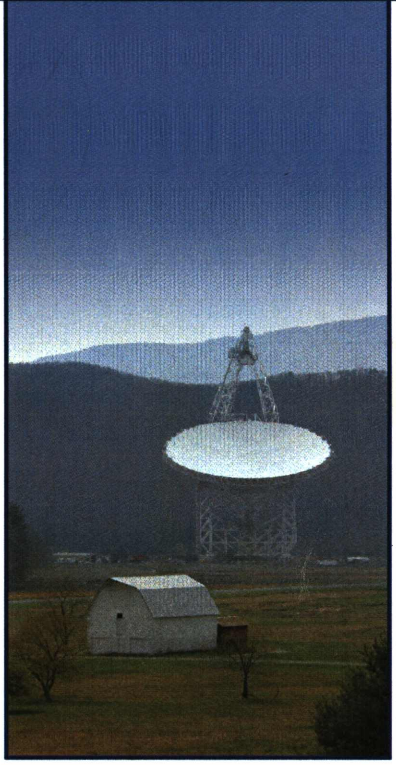
Program Plan 2001



National Radio Astronomy Observatory

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

NATIONAL RADIO ASTRONOMY OBSERVATORY

2001 PROGRAM PLAN

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Mission Statement

The mission of the National Radio Astronomy Observatory 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.

Introduction

The year 2001 will see several major milestones for the National Radio Astronomy Observatory.

It will be the final year of the design and development phase of the Atacama Large Millimeter Array (ALMA). *Although the proposed budget for the NSF will not be public until early 2001, for purposes of planning we are proceeding on the assumption that ALMA construction will begin in FY2002.* The deliverables of the design and development phase will be in hand by that time: an established scope and cost, an international partnership, and a site. Indeed, these deliverables are already available in large part, with substantial progress toward final, official agreements on the international arrangements for a well defined project. ALMA has received top-level endorsements from the astronomy and astrophysics survey review committees of all the participating countries. It is clearly recognized as the most important new ground-based facility required to address the research issues of the new century.

This Program Plan for 2001 anticipates a successful review of the proposal submitted for Phase I of the Expansion of the Very Large Array (EVLA) that will lead to approval and funding for this project. The entire EVLA project, which will improve all the performance specifications of the Very Large Array (VLA) by a factor of ten, was very highly ranked by the Astronomy and Astrophysics Survey Committee. In Phase I 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 over a period of nine years. Phase II will improve angular resolution by adding antennas and distances intermediate to A configuration and the Very Long Baseline Array (VLBA). Studies leading to a proposal for Phase II will begin in 2001.

The year 2001 will be the year for starting operation of the Green Bank Telescope (GBT). The GBT was accepted from the contractor September 2000. Outfitting of the GBT with instrumentation is expected to occupy the remainder of the year 2000, with commissioning of the various observing systems proceeding in a series from low to high frequency throughout much of 2001. A call for proposals for a program of *first science* was issued October 2000. This program will lead to a series of scientific results that demonstrate the capability of the GBT and its instrumentation, starting at long wavelengths and proceeding to the millimeter band. 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 VLBA will be completed in 2001. The primary emphasis of the VLBA program in 2001, beyond millimeter observing, will be to make the VLBA more accessible and user friendly to the astronomical community. Studies of potential long-term improvements will also be made, especially in the area of increasing the recorded signal bandwidth and the possibilities for transmitting antenna signals to the correlator over high-speed data networks rather than using tape.

Three activities cut across all NRAO observing facilities and each require a major strengthening in the year 2001: electronics development in the Central Development

Laboratory (CDL); coordination of computing and software development in a central Data Management office that will also organize new initiatives in data management; and the Observatory program in education and public outreach.

The principal requirement for the CDL is an investment in electronics test equipment that would begin in 2001 and continue for several years. Test equipment is also required at the operating sites, and those needs are included in the CDL program. The CDL also needs a program of investment in advanced Indium Phosphide (InP) transistors and millimeter integrated circuits.

Data Management activities for 2001 include submission of a proposal for establishment of a National Archive for Radio Astronomy (NARA), a cooperative initiative with university groups aiming for funding from the NSF Information Technology Research (ITR) program. NARA is a prerequisite to the participation of radio astronomy in the National Virtual Observatory (NVO), a data archive with mining tools that is to stretch across all wavelengths. NARA is also essential to NRAO's goal of establishing an end-to-end data management system for the users of its facilities. Other Data Management activities for 2001 include significant expansion of AIPS++, and continued coordination of NRAO computing.

During 2000 the Observatory expanded its Education and Public Outreach function and this will continue in 2001. The re-work of all brochures, posters, and displays will continue. A new education center in Green Bank will be built and plans will be developed for a new education center at the VLA site. The NRAO web site will be improved and multimedia products presenting NRAO facilities and projects will be offered.

A major goal for 2001 is the establishment of stronger communications with the astronomical community, increased involvement of the community in strategic planning, and additional support for university-based radio astronomy groups. Following the recommendation of the U.S. Astronomy and Astrophysics Survey Committee that grants of observing time be accompanied by funds to support observing on ground-based telescopes, as is done for space missions, we are proposing to initiate such a program for observing programs on NRAO telescopes that involve student dissertations.

In this Program Plan a description of NRAO current status and goals for 2001 are presented. This Plan is written to two levels of funding: that of the NSF request for the NRAO for 2001 (a flat budget of $32M), and that corresponding to our mission requirements. A flat budget will continue the long pattern of stagnation at the Observatory despite the extra resources provided by the closure of the 12 Meter Telescope. Normal increases in operating costs due to inflation, program demands that cannot be postponed any longer such as non-competitive salaries for technical staff and increasing the pace of the VLA maintenance program, together with the cuts in available resources from reductions or outright loss of programs funded by other agencies, exceed the cost savings from closure of the 12 Meter. The program *required* to accomplish our long term mission is presented as a set of initiatives, with costs and schedules, throughout the description of the 2001 program. The section giving the "Organizational Plan" summarizes both budget levels in two columns: "Presidential Budget Request" and "Mission Requirements."

