jets in a sample of low-luminosity radio galaxies chosen for resolvability and to span a range of orientations to the line of sight. These data will be compared in detail with models of radio emission from decelerating relativistic jets, to examine (a) the detailed applicability of such models, (b) the similarities of deduced kinematic parameters and magnetic configurations from galaxy to galaxy, and (c) how well the inferred mass fluxes down the jets agree with those expected to be injected into them by normal stellar processes.

Seyfert galaxies have long been known to be divided into two main observational classes, those with broad permitted emission lines in their nuclei (Seyfert 1 galaxies), and those with only narrower permitted and forbidden lines (Seyfert 2 galaxies). Almost all known quasars have optical spectra similar to Seyfert 1 galaxies, and the question of the existence of "Quasar 2" objects has long been a subject of interest. An objective prism survey apparently has identified a population of these type 2 quasars at redshifts near 0.3. Deep VLA observations of 19 such objects have been carried out, with 13 detections made; the detected objects have radio/[O III] ratios consistent with Seyfert 2 galaxies. Analysis of the sample will be completed, and higher resolution VLA observations proposed, during the upcoming year.

VLA observations of weak Seyfert galaxies from the Palomar Bright Galaxy spectroscopic survey, at 6 and 20 cm, revealed a large population of flat-spectrum radio sources that are not seen in higher luminosity Seyferts. Three of these were imaged with the VLBA in 2001, and shown to be completely unresolved, as well as having slightly rising spectra from 1.6 to 8.4 GHz, very similar to the Galactic Center source SgrA*. The spectral shapes eliminate free-free absorption as a possible cause of the VLA spectral indices, shapes, and point to an origin in either advection-dominated accretion disks or compact radio jets. Analysis of the initial VLBA observations will be completed, and higher frequency VLBA observations will be carried out to distinguish between the two main models. VLA imaging of a subset of 30 late-type H II galaxies from the same Palomar sample has been carried out, and none of these objects show compact radio emission. The current interpretation is that these objects lack the massive black holes seen in more bulge-dominated galaxies; this result will be quantified, and the study completed, in 2002.

Massive black holes in galactic nuclei may often result from mergers of galaxies that each contain black holes in their centers. For some period thereafter, double black holes may be present in the nuclei of the merged galaxies, and may actually be resolved by the VLBA at 43 GHz. In 2001, the VLA was used to carry out a 43 GHz finding survey of 28 nearby E and S0 galaxies having cores that are unresolved by the VLA and have 5 GHz flux densities above 5 mJy. Those objects containing sufficient 43 GHz flux in their cores will be imaged with the VLBA at high frequencies in 2002 in order to attempt to detect the two-component radio emission from possible binary black holes.

VLBA studies of the parsec-scale structure of Seyfert galaxies will continue, based on several observational programs. Objects with flat-spectrum cores will be studied to determine the ubiquity of free-free absorption. Properties of the gas required for this absorption will be compared to those expected from observations of water megamasers and X-ray absorption in the same galaxies. Multi-frequency, multi-epoch observations of two Seyferts, Mrk 231 and Mrk 348, will be analyzed to confirm and extend previous measurements of low component separation speeds and strong free-free absorption (~0.1c) within the inner parsecs of the galaxies. This is of particular interest for Mrk 348, which underwent an extremely strong radio flare (brightening by a factor of ~5) between 1997 and 2000. Possible ejection of a new component, and the speed of that component, will be used to extend previous comparisons of Seyfert galaxies and their much more powerful quasar "cousins."

Observations of water masers have been used to reveal the geometry and dynamics of molecular gas within a parsec of the central engine in AGN. In particular, one of the most interesting results from radio astronomy in recent years has been the detection of a sub-parsec, edge-on disk in the nucleus of LINER galaxy NGC 4258. The disk is traced by a characteristic triply-peaked maser spectrum, with emission being detected from the near side of the disk (at the recession velocity of the galaxy) and from the two tangential edges of the disk (at velocities offset from the recession velocity by roughly 1000 km/s due to rotation of the disk). Detailed studies of the variability of the disk and its structure revealed by the VLBA lead to accurate determinations of the central black hole mass, and to the distance of the galaxy itself. The distance determination is particularly noteworthy because it is calculated strictly from geometric principles rather than being based on the usual distance ladder. Recent modifications to the Cepheid distance scale are now in agreement with the VLBA distance to NGC 4258.

The maser emission from the tangential edges of the disk in NGC 4258 is critical to understanding the nuclear disk, but these maser features were detected only serendipitously during testing of a wide-band AOS spectrometer at Nobeyama. The typical bandwidth used to study these masers with other telescopes, 50 MHz or so, does not cover the complete spectrum of maser emission from NGC 4258, which spans about 150 MHz. The new GBT spectrometer will allow up to 800 MHz of simultaneous spectral coverage. Since the range of velocities is not known for other potential megamaser galaxies, wide coverage is essential during both searches and monitoring.

Despite searches covering several hundreds of galaxies, only 18 megamasers have been detected. NGC 4258, being one of the brightest, lends itself to the detailed studies required to probe the nuclear disk. The most obvious and immediate benefit of the GBT in studies of water vapor megamasers will be its sensitivity. Searches for water masers have been sensitivity limited, and so many new megamaser galaxies should be discovered with this telescope. In addition, monitoring of known sources, which can be used to track the orbital motion of the molecular gas from which the masers radiate, can reveal weaker components in the spectrum and hence give a more complete picture of the nuclear disks that may be involved. An interesting example is NGC 2639. The maser in this galaxy has several characteristics that suggest it could have a disk like the one in NGC 4258, but NGC 2639 is more distant and the maser lines are much more difficult to detect. Observations with the GBT will have the sensitivity required to determine whether a nuclear disk exists in this galaxy.

As an element in the VLBA array, the GBT will allow for interferometric mapping of sources for which the maser emission is prohibitively weak using the VLBA alone. Mapping of the maser features relies on self calibration techniques, and so the very sensitive GBT-VLA baseline will open the possibility to include many of the masers currently too weak to map.

The VLBA will be used in a continuing study of compact steep spectrum radio sources measuring the Faraday rotation induced by the ionized ISM. These observations will help in the understanding of the gaseous environments of the nuclear regions of these galaxies.

VLA and VLBA studies of nonthermal nuclei in nearby galaxies will continue. Projects include studies of (a) the inner regions of UGC galaxies at 1.49 GHz; (b) jet collimation regions in NGC 4278, NGC 4374 (M84), and NGC 6166; (c) proper motions in the Fanaroff-Riley I radio galaxy M84; and (d) thermal and nonthermal plasmas in NGC 1052. Work will also continue on an NRAO VLBA survey of 100 FIRST sources in the NOAO deep wide field J1432+3416; one in four sources were detected in a recent pilot program.

VLBA observations of the morphology, polarization, and kinematics of the relativistic flow in quasars and AGN are continuing with the goal of characterizing the nature of the relativistic flow and the effect of differential Doppler boosting on the appearance and distribution of apparent velocity. Particular attention is being given to the AGN found in the FR II radio galaxies 3C 111 and 3C 390.3 with their rapid outflow; the torus of ionized and molecular gas which appears to surround the central engine in NGC 1052 and NGC 1275; the apparent twisted double jet structure and faint counterjet in M87, the CO rich AGN 1345+126 with its sharply bent relatively long jet, and gamma-ray loud quasars.

VLBA observations provide good constraints on the magnitude and spatial distribution and of ionized material on parsec scales associated with the NGC 1275 (3C84) accretion disk. New VLBA observations will allow a search for changes in the ionized medium since 1995. A simple accretion disk might not be expected to be hot enough to have ionized gas on the parsec scales on which it is observed. Some ionizing mechanism must be at work. Possibilities include illumination by hard radiation from the central engine, either taking advantage of a flare or warp or through scattering above the disk. It is also possible that a wind or corona above the disk is involved, allowing material to be illuminated directly by the core. Constraints on the rate of variability will help constrain models. VLBA imaging of the sub-luminal nuclear jet in NGC 1275 will continue. The images, at 7 mm wavelength with 0.15 mas resolution, show jet acceleration, bending, and brightness modulation on scales under one light-year. The movie of jet kinematics (now 7 epochs over five years) will be compared in detail to hydrodynamical models of relativistic flow with variable Mach number.

Continuation of long term monitoring observations of 3C120 at 1.7 GHz using the VLBA are planned. The 3C120 jet shows a combination of moving and stationary features that is suggestive of relativistic material moving on a helical path. If such a path is the result of instabilities, theory suggests that the medium external to the jet is relatively cool. The requested data cover a period over which some of the moving features are expected to pass through one of the stationary features. What happens during this period should allow much stronger statements to be made about the reality of the helical path and its implications.

The VLBA is being used to image HI and free-free absorption from the circumnuclear environment around other AGN in general and edge-on radio galaxies in particular. The detection of broad H I absorption toward the nuclear components of some edge-on radio galaxies (e.g., Hydra A, 1946+708, and PKS 2322-123) lends support to unified schemes for AGN that require an obscuring parsec-scale torus. The VLBA is also being used to identify an intriguing new class of AGN known as Compact Symmetric Objects (CSOs). These sources appear to be baby radio galaxies (only thousands of years old), that may evolve into classical double radio galaxies.

VLBA observations will investigate magnetic fields in the AGN environments using high-resolution, multi-frequency polarimetry to map the Faraday Rotation Measure distribution on the parsec scale. Faraday RMs up to 40,000 radians/m^2 have been detected in the cores of quasars, yet within 50-100 pc of the central engine the RMs in the jets fall to under 100 rad/m^2. The high central RMs have also been found to be variable and this may help to explain the low and highly variable polarization properties of quasar cores.

Space VLBI observations of several blazars using HALCA and the VLBA have revealed complex magnetic field structures on the parsec scale consistent with higher-radio frequency ground-based VLBA observations (which have similar or better resolution). Since the significant level of polarization implies ordering of the magnetic field, these observations, combined with simple assumptions about the stability of the jet structure, imply that projection effects are likely exaggerating an otherwise relatively regular ordering of the field according to the jet structure (e.g., shocks and boundary layers) and mild variation in local orientation. The HALCA-VLBA observations are important, not only because they allow spectral combinations (with ground array observations at higher frequencies, for Faraday and optical depth studies) with a minimum of systematic difficulties associated with matching resolution, but because they resolve material that is more difficult to detect at the higher frequencies at which ground arrays must observe to achieve the same resolution. This potentially enables a more detailed characterization of the cross-sectional structure of AGN jets. A principal goal of the continuing study will be to determine the extent to which the interaction of cross-sectional and orientation effects (including degree of bending) influence the radio classification (vis-a-vis optical classification) and the identification as gamma-ray sources. These studies will take advantage of continuing HALCA experiments as well as multi-frequency VLBA observations and will involve detailed analyses of spatial and temporal variation in the spectrum and polarization at sub-milliarcsecond scales.

Space VLBI with HALCA is contributing also to AGN science via the 5 GHz VSOP Continuum Survey. The efforts of a large international collaboration demonstrate that the compact radio sources in AGN are dominated by an unresolved (core) component at this observing frequency, i.e., their visibility functions flatten significantly as baseline length increases. Consistent with the polarization investigations described above, this flattening indicates that a physically important scale (or transition between scales) is accessible to space-VLBI observations at gigahertz frequencies. Future space VLBI missions will attempt to resolve the compact cores further on longer baselines, at higher frequencies, and with higher sensitivity.

Research on gamma-ray bursters will continue in 2000. The VLA is the focus of a world-wide network of radio telescopes designed to respond rapidly to gamma-ray bursts. The observational goal of this program will be the acquisition of high-quality radio light curves and spectra in the radio band. These radio data will be used with optical and X-ray observations taken on the ground (Palomar, Keck) and with space-based facilities (Chandra, HETE-II, ASCA, HST, and BeppoSAX). Broad-band spectral and temporal studies of the radio, optical and X-ray "afterglows" from gamma-ray bursts can yield insight into the nature of the GRB progenitor population by giving us information on the total energy of the burst, the geometry of the fireball and the type of environment into which the GRB explodes.

The VLA and Owens Valley Radio Observatory (OVRO) are being used to obtain near-simultaneous observations of the radio afterglow of gamma-ray bursts (GRB) at centimeter and millimeter wavelengths. Once a GRB is detected with the VLA at centimeter wavelengths, bright sources are observed at 3.3 mm with OVRO. Millimeter continuum emission has been detected in three GRBs and has been used to constrain model parameters for the circumburst environment and the evolution of the GRB.

Normal Galaxies

New multi-configuration VLA observations and archival data analysis of an age-ordered sequence of interacting/merging galaxies have been carried out to find compact radio continuum sources that are caused by supernova remnants and H II regions. This is part of a study to determine star formation rates in these objects and find the interaction stages in which the bulk of the massive star formation occurs. First results for "the Antennae" (NGC 4038/4039) were published in 2000; the radio images revealed regions of extremely intense star formation that are completely obscured optically. In 2000 and 2001, data were acquired, calibrated, and imaged for the remaining six galaxies in the sequence: NGC 520, NGC 3256, NGC 3395, NGC 3690, NGC 4194, and NGC 7252. During 2002 and 2003, the images of these galaxies will be analyzed to study the star formation rates and determine the dependence of massive star formation on the interaction age.

The VLA was used to map a sample of three edge-on superthin spiral galaxies in the H I 21 cm line. The sample spans a range of interaction stages, and is intended to probe the physical and morphological changes induced by mild galaxy interactions, and to test the possibility that interactions can cause transformations of thin, dynamically cold Sd disks into Magellanic-type systems. Optical broad- and narrow-band imaging have also been obtained for this sample. Analysis of these data sets is underway.

A project using the Nancay Radio Telescope to obtain H I maps of a sample of giant low surface brightness (LSB) galaxies has been completed. LSB Giants have sizes and luminosities at the high end for spiral disks, but their mean surface brightnesses are on the order of a magnitude or more fainter than the canonical Freeman value. Giant LSB galaxies occupy a unique realm of physical parameter space, and these relatively rare objects may share evolutionary histories unique from other low surface brightness spirals. The H I observations reveal that LSB Giants often have H I extended significantly beyond their stellar disks, and frequently have ratios of H I mass to B-band luminosity several times those of normal spirals with similar Hubble types.

Monte Carlo simulations in combination with multiwavelength observational data have been used to explore for the first time the dust and molecular gas contents and distributions of low surface brightness (LSB) galaxies. It is found that while the dust contents of LSB galaxies are low, these systems are not dust free, and they can support modest clumpy, multiphase interstellar media. The implications of these results for understanding the physical conditions in the ISM and star formation processes in LSB galaxies are now being explored. In spite of their modest dust contents, it is found that dust reddening is insufficient to explain the large radial color gradients seen in some LSB galaxies, implying these systems sometimes harbor significant stellar population gradients and have likely been built up slowly with time.

Studies of individual galaxies from ongoing mergers to evolved ellipticals will continue, with the aim of understanding the evolution of the gas content of systems which undergo violent encounters. In particular, we wish to understand what the expected properties of such violent encounters are, in terms of the morphological properties of the remnants, and in terms of the distribution of the gas among the various phases in the remnants (cold atomic, cold molecular, and hot X-ray). By observing systems that span all evolutionary stages of merging (from ongoing mergers to very evolved merger remnants) at a wide variety of wavelengths (from cold atomic gas, to cold molecular gas, to warm ionized gas, to hot X-ray gas) and using knowledge of the dynamical evolution gained from running numerical simulations, we hope to shed considerable light on these questions. In the past few years we have concentrated our attention to on-going mergers and very evolved remnants. In the coming year we will bridge the evolutionary gap between these objects and study recent merger remnants, with dynamical ages of a few thousand years since merging.