Unless resources beyond the flat budget scenario can be found, in a combination of new initiatives and an increase to the base budget, the Observatory will once again be forced to search for ways to reduce its scope of activities.

Scientific Programs in 2001

Very Large Array

In celebrating the 20th anniversary of the VLA in 2000, we looked back on more than 10,000 completed observing projects, many of which have had major impacts across the entire breadth of astronomy. The VLA enters its third decade of full operation as 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 NVSS and FIRST surveys remains 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

At the end of 2000, the Cassini spacecraft, on its way to Saturn, will pass by Jupiter, coming within about 140 Jupiter radii of the planet. The spacecraft's instrumentation will study Jupiter for several months during the flyby period. Two teams will use the VLA to observe Jupiter at wavelengths ranging from 3.5 to 90 cm during the flyby period, to construct 2-D and 3-D maps of the planet. The VLA data will be compared to Cassini data at IR, visible and UV wavelengths, as well as data taken simultaneously by the Galileo (in-situ solar wind and magnetospheric measurements) and Chandra (X-ray) spacecraft. The research is expected to shed new light on the mechanisms of Jupiter's thermal and synchrotron radio emission.

Using the NVSS, observers have identified radio sources that may be occulted by Saturn's ring system over the next four 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.

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

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.

Taking advantage of the increased number of Q-band (40-50 GHz) receivers as well as the availability of the Pie Town link, observers will seek to discover and precisely locate stars with SiO masers within about 10 arcseconds of Sgr A* at the Galactic Center. The new VLA capabilities will provide these researchers with twice the sensitivity and four times the resolution previously available for such studies. They will use the VLA images of the SiO masers to calibrate and register infrared images and locate Sgr A* to within one milliarcsecond on the IR images. This will allow them to establish their IR luminosity, to check for gravitational lensing of background stars, and to calculate stellar orbits in the region, where IR star proper motions are showing curvature. The greatly improved position for Sgr A* should allow the observers to determine if Sgr A* lies at the focus of the stellar orbits, thus providing unequivocal confirmation of its status as a supermassive object.

The pulsar PSR B1951+32 in the supernova remnant CTB 80 will be observed in an attempt to determine its proper motion. Observed with the VLA in 1989-93, this pulsar is thought to be much older than most pulsars associated with SNRs, while the SNR itself has an unusual morphology. The anomalies can be explained if the pulsar is catching up with and penetrating its own blast wave. Accurately determining the proper motion will provide a critical test of this model.

Four Galactic supernova remnants will be observed at low frequencies (74 and 330 MHz) to study absorption from low density ionized gas in the interstellar medium. The observations will help constrain the physical size of the absorbing gas and to differentiate between absorption mechanisms internal and external to the SNR. In addition, the resulting images can be used to test the predictions of shock acceleration in SNRs, which is a leading candidate for the source of Galactic cosmic rays.

Wolf-Rayet galaxies are galaxies showing evidence of extraordinary numbers of young, hot massive stars, many hidden by dust, formed during short, intense starbursts. As such, they are expected to harbor large numbers of radio supernovae. Some 20 relatively nearby Wolf-Rayet galaxies will be observed in an attempt to detect radio supernovae. The results are expected to yield new information on the starburst phenomenon. Also, since many radio supernovae found in these galaxies are expected to arise from very massive (greater than 20 Solar masses) stars, and there are few well-studied examples of such radio supernovae, the results may have implications for theories of stellar evolution.

In 1999, the Chandra satellite found an X-ray point source near the center of the supernova remnant Cassiopeia A. The VLA will be used to make a deep radio search for a radio counterpart. The objective is to determine the nature of the X-ray source—is it the long-sought neutron star remaining from the supernova explosion, or a chance juxtaposition of an X-ray binary or background quasar?

The Galactic microquasar GRS 1915+105 was the first Galactic object to display superluminal motion, discovered with the VLA in 1994. The target of numerous subsequent observations at many wavelengths, this binary system will be observed by the VLA in conjunction with simultaneous observations at X-ray (XMM) and infrared (ESO) wavelengths. The coordinated observations are aimed at providing an understanding of the mechanism that "evacuates" the accretion disk during the observed sudden drops in the X-ray luminosity and the production of the radio jets. The new data also may provide clues to understanding the quasiperiodic variations seen in the thermal X-ray and synchrotron radio and IR emission.

Scientific Programs in 2001

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

Using the VLA's expanded set of Q-band (40-50 GHz) receivers, along with the Pie Town link, researchers will make a survey of late-type stars to seek SiO maser emission from their stellar envelopes. They will seek to map the maser emission from semi-regular variables, Mira variables, supergiants and OH/IR stars. The hope is to correlate the degree of asymmetry in the maser shells with stellar type in order to better understand the evolution of these stars along the asymptotic giant branch toward the planetary-nebula stage. Another study, also at Q-band, will image the radio photospheres of a sample of long-period Mira variables. This study will image the radio photospheres in the region where dust is expected to be forming, and will produce data constraining physical models of this region and perhaps help explain how material is transported above the optical photosphere into this region.