Past studies have demonstrated repeatedly that the copious amounts of cold atomic gas found at large radii in disk galaxies give rise to extensive gaseous tidal features. Twenty-one cm spectral line mapping of such features is a powerful and unique tracer of the dynamics of such encounters. With this in mind, visualization tools have been developed to allow a direct inter-comparison between the 3-dimensional spectral line data cubes and 6-dimension data from N-body simulations. This tool is coupled with an N-body "toolkit" to allow a quick survey of the disk orientation and viewing angles to greatly facilitate the model matching process, and will be ported to Java so it may be made more widely available to the community.

Several observational programs seek to understand the finer details of the tidal tails. Such features show a wealth of substructure, from individual super-star clusters up to and including the putative "Tidal Dwarf Galaxies." High-resolution 21 cm spectral line mapping with the VLA and HST WFPC imaging offers the only means to observationally compare the dynamics of the clumps with the inter-clump material in order to evaluate whether they are distinct dynamical entities. B-array (4" resolution) H I observations of several tailed systems will be compared with HST observations to see how the optically detected condensations are related to the underlying kinematic field and gas content.

Face-on collisions of spiral galaxies can strip the H I from both galaxies but leave the dense molecular clouds to anchor magnetic fields. As the galaxies separate following such a collision, radio continuum emission from cosmic rays trapped on field lines stretching like strands of taffy between the galaxies, provides a historical record of the collision and "crash tests" theoretical models for the radio emission from normal galaxies (e.g., the calorimeter model for the far-infrared/radio correlation). The second "taffy" pair was discovered recently and will be studied with the VLA to help distinguish characteristic features of the phenomenon from possible peculiarities of just one example.

H I synthesis observations have been made with the VLA of five galaxies selected from a sample of apparently isolated spirals whose integrated H I profile is known with high precision. The galaxies each exhibit asymmetry in the single dish profile. One of the galaxies is shown to be a simple double system, two of the galaxies are systems showing strong interaction between the principal galaxy and a dwarf companion, and two galaxies show a marked asymmetry in the hydrogen distribution but no perturbing companion is seen. The study will use these results, augmented by data from other H I mapping programs as appropriate, to address the questions of the lifetime of the perturbation which is manifested in the profile asymmetry and of the frequency of such interactions.

The extent of the neutral hydrogen (H I) in a normal galaxy is greater than its optical size. Does this H I serve as a reservoir for future star formation? If so, how is this accomplished? Is the ratio of H I/optical sizes a function of type? There are a variety of questions relating to this ratio and yet it is only poorly determined. A program using the GBT is planned to study this parameter for a group of relatively isolated galaxies. The first part of the experiment is in hand: 140 Foot observations of approximately 100 galaxies. By observing this sample, one which covers all spiral types, with the GBT and its smaller beam a measure of the H I extent can be derived. It will form a basic sample in the study of the global properties of galaxies.

High-velocity gas (HVG) has been known to exist in the Milky Way galaxy for some time yet has only recently been observed in other galaxies. Since the number of known galaxies with HVG is small, it is difficult to compare the properties of galaxies with and without HVG and, therefore, difficult to determine what causes the phenomenon. As shown by preliminary observations with the 140 Foot Telescope, high signal-to-noise observations of a large sample of face-on galaxies should increase significantly the number of known galaxies with HVG. Galaxies detected to have HVG will then be statistically compared and studied at high resolution with the VLA in order to help solve the riddle of the nature of HVG. A VLA search will be conducted for OH absorption from known HVC's, after the recent detection of HCO^+, a molecule which is seen to be closely related to OH in surveys of local diffuse gas. The use of a cm-wave transition renders more lines of sight accessible to absorption studies.

A program is underway to image nearby galaxies at ultraviolet (UV) wavelengths using the Wide Field and Planetary Camera 2 aboard the Hubble Space Telescope. Numerous high-redshift galaxies have now been uncovered by various workers, and these data hold the promise to further our understanding of galaxy birth and evolution. However, interpretation of these results is complicated by the fact that many of the distant galaxies are actually viewed in the rest frame UV, where the morphologies of galaxies can be drastically different from those at optical or near-infrared wavelengths. Until now, suitable comparison samples of nearby galaxies at UV wavelengths that can allow the separation of bandshifting versus evolutionary effects had been lacking.

The Interstellar Medium, Molecular Clouds, Cosmic Masers, Planetary Nebulae, Star Formation, and Stellar Evolution

The Plateau de Bure Interferometer will be used to continue several large chemical surveys of polyatomic molecular abundances in diffuse interstellar gas. Much of the new work will focus on searches for those complex ions that, through recombination, are the proximate sources of more commonly observable molecules such as HCN, CCH, and the like. The VLA will be used to study the abundances of carbon chain radicals and cumulene carbenes (C_4H, C_4H_2, etc.) and other species (for example, NH_3) whose spectra are most sensitively probed at wavelengths longer then 6 mm.

Observations with the VLA determined the Faraday rotation measures of about 35 sources in a 100 square degree region of the sky. These observations will be combined with Hα observations in order to determine the characteristics of the turbulent magnetic field in the interstellar medium. The results will be used to test the theory that the decay of turbulence is a significant heating source of the interstellar medium.

The optical observations imply that star formation in two newly discovered Wolf-Rayet galaxies occurs in brief bursts with an unusually flat initial mass function (IMF). VLA observations of these Wolf-Rayet galaxies have been partially completed. VLA scaled arrays are being used to observe this type of galaxy at 20, 6, and 2 cm to determine whether there are very young starbursts in this type of galaxies.

The VLBA will be used to obtain contemporaneous maps of local (galactic) H I and OH absorption in directions which have been studied intensively in surveys of diffuse cloud chemistry. The idea is to study small-scale spatial variations of atomic hydrogen in both atomic and molecular diffuse gas while OH is observed in the latter, to understand what is the origin of the AU-scale spatial variations in atomic and molecular absorption spectra at centimeter and millimeter-wavelengths.

A model of the heating, cooling, and H_2 formation in diffuse gas will be used to study the effects of differing metallicity and grain abundance. The point is that we can now take a variety of sensitive spectra in gas having lower metallicity in the halo and outer disk, in HVC's, in the Magellanic Clouds and other dwarf systems, and in damped Ly-α systems at high redshift, but there exists no general discussion of how our understanding of the diffuse ISM—all gained locally—applies to observations of the same kind of gas in these other systems. Conversely, we can observe inward in the Galaxy to regions of higher metallicity although it is harder to isolate diffuse gas under such circumstances.

The VLA will be used in the A array at 7 mm to image the hyper compact H II components G1 and G2 in the luminous H II region W49A. Based on existing continuum images, the $H_{52}\ \alpha$ line at 45 GHz will be used to study the kinematics of individual sources with an angular resolution of 0.04 arcseconds. The increased number of 7 mm front-ends at the VLA are crucial for this observation.

The VLA will be used to make sub-arcsecond resolution images of the emission from SiO, in various of its isotopomers and vibrational states, to investigate the acceleration of molecular material by protostellar winds and jets to form molecular outflows. Observations of two young, low-mass, protostars in the vibrational ground state J=1-0 transition of SiO follows up some recent results showing shock entrainment of molecular gas and dust within a protostellar jet, and will be used to test the ubiquity of this acceleration mechanism. A multi-configuration VLA study of thermal SiO emission and SiO masers in Orion will enable a similar investigation of a high-mass protostar, and polarization measurements of the masers will also be able to constrain the role of magnetic fields.

The only available probe of the inner AU or so of a protostar remains water maser emission. A program of mapping masers over time to determine true space motion of the flow continues, using the VLA, the VLBA, and the Pie Town link. Class 0 sources are thought to be in an active accretion phase, with observed highly collimated powerful molecular outflows. These flows, and protostellar jets which power them, are thought to play an essential role in the evolution of a protostar into a star approaching the main sequence. In the dominant paradigm, the jet dominates angular momentum transport in the accretion disk; it regulates protostellar rotation so that the star continues to accrete without reaching breakup speeds. As the outflow dissipates angular momentum, it also dissipates the parent core. Therefore, jets determine the final stellar mass by controlling infall and outflow motions; the acceleration and collimation of the jets probably involves magnetohydrodynamic processes in the vicinity of the stars. Until ALMA is built, the only mechanism we have of imaging these processes is through water maser emission generated at the shocks where the jet impinges on the cloud, whether these lie where the outflow shocks ambient material or at the protostellar accretion shock. We will use the VLA/VLBA/Pie Town link to investigate this region in a number of objects with Class 0 SEDs during the coming year.

The VLBA will be used to observe the Zeeman effect in OH using the 1720 MHz line. Three galactic supernova remnants will be observed. The major goals are to determine whether the magnetic fields strengths depends on resolution by comparison with previous VLA A-array data and to attempt to resolve the maser spot sizes. Research will continue in order to determine whether the observed sizes are intrinsic or are a result of interstellar scattering. The VLBA will also be used in a coordinated program with Infrared interferometers to study the changes in the molecular envelopes around Mira stars. Observations of Silicon monoxide masers at 7 mm will help in the understanding of the formation of the dust shells around these objects.

The GBT will be used to measure the hyperfine 8.7 GHz $^3He^+$ line in a sample of Galactic planetary nebulae (PNs). Standard stellar evolution models predict that low-mass stars should produce ^3He in copious amounts and that over the life-time of the Galaxy the interstellar medium should be enriched over the primordial value. Although H II regions are expected to be zero-age objects there is no evidence for any stellar enrichment during the last 4.5 Gyr with a constant abundance of $^3He/H = (1.5 \pm 0.6) \times 10^{-5}$ by number throughout the Galaxy. Stellar evolution models which employ non-standard mixing can account for this lack of ^3He production in the Galaxy if such processes occur in over 90 percent of the low-mass stars. Currently, only one solid detection of $^3He^+$ has been made in PNs using the MPIfR 100 meter telescope with a high abundance of $^3He/H = (2\text{-}5) \times 10^{-4}$ by number, consistent with ^3He production. Standing waves produced by the blocked aperture of this telescope are the limiting factor in the sensitivity of such measurements. Therefore, the GBT will be a significant improvement. To reconcile observations with theory requires that a sample of PNs be observed.

A survey of optically selected dark clouds for submillimeter dust emission has revealed several new protostars not identified by infrared surveys and suggests that different star forming processes apply in different environments. In support of this conclusion, recent limited studies of the Perseus molecular cloud indicate that it contains an unusually high fraction of very young, Class 0, protostars, compared with Taurus and Ophiuchus. To enable good estimates of the lifetimes of the Class 0, I, and II protostellar phases, and to enable the dependence of star formation on cloud structure to be investigated, a complete submillimeter continuum survey of the Perseus cloud is being undertaken using the JCMT. This will be complemented by observations of molecular line emission using FCRAO of the same cloud, to determine the kinematics of the cloud and to assess whether the dense cores are gravitationally bound. Similar observations will be made of the optically-selected dark clouds, enabling a direct comparison of star formation in these different environments.

The youngest stars have not yet heated their birthplace, nor have they even accreted most of their mass from it; they inhabit the coldest of molecular cloud cores. Within these cores, the spectral energy distribution has yet to be shaped by the star; it peaks in the submillimeter with a characteristic temperature of only tens of degrees Kelvin. Cores showing these so-called "Class 0" energy distributions (SEDs) have been targeted for ammonia imaging with the VLA; maps of another half dozen are scheduled for observation. Apparently simple cores, characterized by cold dust and bipolar flows, have been targeted to determine the rotational properties of the cores in these early stages. Presumably, as material has not yet settled into a circumstellar disk, the angular momentum of the parent cloud may be measured through the ammonia images and contrasted to properties of the bipolar flow. In the single-protostellar objects HH211, HH212 and HH111, linear gradients have been observed in the ammonia core; a link will be sought between source age, outflow momentum and outflow character in a further set of sources. This further set includes multiple objects; we hope to discover how formation of multiple objects alters the angular momentum and energy budget between circumstellar gas, embedded sources, and outflowing jets.

Ammonia spectroscopy offers the opportunity to measure temperatures within the core, thus examining the heating of the core by the embedded source. A program has begun to image these same cores in the lines of formaldehyde at 1.3 mm, using the BIMA interferometer. These lines lie at nearly exactly the same energy as the ammonia lines; any difference in the images should stem primarily from chemical differences. The purpose is to develop millimeter wavelength probes of temperature and density analogous to ammonia for the higher frequency ranges to be imaged by ALMA. However, our first results show that chemical differences can be important—in the S68N protostar, ammonia shows only modest heating near the young star, while in formaldehyde images, the outflow dominates the protostar's environment. The sample will be increased in order to determine if chemistry dominates other similar regions appearance on arcsecond scales.

Another excellent probe of cold near-protostellar material is provided by deterium isotopomers of abundant molecules. A program continues at BIMA to image protostellar cores in various appropriate lines. Several cores in the Serpens cloud and in NGC 1333 have been mapped so far in a number of isotopomers. One goal, for example, is to separate the effects of grain chemistry in the envelope by contrasting emission from deuteroammonia, which may form on grains and be released by energetic events near the protostar, with the deuterated formyl ion, which does not participate in grain chemistry.

More than two dozen ring nebulae have been identified as arising in the interaction of strong stellar winds from Wolf-Rayet stars with the surrounding interstellar medium. The study of these objects has progressed vigorously at optical wavelengths, yielding good dynamical information as well as evidence for enrichment of the interstellar medium in, for example, nitrogen. More recently, information about the distribution of neutral hydrogen in the neighborhood of the nebulae is becoming available. Now, new maps of the distribution of CO around four of these objects have been obtained with the 12 Meter Telescope and will be used to identify the ambient material into which the WR wind is expanding. This will enable a better estimate of the shell dynamics and thus an improved value of the stellar mass loss, and may give information as to whether the stellar wind is aspherical.

The VLA and Owens Valley Radio Observatory (OVRO) will be used to image outflows and disks associated with luminous young stellar objects (YSO). The CO outflows and 1 and 3 millimeter continuum emission from thermal dust are imaged with OVRO at resolutions of 1" to 10" (depending upon the size scale of the source structure). The VLA provides complementary information about the compact region immediately surrounding the central protostar with resolutions of 0.05" to about 1". VLA observations from 7 mm to 6 cm will be used to image ionized gas in the ultra compact H II region within a few hundred AU of the central star as well as ionized gas in collimated jets which at least partially power the more extended molecular outflow, and also to image SiO(J=1-0) emission near the base of the jet and water masers that are produced in the disk and/or jet. Observational efforts focus on sources that are well-suited for study with an interferometer and may provide specific constraints for theories of outflow/jet production mechanisms.

The observational constraints derived from the VLA and OVRO images will be used to examine the relationship between stellar mass, accretion rates, and the ejection-to-accretion ratios in molecular outflow sources of low and high luminosity. A new approach to this analysis is being developed which, for the first time, provides a way to estimate the mass accretion rate in luminous YSOs using the source age (estimated from the molecular outflow), bolometric luminosity of the YSO, and high accretion rate stellar birthline tracks.

The 8 m Very Large Telescope at Paranal is being used to obtain a large number of stellar spectra of giants in local dwarf galaxies, centered at the near-IR Ca triplet in order to obtain accurate metallicities for the Leo I and Fornax galaxies. A program of wide-field color-magnitude diagrams in areas of the Large Magellanic Cloud designed to study the evolution of its population over large areas to faint magnitudes and, most importantly, with significant number statistics, is being conducted with the CTIO 4 m telescope.

The 3.6 m telescope at La Silla is being used to obtain integrated spectra of the LMC bar in areas for which deep HST color-magnitude diagrams exist. For these areas the stellar population content is reasonably well understood. The spectroscopic observations, covering the 3400A-1 micron spectral region at intermediate resolution, will be used to synthesize the integrated light of the LMC, thus providing for the first time a "reality check" for spectral synthesis.