Both 1.3 cm continuum and water-maser emission from a sample of young stellar objects (YSOs) will be observed, using the strong masers for cross calibration to achieve high positional accuracy. The resulting data will provide high-resolution images of the YSO continuum emission, including images of jets. This will allow the researchers to make a statistical study of radio jets in YSOs and to study the positions and kinematics of the masers, all with the aim of understanding the roles of jets and circumstellar disks in the process of star formation. In particular, it is hoped to learn from this study if the presence of radio jets and the spatial distribution and observed kinematics of water masers is an indicator that circumstellar disks are present.

A very active Class 0 YSO in Serpens periodically ejects material into an active radio jet in which knots display readily-measurable proper motion. A central radio source in this object is elongated and its orientation is different every time there is an ejection, presumably because of precession. A monitoring program will seek to measure this precession, as well as the proper motions and brightness changes of the knots. This offers a unique look at a young, active, precessing object, and will help the research team constrain numerical models that they are developing.

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 specifically geared 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.

The FU Orionis objects are young stars that increase greatly in brightness on timescales of months. The brightening has been attributed to an increase in the mass accretion rate of the protoplanetary disk. However, some of these objects recently have been shown to be close radio binaries. This discovery suggests that the brightening could instead be caused when orbital motion reveals the brighter of the binary components as it comes out of occultation by the other star's accretion disk. An example of this type of object, V1057 Cyg, will be observed to test this hypothesis.

Observations using the Pie Town link will seek to provide unique information on a tantalizing radio source in the Orion BN/KL star-forming region. The source is thought to be a high-mass protostar with a jet and disk surrounded by dense, hot gas with SiO maser emission. Other observations of this region will follow-up earlier studies and provide information about the possibility of variability in radio sources that may have X-ray counterparts recently discovered by Chandra.

While ultracompact H II regions have been known for nearly 20 years, a smaller and denser class of H II regions, dubbed "hypercompact" H II regions, has been found only in the past few years. The nature of these hypercompact regions is not clear; they are alternatively considered as either H II regions that formed in very dense and high-pressure environments or very young regions just beginning their expansion phase. A high-resolution, multifrequency VLA study will seek to find more hypercompact regions and to better characterize those already known.

T Tauri, the prototype for an early-type star, is a complex system that has been observed at optical, infrared, and radio wavelengths. T Tauri is a double system where one component is bright at optical wavelengths and the other at IR. The optically-bright component has a radio counterpart at the same position, but the IR-bright source is not at the same position as its presumed radio counterpart. Recent work has indicated that this second source may itself be a binary. VLA observations will seek to learn if the radio source is coincident with the companion and, if so, to estimate orbital elements. The study also will seek to determine the nature of the mechanisms producing the radio emission.

Normal Galaxies

An increasing body of evidence is mounting that nearly every galaxy contains a black hole. An optical spectroscopic survey showed evidence for a black-hole-powered low-luminosity active nucleus in about half of nearby bright galaxies. Dynamic studies are increasing the number of galaxies whose black hole masses can be estimated. The VLA and VLBA have proven to be efficient tools for finding the radio sources diagnostic of accreting black holes. VLA studies of a population of low-luminosity Seyferts and LINERS will seek to determine the true incidence of accreting black holes, with important implications for models of galaxy and black hole formation and evolution.

The nuclear region of M82 will be observed to monitor the flux density of 24 compact radio sources, presumed to be supernova remnants. This monitoring program goes back to 1981, so the time base for studying flux-density variation, so far detected in two-thirds of these sources, will be extended to 19 years.

Scientific Programs in 2001

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

In an effort to test unification models for active galactic nuclei (AGN), observers will seek evidence of H I absorption in the cores of some relatively nearby narrow line radio galaxies. According to the unification schemes, the absorbing H I in these cores should reside in the obscuring torus surrounding the active nucleus. The VLA observations will seek to map the absorption with sufficient accuracy to test the unification hypothesis.

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, and since then 15 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.

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

The International Celestial Reference Frame (IRCF) is defined by the VLBI-determined positions of extragalactic objects. The Full-sky Astrometric Mapping Explorer (FAME) satellite, scheduled for launch in 2004, is expected to 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 IRCF. Using the Pie Town link to improve resolution, VLA observers will precisely measure the positions of some 50 radio stars in order to allow accurate linking of the FAME and IRCF reference frames.

A pair of VLA observing projects will greatly augment ongoing studies using the SCUBA submillimeter facility on the James Clerk Maxwell Telescope. Very deep VLA studies will be made of fields observed in a deep SCUBA survey. The added resolution provided by the VLA will allow the researchers to identify radio counterparts to the submillimeter galaxies and determine some of their morphological and spectral characteristics. The spectral index between the VLA 20 cm observations and the SCUBA 850 micrometer observations will help constrain the redshifts of these objects. Another, similar study will focus specifically on fields centered on very distant, luminous radio galaxies and quasars. This study will attempt to test hierarchial models for galaxy formation that predict clustering of massive galaxies in the early universe. Deep VLA images of these fields will identify radio counterparts to the submillimeter sources seen near the bright radio galaxies and quasars, and the redshift constraints provided by the spectral indices will test the clustering hypothesis.

Following up on pioneering work on deep imaging at 73 MHz using the new VLA receivers for that wavelength, observers will search at higher frequencies for evidence that may reveal the first radio-bright quasars at redshifts greater than four. Detection of such objects is needed to address unresolved questions about the features of galaxy-galaxy mergers that trigger AGN activity in the early universe and whether there is evidence for evolution of the torus in such young objects.

Increasing computer power and improved software are allowing observers to tackle low-frequency projects that were not feasible a few years ago. One 327 MHz project will study a field already imaged deeply by optical, infrared and 20 cm radio observations. The result will be the first deep radio source identifications at such a low frequency and new information on the radio spectral properties of elliptical, starburst, and high-redshift radio galaxies as well as other types of AGNs.