The Galactic Center, Pulsars, Novae, Supernovae, Microquasars, and other Radio Stars

The VLA will be used to continue the monitoring of the 106 day periodicity of Sgr A*, the compact radio source associated with the 2.6 x 10^6 solar mass black hole at the center of the galaxy. The VLA will be used with an interval of about ten days in all arrays and wavelengths (0.7, 1.3, and 2 cm) for which the baselines exceed 80,000 λ (in order to avoid confusion from Sgr A - West). In case an "outburst" (typically 0.1 - 0.3 Jy) is observed, follow up VLBA observations will be carried out. These VLBA observations will be able to detect low velocity outflows ($\geq$0.0003 c, less than the escape velocity of 0.1 c from the black hole at a distance of 5 AU).

The VLA will also be used to search for the stellar winds associated with massive stars near Sgr A*. Previously free-free emission associated with the ionized winds of more than a dozen stars in two galactic center clusters (Quintuplet and Arches) have been detected at the VLA. The central cluster surrounding Sgr A* (radius ~ 0.5 arc sec) may contain stellar winds at the 0.1 mJy level. Sgr A* will be used for self-calibration in the A array. The source is unresolved (< 1 mas) at 7 mm and the resolution will be ~ 40 mas.

The circular polarization in pulsars and their average profiles occasionally changes sense in an antisymmetric fashion with pulse longitude. This distinctive pattern of sign-changing circular (SCC) polarization could be produced by curvature radiation or by overlapping beams of orthogonally polarized radiation. While both mechanisms produce similar SCC patterns, additional polarization features of the mechanisms are quite different and can be used to determine which mechanism actually produces SCC. Initial studies of SCC have been inconclusive regarding its origin because the pulsars studied to-date do not show SCC in their average profiles and consequently, show limited occurrences of SCC in their individual pulses. A thorough investigation of SCC will be made by selecting pulsars that show SCC in their average profiles and observing the polarization of their individual pulses with the Arecibo radio telescope.

The study of radio supernovae has been largely driven by observations made at the VLA over the past two decades. VLA images are made of new, nearby optically detected supernovae in order to detect prompt radio emission associated with the explosion. Observations are made on time scales ranging from a few weeks to a couple years after the optical detection. Between mid 1997 and mid 2000, 275 supernova observations at frequencies ranging from 327 MHz to 43 GHz were made. During this period, 23 new optical supernovae were added to the monitoring program. Of these 23 objects, 17 were Type II or IIn, four were Type Ib or Ic, and two were Type Ia supernovae. This resulted in two positive detections, SN1997eg and SN1998S. Both are Type IIn supernovae. A third object, SN1999em, a Type II, is a possible detection. Rudimentary radio light curves were developed for these objects. This research will continue to be pursued vigorously in the coming year.

Detailed modeling of the multiple imaging event of PSR 0329+54 will be performed. This will allow the size and distance to the screen to be established. The space-VLBI images during this event have already confirmed that multiple images of the pulsar exist and the image separation provides the last bit of information needed to derive a detailed model.

The "Duck" supernova remnant, G 5.4 - 1.2, is possibly associated with the pulsar B1757 24 and a pulsar wind nebula. There has been recent evidence that the nebula has a slow velocity (< 600 kms^{-1}, 5 σ) at 3. 6 cm based on VLA data over 6.7 years. If the pulsar is moving at the same rate as the nebula, and the association holds, the pulsar's true age is then made larger than the spin down age of ~ 16,000 years. However, up to the present, the pulsar's proper motion has not been determined. VLBA observations were attempted, but the nearest calibrator 3 degrees away is scattered to a size of 50 mas. The VLA will be used in the gating mode to separate the pulsar from the pulsar wind nebula. In 1998, the system was observed with the A array. The pulsar will be observed again with the A array plus Pie Town. A proper motion accurate to ~ 10 mas/year is possible. If the pulsar is associated with the supernova remnant, the expected proper motion is 70 mas/year. The limit on the motion of the pulsar wind nebula is less than 25 mas/year.

The Type II supernova SN 1970G in M101 (the first extragalactic supernova detected in the radio) will be observed again using the VLA. The last observations were in 1990 when the 20 cm continuum flux density was ~ 0.2 mJy. The power law index of the decay is about -2. An observation of this object at an age of 30 years will be important in understanding the nature of radio supernovae and the transition of supernovae into supernovae remnants. The current luminosity of SN 1970G is intermediate between Cas A and the Crab.

Microquasars are nearby laboratories for black hole accretion and associated synchrotron jet outflow. Since the time evolution scales with the black hole mass, microquasars of a few Solar masses reveal in minutes a richness of phenomena analogous to a quasar observed for decades. Multiwavelength observations of microquasar GRS 1915+105 will continue using the VLA, and VLBA, the X-ray satellite RXTE, and UKIRT (infra-red). The QPO properties of the hard X-rays from the corona were found to be correlated with the strength of radio emission from the AU-scale jet, a relationship that will be further investigated with Chandra observations of iron lines from the accretion disk.

Simultaneous large flares in X-ray and radio emission require special effort to observe in a timely manner and follow the transient superluminal motion. Time-lapse images permit the measurement of the velocity of the ejecta within a few hours. High-resolution VLBA images of GRS 1915+015 have revealed an AU-sized "baby-jet" within the nucleus, aligned with the axis of the larger-scale ejecta. The AU-scale radio and IR emission are found to be closely coupled to the dynamics and instabilities of the X-ray emitting accretion disk. The nuclear jet varies in ~30 minutes during minor X-ray/radio outbursts, and re-establishes within 18 hours of a major flare, indicating the robustness of the disk/jet system to disruption. VLBA astrometry has located the black hole to ±1.5 mas, (after accounting for its secular parallax of 5.8±1.5mas/yr from Galactic rotation at 12 kpc), and placed a limit of < 100 km/s on its proper-motion.

VLA observations have yielded an accurate position, and measured a curious inverted spectrum for the new X-ray emitter XTE J1118+48. The unusual location of this X-ray binary, far out of the galactic plane, implies high velocity and/or extreme proximity. VLBA astrometry combined with optical velocity information yields the space velocity of this black hole adrift in the galactic halo. Models for the kick velocity and galactic orbit are being investigated.

A newly determined complete sample of the radio stars from NVSS is being observed with the 2.16 meter optical telescope of Beijing Astronomical Observatory along with their radio and X-ray properties.

The Solar System and other Planetary Systems

With the recent visit of comets Hyakutake and Hale-Bopp, interest in the molecular spectral line emission from comets has increased dramatically. Studies of data taken at NRAO telescopes on these and other comets will continue through the coming years. These studies will include:

- Analysis of images of the HCN, CO, H_2CO, HCO+, and CH_3OH emission of comet Hale-Bopp taken at the 12 Meter Telescope, in order to determine the kinetic temperature and outgassing evolution;
- Analysis of NH_3 detections of comets Hale-Bopp and Hyakutake from data taken at the 43-m telescope, to determine the abundance of ammonia in such comets; and,
- Analysis of observations of the OH molecule in comets Hale-Bopp, S4LINEAR, and Giacobini-Zinner, performed at the VLA (including both mapping and background source occultation data), in order to probe variations of OH, and hence water, in cometary nuclei.

The GBT will be used to observe spectral line emissions from not only any future bright long-period comets, but short-period comets as well. The GBT should prove to be a very powerful instrument for such studies.

Comets are not the only icy bodies in the solar system receiving increased attention in recent years. With the discovery of Kuiper Belt Objects (KBOs), the outer edge of the solar system is being pushed further outwards, and interest in all icy bodies in the outer solar system has increased. At the large end of the distribution of these bodies are the large icy satellites, and the Pluto/Charon system. High frequency (Q-band) observations of Pluto/Charon and Neptune's largest moon Triton have been undertaken at the VLA in the last two years. This is a difficult observation, as these objects are very weak, are in southern sky, and have no good nearby calibration sources. Additionally, the VLA configurations have not been optimal at the right season (winter) for these observations. However, such observations will continue, hoping for the right combination of conditions to allow for detections of these bodies at these (relatively long) wavelengths. The improvements in the high frequency performance of the VLA will certainly aid in these attempts. Detections of these bodies will allow discrimination between the types of ices proposed to exist on their surfaces, as well as placing constraints on the physical temperatures.

The improvements in the long wavelength systems at the VLA (1-m and 4-m bands) and in the data reduction procedures have allowed new studies in observations of solar system bodies at these wavelengths. The emissions from Jupiter at these wavelengths come mostly from energetic electrons in the gigantic magnetosphere of the planet. Reduction of the data from recent observations of Jupiter at these wavelengths will continue, and will allow more detailed models of the magnetospheric structure and characteristics of the energetic electrons to be constructed. New data will be taken, allowing for studies of the time variability of this emission. Venus will also be observed at 330 MHz, in order to attempt to determine the properties of the upper meters of its subsurface.

Shorter wavelength observations (2 cm and shorter) of Venus at the VLA allow tight constraints to be placed on the abundance and distribution of temperature and sulfur-bearing molecules in the lower atmosphere of the planet. Studies of such data taken over the past five years at the VLA will continue, yielding this important information.

Astrometry, Geodesy, and Geophysics

Two enhancements to the Jodrell Bank VLA Astrometric Survey (JVAS) will be completed: (a) a search for more JVAS-like sources in the northern Galactic Plane and (b) an extension of JVAS to southern declinations.

The VLBA participates regularly in observations specifically designed for astrometry and geodesy. Some of these are large, 24-hour programs typically involving 20 stations located around the world, several of which are used exclusively for geodesy and astrometry. The observations are analyzed by groups at NASA's Goddard Space Flight Center and at the U. S. Naval Observatory. The data will eventually become part of the data base of all geodetic VLBI observations that is used by various researchers to establish fundamental reference frames for geodesy and astronomy and to study a variety of geophysical phenomena. For example, tectonic plate motions can be measured and compared with predictions of models, while Earth rotation rate and orientation data provide key information on the nature of the Earth's core and the interaction between the Earth and its atmosphere.

The geodetic observations are important to the VLBA in terms of what they provide. Phase referencing has become a very important part of what the VLBA does, increasing the available sensitivity by one to two orders of magnitude. It is used in roughly half of all VLBA observations. The ease of phase referencing that we now experience is the result of using a very high quality geometric model on the correlator and using accurate source positions, station positions, and Earth orientation parameters. Both the model and the accurate positions are provided by the geodetic/astrometric community. A recent contribution of that community is the generation and distribution of models of the ionosphere that have recently been demonstrated to be useful for correcting VLBA data. These models are based on the GPS data that is also used by the geodesy community and includes contributions from geodetic GPS receivers that are located at some VLBA sites.

Instrumentation

New designs for submillimeter wavelength radio telescopes will be studied, principally to meet the requirements of the ALMA Project. Particular problems to be investigated include new, cost effective ways to meet demanding reflector surface accuracy and pointing requirements. Work during next year will concentrate on the evaluation of the newly developed broadband fully-integrated (MMIC) 600 - 700 GHz SIS mixer for ALMA and the development of a tunerless SIS mixer for the 86 - 116 GHz band. Special design considerations will be given to minimize the mixer output capacitance and the inductance so that the design will be compatible with the 4 - 12 GHz IF proposed for the ALMA. This is a single-ended mixer, which will later be used as a building block in balanced and sideband-separating mixers for the ALMA.

We are continuing improvements of the high frequency capabilities at the VLA by completing the 7 mm system and improving the 1.3 cm system. These improvements include surface adjustments based on holographic measurements and an upgrade to the encoders for better pointing. We also are continuing research into phase calibration techniques, including fast switching and water vapor radiometry, and are exploring options for contingency scheduling using monitors of local tropospheric conditions at the VLA site.

Six VLBA antennas were outfitted with receivers by March 2001, participating in the CMVA run of April 2001 and in several stand-alone VLBA 3 mm observations with dynamic scheduling. Two new receivers are nearing installation on the MK and HN antennas, in time for the fall season. Tests on the new receivers indicate that 100K T_{sys}, stable broadband operation, and low VSWR, similar to the receiver already in astronomical use on the OV antenna.

The 12 GHz holography system is producing surface images at the 150 micron accuracy level. At this accuracy, the indications are that the PT antenna errors are in the subreflector, not in the panels on the main reflector. Systemic errors will be further improved over 2001-2002, and the system made more portable for use at all the VLBA sites. Options to correct the subreflector errors, e.g., via a correction lens or re-shaping of the surface, will be pursued.

The VLBA was designed to be upgradable for operation at 3 mm wavelength. Efforts toward realizing this capability were started in several areas in 2000. At this short wavelength, many of the VLBA subsystems which produce such high-quality data at longer wavelengths are required to operate much closer to their design limits, and enhancements are necessary to make routine 3 mm observing feasible.

With low correlated flux at the highest spatial resolution, limited antenna efficiency, and relatively high receiver and sky temperatures, sensitivity is at a premium in the 3 mm band. Continuum sensitivity will be enhanced by completion of the VLBA's long-planned 512 Mbps, dual-recorder capability. Four VLBA stations have been upgraded, and new VLBA formatter modules sufficient to upgrade an additional three stations have passed operational tests. The 512 Mbps capability will become available on the VLBA in 2001. A study of the feasibility and cost for a final upgrade, to the VLBA recording system's planned maximum capacity of 1 Gbps, was completed at the end of 2000.

The reliable imaging of low surface brightness structure in the milliarcsecond scale jets of AGN requires accurate deconvolution of the typically more compact bright structure, and vice-versa. This is especially true of HALCA observations where the range of scale sampled is typically too large for deconvolution at a single resolution to be effective. Thus, an adaptive u,v-data weighting scheme (and it's mutual impact on self-calibration) is under study for development in AIPS++, where some multi-scale deconvolution algorithms have already been implemented.

A proposed future Space VLBI mission, ARISE, has been recommended by the National Research Council's decadal review committee, but is not likely to be launched before 2010. ARISE would be based on a 25 meter orbiting radio telescope with sensitivity equal or better than a VLBA antenna at frequencies up to 86 GHz. Work will be carried out to broaden the scientific scope of the mission and to relate the scientific requirements to different options for the engineering design of the spacecraft and mission.

NRAO staff are participating in the national and international efforts to develop the next generation of centimeter-to-meter wavelength radio telescopes. Particular attention will be given to the suppression of man-made radio frequency interference, and optimizing the array configuration to obtain high angular resolution along with the good image quality needed to mitigate the effects of confusion.

D. S. Balser - Galactic structure and abundances, H II regions, and planetary nebulae; GBT scientific support.

T. S. Bastian - Solar/stellar radio physics, interferometry, image deconvolution and reconstruction; frequency agile solar radio telescope (FASR) planning.

J. M. Benson - Extragalactic radio sources, VLBA image processing; scientific support for VLA/VLBA correlator and real-time software development.

R. C. Bignell - Planetary Nebula, polarization; Head, Green Bank Telescope Operations.

R. Bradley - Millimeter electronics, low-noise amplifiers, array receivers, adaptive RFI excision; advanced receiver development.

J. Braatz - Masers, active galactic nuclei and cosmology; AIPS++.

A. H. Bridle - Extragalactic radio sources; Data Management and VLA scientific support.

W. Brisken - Pulsars and antenna design; EVLA.

R. L. Brown - Theoretical astrophysics, interstellar medium, quasar absorption lines; Deputy Director.

E. W. Bryerton - Power amplifiers and local oscillator systems; ALMA.

B. J. Butler - Planetary astronomy; ALMA Project scientific support.

C. Carilli - Galaxy formation, radio galaxies, QSO absorption lines; VLA scientific support.

C. Chandler - Star formation, circumstellar disks, protostellar outflows, millimeter-wave interferometry; VLA scientific support.