The VLA will continue its prominent role in searches for and studies of gravitational-lens systems. Candidate radio sources are systematically observed 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. 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

With the routine capability to produce images with milliarcsecond resolution, 10 to 100 times better than that of the Hubble Space Telescope, the VLBA remains a valuable and popular tool for a wide range of astrophysical inquiries. Newer capabilities such as pulsar gating and the growing suite of 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

The resolving power of the VLBA will allow observers to measure parallaxes and proper motions of three 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.

Observers will use the VLBA to study three Galactic supernova remnants to study the Zeeman effect on the emission of OH masers at 1720 MHz. The three SNRs are at different distances, and the study seeks to understand if observed SNR magnetic-field strengths depend on resolution by comparing the VLBA Zeeman observations with similar VLA A configuration observations. In addition, the range of distances also will help determine if interstellar scattering affects the observed sizes of such masers, as has been suggested by previous observations.

The RS CVn binary system UX Arietis will be observed at intervals over the course of one orbital period of more than six days. The objective is to make high-resolution polarization measurements that will reveal the structure of strong magnetic loops believed to have sizes comparable to that of the binary system itself.

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

It is generally recognized that magnetic fields play an important part in star formation, and the Zeeman effect is the most direct method for measuring the strength of magnetic fields in star-forming regions. The relationship between magnetic field strength and gas density is an important parameter, but there is little information available about this relationship at high densities. Observers will use the VLBA to measure magnetic field strengths in high-density regions using the 22 GHz water-maser line. In particular, they will follow-up on an observation in which VLBA data showed that a maser seen in a VLA image was, in fact, three distinct masers, whose lines were offset so as to partially wash out the Zeeman effect and yield an inaccurate field-strength estimate. The new VLBA observations will seek to learn if such an effect also is present in other star-forming regions.

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

The VLBA's discovery of a rotating disk with water masers in the nucleus of the galaxy NGC 4258 has produced extremely valuable results. These include a measurement of the mass of the galaxy's central black hole, and, using proper-motion measurements of the maser spots, a direct geometric measurement of the galaxy's distance—a measurement now being used to recalibrate the entire extragalactic distance scale. Nuclear water masers in another galaxy, NGC 5793, discovered in 1996, now are flaring, and observers will take advantage of this to make high-resolution VLBA studies aimed at clarifying earlier indications that this galaxy, like NGC 4258, also has a rotating maser disk at its center.

A high-frequency polarization study of a number of active galactic nuclei will be completed, providing statistically-complete data on the connection between the parsec-scale magnetic fields of AGN jets and their overall properties. The sample has been studied extensively at a variety of wavelengths and angular scales, and the new VLBA data should provide valuable information on the properties of the cores and jets, including differences in magnetic-field properties that could test models seeking to account for the differences between BL Lac objects and quasars.

Scientific Programs in 2001

The high resolution of the VLBA provides a unique capability to investigate the ubiquitous phenomena associated with the central engine of quasars and active galactic nuclei. Time lapsed movies show direct evidence for highly collimated relativistic motion in quasars and AGN with apparent velocity typically 5 to 10 times the speed of light. New observations are planned to answer the questions: Where does the relativistic flow get accelerated and collimated to form jets? Does the flow follow curved or straight trajectories? Do different features within a jet follow the same or different trajectories? Do they have the same or different speeds? Are there accelerations or decelerations? Is the apparent velocity related to luminosity, X-ray or gamma-ray emission? Or to anything else? Is the time of appearance of a new component emerging from the nucleus related to the start of a flux density outburst? Are there any observed differences in the kinematics of radio galaxies, quasars, or BL Lac Objects? Are the simple ballistic models correct, or are there differences between the bulk flow velocity and the pattern velocity as might be expected if the observed motions are due to the propagation of shocks rather than the flow of material. The new 3 mm receivers which will be implemented during the year 2001 will eventually provide a factor of two improvement in resolution, allowing observations as close as a few hundredths of a light-year to the putative black hole in nearby AGN. The analysis of observed angular velocity vs. redshift may also provide a powerful measure of the matter density of the universe.

A multifrequency project to observe four BL Lac objects over the course of a year will seek to resolve outstanding questions about the velocities of ejected jet components near the cores. Separate, earlier observations have suggested that the observed proper motions may depend on the observing frequency. The new, multifrequency program seeks to resolve this question.

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 colimation of relativistic jets.

In some radio galaxies with a symmetric two sided structure, the appearance of the source is frequency dependent suggesting free-free absorption from a thin disk or torus, probably associated with the accretion disk surrounding the central engine. Planned new observations will provide a unique means to directly study the accretion on to a massive black hole from the surrounding disk or torus, where the density of the ionized material is of the order of $10^{4\text{-}5}$ cm^{-3} within one parsec from the black hole (e.g., this is comparable to the density of the optical broad-line emission region suggesting that the two may be identical). Other observations will image the neutral hydrogen content in the circumnuclear environment around AGN.

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

Damped Lyman-α systems seen in the spectra of background quasars indicate the presence of an intervening mass that, while raising the possibility of gravitational lensing, is insufficient to produce multiple lens components separated by more than a few milliarcseconds under expected observational conditions. Observers will search a sample of damped Lyman-α systems in hope of finding multiple images of the quasar's core at such separations. If successful, they will have found a new class of gravitational lens; if unsuccessful, they will place limits on the properties of the intervening masses.

Continued observations with the VLBA of reference stars for the Gravity Probe-B will be used to increase the precision of this NASA mission which will make a new test of General Relativity.