J. Cheng - Structural engineering and antenna design theory; Antenna Division - ALMA Project.

B. G. Clark - VLBA control and software development; VLA/VLBA scheduling.

M. J. Claussen - Masers, H II regions, molecular spectroscopy, spectropolarimetry, and radio recombination lines; space VLBI support.

J. J. Condon - QSOs, normal galaxies, and extragalactic radio sources; NRAO sky surveys.

T. J. Cornwell - Interferometry, image reconstruction methods, coherence theory, and radio source scintillation; Associate Director, Data Management.

W. D. Cotton - Extragalactic radio sources, interferometry, computational techniques for data analysis; scientific support: NRAO sky surveys and VLBI.

L. R. D'Addario - Telescope design, correlators, millimeter receivers, cryogenics, and radio astronomy from space; Cryogenics - ALMA Project.

V. Dhawan - Extragalactic and galactic jets, and millimeter VLBI development; VLBA scientific support.

D. T. Emerson - Nearby galaxies, millimeter VLBI observations, millimeter instrumentation, and history of millimeter research; spectrum management, ALMA.

J. R. Fisher - Cosmology, signal processing, and antenna design; advanced receiver development.

E. B. Fomalont - Interferometry, extragalactic radio sources, relativity tests; space VLBI coordination.

D. A. Frail - Interstellar medium, pulsars, supernova and nova remnants, and radio stars; on leave during 2002.

R. W. Garwood - Galactic 21 cm line absorption, interstellar medium, and high redshift 21 cm line absorption; AIPS++ Group.

F. D. Ghigo - X-ray binaries, AGNs, interacting galaxies; GBT scientific support (VLBI).

B. E. Glendenning - ALMA Computing.

K. Golap - Wide-field low-frequency imaging; AIPS++.

M. A. Gordon - CO, galactic structure, gas-rich galaxies, and interstellar medium.

W. M. Goss - Galactic line studies, pulsars, and nearby galaxies; on leave during 2002.

E. W. Greisen - ISM structure and computer analysis of astronomical data; AIPS Group.

E. J. Hardy - Cosmology, galaxies, and stellar populations; NRAO general manager in Chile.

J. E. Hibbard - Extragalactic HI, galaxy evolution, and merging galaxies; AIPS++ and REU.

D. E. Hogg - Radio stars and stellar winds, and early-type galaxies; scientific support-VLA.

M. A. Holdaway - Image reconstruction methods and VLBI polarimetry; AIPS++ Group.

G. C. Hunt - Advanced communication technologies for astronomy, real-time computer control techniques; Deputy Assistant Director, Data Management.

P. R. Jewell - Interstellar molecules, molecular spectroscopy; Assistant Director, Green Bank Operations

K. I. Kellermann - Radio galaxies, quasars, cosmology, and radio telescopes; Chief Scientist.

A. J. Kemball - Spectroscopy and polarimetry in VLBI, interstellar masers, and astronomical software; AIPS++ Project Manager.

A. R. Kerr - Millimeter-wave instrument development; SIS design - ALMA Project.

L. J. King - Antenna structural/mechanical analysis, design, and optimization; NRAO antenna engineering.

L. Kogan - Maser radio sources, theory of interferometry, and software for data reduction of VLBI; AIPS Group.

D. Koller - Optical components and cryogenic systems; ALMA.

G. I. Langston - Gravitational lenses and computational techniques for synthesis imaging; space VLBI scientific support.

H. S. Liszt - Molecular lines and galactic structure; foreign telescope travel support program.

F. J. Lockman - Galactic structure, interstellar medium, and H II regions; GB education and outreach, GBT scientific support.

R. J. Maddalena - Molecular clouds, galactic structure, interstellar medium; GBT scientific support.

J. G. Mangum - Star formation, astrochemistry, and molecular spectroscopy of comets; ALMA.

R. G. Marson - Aperture synthesis algorithms, optical aperture synthesis, and imaging stellar surfaces; AIPS++ Group.

M. M. McKinnon - Pulsar astrophysics, polarimetry, stochastic processes; Deputy Assistant Director, VLA.

J. M. McMullin - Astronomical software systems; Deputy AIPS++ Project Manager.

A. H. Minter - Interstellar turbulence and galactic HI; GBT scientific support.

G. Moellenbrock - VLBI polarization, AGN, interferometry calibration and imaging; AIPS++.

S. Myers - Cosmology, cosmic background radiation, and gravitational lenses; VLBA scientific support.

P. P. Murphy - Clusters of galaxies, galaxy evolution, scientific visualization; Division Head, Charlottesville Computing; Webmaster.

P. J. Napier - Antenna and instrumentation systems for radio astronomy; EVLA Project Manager.

F. N. Owen - Clusters of galaxies, QSOs, and radio stars; EVLA and Data Management scientific support.

S. K. Pan - Design of superconducting circuits and SIS devices; CDL device development.

J. M. Payne - Telescope optics, millimeter-wave receivers, metrology systems, and cryogenic systems; Local oscillator development - ALMA.

R. A. Perley - Radio galaxies, QSOs, and interferometer techniques; EVLA Project Scientist.

M. Pospieszalski - Low-noise amplifiers, and theory and measurement of noise in electronic devices and circuits; CDL device development.

R. Prestage - Telescope and instrument control; Deputy AD, Green Bank.

S. J. E. Radford - Starburst galaxies and millimeter interferometry; ALMA Site Testing.

M. Rafal - Electro-optical systems, large project management; ALMA Project Manager.

J. D. Romney - Active extragalactic radio sources, VLBI, and interferometer imaging; space VLBI scientific support, spectrum management.

F. Schwab - Applied mathematics, numerical analysis, radio-astronomical data analysis, synthesis imaging, hybrid numeric/symbolic computing.

D. S. Shepherd - Star formation, molecular outflows, disks around luminous young stellar objects, molecular chemistry, millimeter emission in gamma ray bursts, millimeter interferometry and mosaic techniques; VLA scientific support.

R. S. Simon - Theory of interferometry, computational imaging, and VLBI; scheduling - ALMA Project.

R. A. Sramek - Normal galaxies, quasars, supernovae, and aperture synthesis techniques; ALMA.

G. B. Taylor - Gamma-ray bursts, active galactic nuclei and their environments, polarimetry; VLBA scientific support.

B. E. Turner - Galactic and extragalactic interstellar molecules, interstellar chemistry, and galactic structure; Newsletter editor.

J. Ulvestad - Seyfert, LINER, and starburst galaxies, blazars; space VLBI, VLA Deputy AD.

J. M. Uson - Clusters of galaxies and cosmology; AIPS++ and Newsletter Science editor.

P. A. Vanden Bout - Interstellar medium, molecular clouds, and star formation; Director.

G. A. van Moorsel - Dynamics of galaxies and groups of galaxies, and techniques for image analysis; Head - Socorro Computing.

R. C. Walker - Extragalactic radio sources, VLBI, and VLBA development; VLBA scientific support.

J. C. Webber – VLBI and space VLBI, superluminal radio source structure; Assistant Director - CDL.

D. C. Wells - Digital image processing and extragalactic research; GBT scientific support.

H. A. Wootten - Star formation, structure and chemistry of the ISM in galaxies, and circumstellar material; ALMA Project Scientist.

J. M. Wrobel - Active galactic nuclei, phase calibrators for synthesis arrays; VLA/VLBA scheduling, Observatory user support programs.

Q. F. Yin - Normal galaxies and imaging techniques; NRAO sky surveys.

The Users Committee is made up of users and potential users of NRAO facilities from throughout the scientific community. It advises the Director and the Observatory staff on all aspects of Observatory activities that affect the users of the telescopes. This committee, which is appointed by the Director, meets annually in May or June. The current membership of the Committee is:

Rachel L. Akeson, Caltech, IPAC
David Boboltz, U.S. Naval Observatory
Steven B. Charnley, NASA/Ames Research Center
Christopher G. De Pree, Agnes Scott College
John M. Dickey, University of Minnesota
Jason Glenn, University of Colorado
Lincoln J. Greenhill, Center for Astrophysics
Mark Gurwell, Smithsonian Astrophysical Observatory
Deborah B. Haarsma, Calvin College
Paul T. P. Ho, Smithsonian Astrophysical Observatory
Victoria M. Kaspi, McGill University
T. Joseph W. Lazio, Naval Research Laboratory
Colin Lonsdale, MIT Haystack Observatory
Kevin B. Marvel, American Astronomical Society
David J. Nice, Princeton University
Robert T. Rood, University of Virginia
Evan Skillman, University of Minnesota
Thomas H. Troland, University of Kentucky
Stephen M. White, University of Maryland
Eric M. Wilcots, University of Wisconsin
Christine Wilson, McMaster University
Min Yun, University of Massachusetts
Farhad Yusef Zadeh, Northwestern University

APPENDIX C - NRAO COMMITTEES

The Program Advisory Committee reviews and provides advice on the long range plan of the Observatory, on new programs and projects being considered for implementation, and on the priorities among Observatory program elements. Current membership is:

James M. Cordes, Cornell University

Donald Backer, University of California

Mark Reid, Harvard-Smithsonian, CfA

F. Peter Schloerb, University of Massachusetts

Jean Turner, University of California, Los Angeles

Eric Wilcots, University of Wisconsin

Lawrence Rudnick, University of Minnesota

Lee Mundy, University of Maryland

Christine Wilson, McMaster University

The NRAO Visiting Committee is appointed by the AUI Board of Trustees to review the management and research programs of the Observatory. The Visiting Committee met in Socorro in 1999 and in Green Bank in 2000, and in Charlottesville in 2001. The current membership of the Committee is:

Geoffrey A. Blake, California Institute of Technology

Lincoln J. Greenhill, Harvard-Smithsonian, CfA

Karl M. Menten, Max-Planck Institut für Radioastronomie

Joseph S. Miller, University of California, Lick Observatory

R. Bruce Partridge, Haverford College

Ethan Schreier, Space Telescope Science Institute

Jean F. Turner, University of California

Stuart N. Vogel, University of Maryland

Ralph E. Pudritz, McMaster University

Jacqueline H. van Gorkom, Columbia University

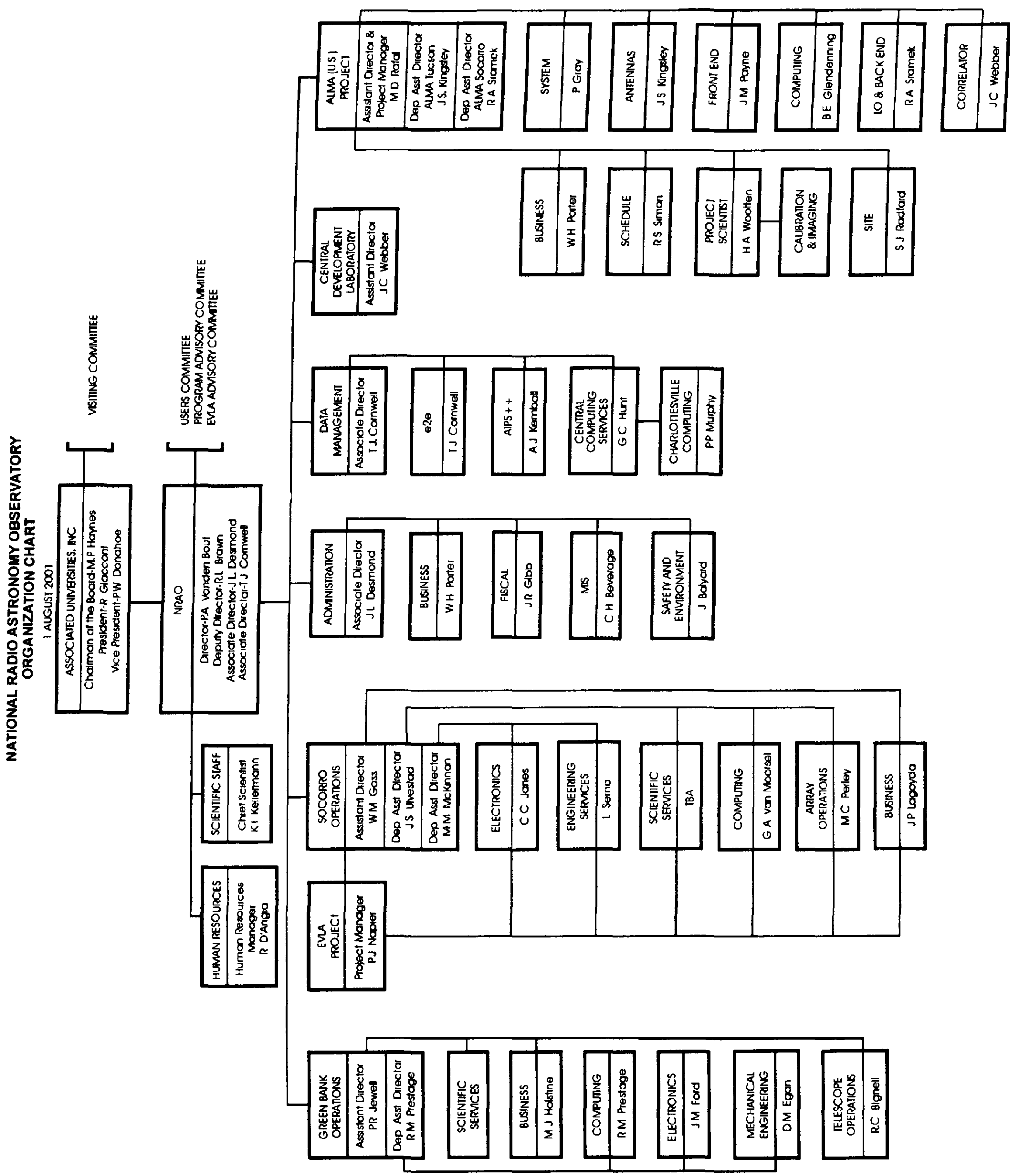
Sander Weinreb, California Institute of Technology

The Atacama Large Millimeter Array (ALMA) project has formed a new committee to provide scientific advice to the project and outreach to the wider community, the ALMA Scientific Advisory Committee. The members of the committee are listed below.

Rafael Bachiller, Observatorio Astronomico Nacional, Spain
Arnold Benz, ETH-Zentrum, Institute of Astronomy
Geoffrey Blake, California Institute of Technology
Roy Booth, Onsala Space Observatory
Leonardo Bronfman, University of Chile
Pierre Cox, Institut d'Astrophysique Spatiale
Dick Crutcher, University of Illinois
Darrel Emerson (ex officio), National Radio Astronomy Observatory
Neal Evans, University of Texas
Yasuo Fukui, Nagoya University
Stephane Guilloteau (ex officio), IRAM
Mark Gurwell, Harvard-Smithsonian Center for Astrophysics
Tetsuo Hasagawa, National Astronomical Observatory of Japan
Ryoahei Kawabe (ex officio), National Astronomical Observatory of Japan
Hiroshi Matsuo, National Astronomical Observatory of Japan
Karl Menten, Max-Planck Institut für Radioastronomie
Naomasa Nakai, Nobeyama Radio Observatory
John Richer, MRAO, University of Cambridge
Seiichi Sakamoto, National Astronomical Observatory of Japan
Nicholas Scoville, California Institute of Technology
Peter Shaver (ex officio), European Southern Observatory
Ken'ichi Tatematsu, Nobeyama Radio Observatory
Masato Tsuboi, Ibaraki University
Ewine van Dishoeck, University of Leiden
Malcolm Walmsley, Osservatorio Astrofisico di Arcetri
William Welch, University of California, Berkeley
Christine Wilson, McMaster University
Al Wootten (ex officio), National Radio Astronomy Observatory

Satoshi Yamamoto, University of Tokyo
Min Yun, University of Massachusetts

The EVLA Advisory Committee will be appointed in late 2001 to advise the director on scientific and technical issues, priority matters, and to assess progress of the project.



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