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

Green Bank Telescope

Much of 2001 will be devoted to commissioning the GBT, but some visitor observations will begin during the year. The first observations will be at the lower frequencies, and will allow, for example, H I and OH spectroscopy and pulsar projects. By late 2001, frequencies approaching 50 GHz will be possible, which will open up the full range of projects mentioned below. The point source sensitivity, high fidelity response, frequency range and agility, and location in the National Radio quiet zone, 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. We can anticipate some of the early uses of the facility.

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. For example, a galaxy with a redshift of 4 will have its CO (1-0) emission (115 GHz rest frame) redshifted to 23 GHz, its CO (2-1) (230 GHz rest frame) redshifted to 46 GHz, its CO (3-2) emission (345 GHz rest frame) redshifted to 69 GHz, and its CO (4-3) emission (460 GHz rest frame) redshifted to 92 GHz. These important lines are all shifted into the frequency bands for which the GBT has excellent gain. The GBT can also be used at lower frequencies to study high redshift OH megamasers and high redshift H I. The comparatively good RFI environment in Green Bank will be a great advantage to these low frequency projects, which are often precluded elsewhere.

Scientific Programs in 2001

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.

H I, OH Spectroscopy

Observations of neutral hydrogen and the hydroxyl radical will greatly benefit 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 21 cm H I profiles can be done quickly and routinely. This will be of benefit to those who need to correct for Galactic interstellar absorption in observations of extragalactic objects in the UV and soft X-ray, for studies of the soft X-ray background, and for comparisons of 21 cm H I spectra with spectra of other species. The low sidelobes of the antenna will make possible study of faint H I in the galactic halo and studies of the energetics of the ISM, which depend on very accurate measurement of the wings of Galactic H I profiles. 21 cm H I profiles from the GBT should have unsurpassed dynamic range and accuracy of calibration.

Pulsar Observing

Pulsar observations, such as searches toward the Galactic Center, will benefit from the GBT's large collecting area, sensitive receivers, excellent sky coverage, and the comparatively low RFI at the site. Both interstellar scattering and the dispersion caused by frequency, make pulsars difficult to detect. The sensitivity of the GBT will allow pulsar observations at high frequency (5 GHz and higher) where the effects of pulse broadening are not as pronounced.

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. There is increasing interest in interstellar molecules of biological importance as they may have influenced the formation of life on Earth. The sensitivity, clean beam, and low standing wave response of the GBT, together with its frequency agility and wideband spectrometer, will be invaluable in studies of heavy molecules.

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. This added sensitivity may allow a large number of projects that were not possible before, including observations of small, solar system objects.

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. 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.

Instruments

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 2000 and a similar or larger number will do so in 2001. Demand for the VLA arises both from the multiwavelength nature of contemporary astronomical research and from the flexibility of the telescope. 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 that 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. 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 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.1. 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	160[2]	Cryogenic HFET
40.0	to	50.0	95[3]	Cryogenic HFET

[1] T_{sys} includes galactic background.
[2] Sixteen antennas have new systems with T_{sys}(K) = 55K.
[3] Twenty-five antennas equipped by end of 2000.

Ongoing Initiatives

High Frequency Systems

During 2000, 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 National Science Foundation and additional funds from the Max Planck Institut fur Radioastronomie. In addition, 16 antennas have new 22 GHz systems, with T_{sys} of 55 K vs. ~160 K for the older receivers. AIPS software has been enhanced and tested to make proper use of the weights for an array of antennas with quite different sensitivities, applicable at both higher frequencies; this capability should be commonly employed by users in 2001.

Components for four additional VLA 22 GHz receivers were purchased in 2000. If funds are made available early in 2001, the receiver fabrication will proceed following the plan outlined below:

Table IV.2 K-band Cost

	2000	2001	2002
22 GHz Receivers			
Parts Cost	$140k	$280k	$170k
Purchase components	#17 - #20	#21 - #27	#28 - #30, plus spare components
Fabricate Rcvrs	#13 - #16	#17 - #23	#24 -#30
43 GHz Receivers			
Parts Cost	----	$300k	-----
Purchase components	----	#26 - #30 plus spare components	-----
Fabricate Rcvrs	#19 - #25	#26 - #28	#29 - #30

Note: The K-band cost shown here differs from than that shown in the EVLA plan since the EVLA plan includes retrofitting the existing receivers to be compatible with the EVLA IF system

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 last few problem areas in using the link were corrected and operational details worked out.

Proposals were accepted for use of the Pie Town link in the A configuration from October 2000 through January 2001, and about 20 observations were scheduled using the link. Use of the link necessitates the loss of two antennas from the VLA, one for use of its back-end electronics, and one to replace Pie Town in the VLBA. In 2001, the success of the link will be assessed, and further improvements made in the hardware and the calibration process, as necessary. The option for 70 MHz bandwidth (see below) will be added on the Pie Town link, and the possibility of simultaneously using Pie Town with both the VLA and the VLBA will be explored. It is anticipated that the link will be made available again in the next A configuration, beginning in early 2002.

Software

A new program has been released for scheduling VLA observations. JOBSERVE 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. In 2001, it is expected that JOBSERVE will take over the bulk of the VLA scheduling from OBSERVE.

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 2001, design and coding will continue. An important aspect will be understanding and designing the interface to the new correlator system that is anticipated for the EVLA.

In the second half of 2000, a significant increase has been made in the scientific staff effort to test the AIPS++ software, with a specific goal of enhancing the capability to reduce VLA data in a routine way. This effort will continue in 2001. The plan calls for AIPS++ to be capable of processing more than half of all VLA observations by the end of the year.

Infrastructure

Significant infrastructure developments during 2000 and planned for 2001 include:

- During 2000, the VLA intermediate-frequency system was retrofitted to permit observations with an effective maximum bandwidth of 70 MHz, up from the 46 MHz currently available. In 2001, the 70 MHz bandwidth will be made available to all users, with the higher bandwidth supported in the new JOBSERVE software.
- 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. Work on the IRIDIUM filters has been temporarily halted while the fate of the satellite constellation is clarified.
- 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. Outfitting of VLA antennas with the new encoders is expected to be complete by 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. Its potential for making real time error corrections to the antenna servo system for precision pointing will also be investigated in 2001.
- There are four remaining telescopes with bad azimuth bearings (see VLA test memo 195). A three-year plan to replace four azimuth bearings beginning in 2001 would require the purchase of two new bearings at the cost of around $45k each, and the refurbishment of one other bearing at the cost of $25k.
- Panel adjustments based on holographic observations at 22 GHz will be completed by the end of 2000. In 2001, panels will be readjusted with holographic observations using the completed 43 GHz system; the goal is 30-40 percent aperture efficiency on all antennas at 7 mm.
- 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. Nearly 5,000 ties were replaced in 1998 and more than 4,000 in 1999, to initiate a program of bringing the track system up to the minimum federal standard for a low speed, light duty track system. Calculations show that the program must continue at the level of 5,000 ties per year for 20 years to achieve this standard. If funding levels improve, resumption of a tie replacement program of 5,000 ties per year and leveling of 2.5 kilometers of track will be planned. In addition, the replacement of approximately 2,000 ties to repair of the worst tie clusters in the array is desirable. At $68 per tie (including temporary labor of $13 per tie), this plan will cost $340k a year. A savings could be realized if we were to stockpile ties and ballast for two years. The optimum level of stockpile at any one time is 20,000 ties and 25,000 tons of ballast. If funding levels remain the same as in 2000, a concentrated effort to repair the worst bad tie clusters will resume in 2001.
- Antenna painting: all quadrupod support legs on the VLA antennas have now been painted and three antennas were completely painted in 2000 bringing the total number of antennas completed to 19. Painting VLA antennas was initiated in 1993, beginning with antennas most obviously stained with rust; three more antennas will be scheduled for painting in 2001.
- Several safety initiatives were undertaken to protect our workforce: (i) A workable fall arrest system has been designed and developed to provide access to the antenna apex in accordance with OSHA regulation. Once the prototype has been approved, the fall arrest system will be installed at the VLA by the end of 2001. (ii) A guardrail system was also designed to protect employees working at the antenna apex. Guardrail installations began January 2000 and should be finished by 2001. (iii) A dish hatch access ladder is undergoing testing to make ascensions into the antenna dish safer, and will be installed during the three-year overhaul cycle.
- Replacement capital equipment is required for maintenance and operations support. In 2001, we require a grader ($200k), a bobcat ($22k) and four new hydraulic pumps for one transporter ($120k).

Table IV.3 Infrastructure Maintenance and Operations Request for 2001

	FY 2001 ($k)	2 yr Stockpile ($k)
5,000 Ties + equivalent ballast	340	
Tie and ballast stockpile		825
Azimuth Bearing Replacement (new bearing + related hardware)	65	
Azimuth Bearing stockpile (1 rebuilt + 1 new)		70
Transporter Pump Replacement (transporter # 1)	120	
Equipment Replacement		
Blade (Road Grader)	200	
Bobcat	22	
Rebuild Hurco CNC Mill	20	
Total	**$767**	**$895**
Sum of Totals ($K)		**$1,662**

Very Long Baseline Array

Present Instrumentation

The VLBA is a dedicated instrument for very long baseline interferometry (VLBI), with ten antennas distributed about the U.S. in a configuration designed to optimize 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.4 summarizes the performance of the ten frequency bands for which the VLBA is outfitted, all with dual circularly polarized receivers. The antennas are remotely operated 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.4. VLBA Receiving Systems

Frequency Range (GHz)	Typical Zenith SEFD (Jy)	Typical Zenith Gain (K Jy)
0.312 to 0.34	2217	0.097
0.596 t 0.62	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] Fort Davis, Los Alamos, Pie Town, Kitt Peak, and Owens Valley installed

Ongoing Initiatives

High Frequency Systems

The major new capabilities expected for the VLBA in 2001 are in the area of high-frequency performance. Specifically, the expected outfitting of six antennas at 86 GHz by the end of 2000 will enable a stand-alone observing capability for the VLBA at this high frequency. Proposals for this capability were accepted at the October 2000 deadline, and the first scheduled observations will take place between February and May 2001. It is anticipated that an additional two antennas, for a total of eight, will be outfitted in 2001. The implementation of systems 5 through 8 has been made possible by funding from the Max Planck Institut fur Radioastronomie. The last two VLBA antennas will not be outfitted until additional funding is secured.

In order to take full advantage of the 86 GHz observing capability, work is planned on a number of fronts during 2001. The pointing performance will be improved by application of the offsets caused by the azimuth rail heights before solving for the rest of the pointing terms; this has been shown to give a significant improvement for Los Alamos in 2000, and will be implemented at all stations by the time 86 GHz proposals are scheduled. As discussed in the infrastructure section, work is proceeding on a local holographic system to improve the antenna surfaces and the 86 GHz aperture efficiency to ~30 percent or better. Progress in 2001 will depend on the availability of funding.

Dynamic Scheduling

Dynamic scheduling has progressed well in 1999 and 2000, with about 40 percent of VLBA observing time now scheduled with a lead time of less than two days. In 2001, the lead time will be shortened as much as possible in order to provide the highest probability that 86 GHz observing will be scheduled during the best weather conditions.

Wideband Recording

Finally, it is expected that all VLBA stations will be equipped with a 512 Mbits per second observing capability by early 2001. This feature will be useful at all frequencies, but especially important at 86 GHz, where continuum observations are typically sensitivity-limited. Operational (tape-changing) constraints will, however, limit the full use of the 512 Mbit per second mode.

User Support

Over the course of 1999 and 2000, a number of initiatives have been started to make the VLBA more user friendly. These have included automatic tape allocation, automated transfer of calibration data, and improved documentation of phase referencing and the entire calibration process. In 2001, the new correlator at the Joint Institute for VLBI in Europe (JIVE) is expected to be fully operational, and will take over the correlation of European VLBI Network (EVN) projects and some global observations. This will permit increased concentration on making the stand-alone VLBA simpler to use. The availability of data reduction scripts in AIPS will be increased. Funding permitting, there will be an effort to provide calibrated data to some users making routine observations. Although delayed somewhat from previous plans, it is anticipated that there will be some significant VLBI capability in AIPS++ by the end of 2001, perhaps simplifying the data-reduction path.

Infrastructure

Significant infrastructure developments during 2000 and planned for 2001 include:

- An enhanced correlator model has been implemented, using the new version of the CALC software developed by NASA's Goddard Space Fight Center with assistance from other geodetic VLBI groups. The improvement in the handling of effects such as precession and nutation has significantly enhanced phase-referencing observations with the VLBA, as have various means of applying ionospheric corrections. These improvements, together with the previous implementation of gating in the correlator, mean that pulsar observations are now fairly routine.
- VLBA Holography. The advent of 86 GHz observing on the VLBA has led to concern about astigmatism of the subreflector surfaces and adjustment of the main

reflector surface panels. Testing of a holography system is currently in progress using a one meter reference antenna attached to the main reflector. If the holography data shows a need to resurface the subreflectors, then the design and development of a resurfacing tool will begin in the year 2001.

- VLBA antenna painting to maintain structural integrity at the "wet" sites is ongoing. North Liberty and Hancock will be reevaluated in 2002. Painting will continue in 2001 at St. Croix.
- 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. Bearing inspections are conducted with every major maintenance visit. Hancock will require a wheel assembly replacement during its next maintenance visit in year 2002.
- 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 telescope sites are targeted for completion in 2001.

Green Bank Telescope

When it begins routine operation during 2001, the GBT will be the most powerful single telescope ever built for radio wavelengths. The GBT is a very advanced and versatile telescope 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 is designed to cover ~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.

Major commissioning milestones for the GBT are listed in the table below. Further information on commissioning and early operations is provided in the document *GBT Comprehensive Management Plan*, available upon request. Other information on the GBT is available on the NRAO web pages at www.nrao.edu/GBT.

Table IV.5 Milestones for Commissioning and Early Operations of the GBT

Milestone	Date
Acceptance of the GBT from the contractor	2000, September 28
Basic outfitting with NRAO equipment completed	2000, October 30
Prime Focus 1 Receiver (290-920 MHz) Commissioned	2001, January 15
Phase I (15 GHz) operation achieved (L, S, X Gregorian Rx's Commissioned)	2001, March 31
Active surface operating in open loop	2001, June 30
Phase II (50 GHz) operation achieved (K & Q Gregorian Rx's Commissioned)	2001, August 31
Active surface / metrology system in closed loop operation	2002, August 31
Phase III (100 GHz) operation achieved	2002, October 31

An initial call for "Early Science" proposals for the GBT has been issued. The aim of this call is to attract proposals for significant investigations made possible by the unique features of the GBT. The call for proposals is described at www.nrao.edu/GBT/proposals.

After taking receipt of the antenna from the contractor the NRAO began outfitting and commissioning it for operation as a radio astronomy observatory. Owing to the complexity of the design and the enormous frequency coverage of the telescope, the commissioning and the introduction of visitor observing will be 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. This will require, among other things, control of the active surface by look-up table. Progression to 100 GHz+ operation will proceed directly from this point as expeditiously as possible.

The commissioning plan calls for an initial period of commissioning of lasting six months. During this stage, the NRAO staff will install electronic subsystems for computer control, receivers, IF transmission, etc. Basic operational features of the telescope will be tested during this period including telescope pointing and tracking, initial setting of the surface figure, low frequency receivers at the prime and Gregorian foci, etc. This commissioning period will be performed largely by NRAO staff. At the end of the initial commissioning period, the telescope should be ready for observations at frequencies up to 15 GHz. Visitor observations at these frequencies would be allowed for a limited fraction of the time while further commissioning proceeds.

The second stage of commissioning will refine the operation of the telescope in general, the requirements of higher frequency capability in particular, will implement open loop control of the active surface, and will commission receivers up to 50 GHz. This stage is expected to be completed within about one year of the time the telescope is received from the contractor. As this stage of commissioning progresses, an increasingly higher percentage of scientific programs will be scheduled.

The final stage of commissioning will allow operation to frequencies up to 115 GHz. This requires that the active surface and telescope pointing and tracking systems be brought under closed-loop control with the laser metrology system. This capability should be available within 24 months from the time NRAO receives the telescope. During this stage of commissioning, a sizeable percentage of available time can be devoted to visitor observing of scientific programs.

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 over 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 that will reduce astronomical and terrestrial confusion from stray radiation from the sky and man-made 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 attack a wide range of astrophysical problems. It will cover more than three decades of observing frequency (~100 MHz to ~100 GHz). 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 for wideband spectroscopy. The telescope will be equipped with back-end for spectroscopy, continuum, pulsars, and VLBI.

Complementarity with the VLA, VLBA, and ALMA

The attributes of the GBT will give the NRAO a powerful, comprehensive observing capability. The GBT will be capable of efficiently providing 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.

National Radio Quiet Zone

Green Bank is situated in a 13,000 sq. mile region known as the National Radio Quiet Zone (NRQZ). The location of the GBT in the NRQZ is a unique attribute that allows observations to proceed at frequencies that have been virtually eliminated at other observatories by the ever-increasing presence of RFI.

By Federal regulation, no transmitters can be erected in the Quiet Zone unless their emitted power falls below prescribed 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 U.S. 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 significant effort by the NRAO during 2000 and the years beyond.

Early Science Proposals

The Green Bank Telescope saw first light at 403 MHz on 22 August 2000. Commissioning will begin this fall at low frequencies (< 5 GHz). The frequency limit will rise steadily, and should reach 50 GHz within one year, with plans for 100 GHz operation within two years. The NRAO will schedule a small number of early science projects during the commissioning process as the observing capability and frequency range permit. These projects will ideally utilize one of the unique capabilities of the GBT—unblocked optics, large fully-steerable aperture, active surface and metrology systems, wide bandwidth spectrometer, and Quiet Zone location—and should offer the possibility of significant and unique scientific results.

A special call for proposals was made in the NRAO Newsletter and the AAS exploder in October 2000. This call is intended for experienced observers willing and able to perform observations in a commissioning environment. Further calls for proposals aimed at a wider audience will be made in 2001 as significant classes of capabilities are fully commissioned, and all proposals will be considered on an equal basis at that time. Proposals in response to this call may be for frequencies up to 50 GHz and may include spectroscopy, continuum, pulsar, and bi-static radar reception observations. Unique VLBI proposals will also be entertained. All proposals will be refereed by a peer-review panel, evaluated by a scheduling committee, and selected on the basis of appropriateness, feasibility, scientific merit, and experience of the observing team. The proposals will be scheduled as the capability becomes available; thus, it may take up to one year before the early science queue is completed.

All proposals must be submitted using the NRAO Proposal Submission Tool, which may be downloaded from http://www.nrao.edu/GBT/proposals/tool.html.

The deadline for receipt of proposals is 1 December 2000, with the earliest possibility of scheduling in the first quarter of 2001.

Technology Development

Electronics

Cooled HFET Development

NRAO has worked on the development of HFET (Heterostructure Field-Effect Transistor) amplifiers for many years and is the recognized leader in cooled HFET amplifiers for radio astronomy use. State-of-the-art Indium Phosphide HFETs were made for NRAO by Hughes Research Laboratories and successfully incorporated into amplifiers starting in 1995. The highest frequency amplifiers cover the band 68-116 GHz with noise performance comparable to SIS mixers and much wider instantaneous bandwidth. This has the potential to provide superior performance in continuum receivers and increased operating ease for spectral line work in the frequency range below 115 GHz.

NRAO has produced many HFET amplifiers for use on NRAO telescopes (VLA, VLBA, 12 Meter, 140 Foot, and GBT) and for others in the radio astronomy community and other research areas. These range from low-frequency amplifiers (< 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 which largely eliminate the need for bulky isolators and have better immunity to the effects of interference.

The MAP amplifier project was completed and all amplifiers were delivered to NASA for spaceflight use. This resulted in a series of InP amplifier designs covering all bands from 18 to 110 GHz.

Two new InP amplifiers developed for the bands 3-13 and 8-18 GHz have recently been released for production. These provide noise temperatures of about 5-6 K over these bands using devices from NRAO wafers, and less than 3 K using experimental devices. They are useful for both front-end and first IF use. We plan to extend this series in InP down to 1 GHz; we will then have modern amplifiers for all useful frequencies up to 115 GHz.

In 2000, a major goal was to complete the development of an integrated IF amplifier into an SIS mixer, covering a 4-12 GHz IF band. This has been successful (see below), resulting in an SIS mixer with 8 GHz bandwidth and good noise temperature. This large instantaneous bandwidth will be needed for maximum continuum sensitivity by ALMA.

A variant of the MAP amplifier design was produced in 2000 which is optimized for the band 80-96 GHz for use by the VLBA. This is being used to replace the MAP prototypes first used at 86 GHz on VLBA antennas with a better design having more gain and better impedance match over the target band, thus improving the sensitivity of VLBA observations at 86 GHz. Another variant of this design covers 68-116 GHz.

A variant of the MAP amplifier design optimized for the band 40-50 GHz has been produced. This amplifier is used in the 40-50 GHz receiver for the GBT, for the completion of 40-50 GHz on the VLA, and eventually as a retrofit for the VLA and VLBA antennas in this band. This will result in significant improvement in sensitivity, since the amplifiers in use employ GaAs rather than InP devices.

Technology Development

A variant of the MAP amplifier design for 18-26 GHz has been produced for the continued upgrade of the VLA at K-band, for which funds for new receivers have been allocated. This production work will continue.

Low-frequency balanced amplifiers for frequencies up to 1.2 GHz have now been developed which 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. In 2000, this technology will be pushed into higher bands, with the goal of producing a prototype for the VLA upgrade which has excellent performance from about 1.2 to 2 GHz.

Table V.1 Current NRAO Amplifiers

Band (GHz)	Name	Noise (K)	Comment
0.3-0.4		2.0	Balanced
0.4-0.5		2.0	Balanced
0.5-0.7		2.0	Balanced
0.7-0.9		3.0	Balanced
0.9-1.2		3.0	Balanced
1.2-1.7	L	3.0	
1.7-2.6	L/S	4.5	
2.6-4.0	S/C	5.2	
4-6	C	9	Production to be phased out
3-13	X	5	InP (2.5K with new devices)
8-18	Ku	6	InP
18-26.5	K	9	InP
26.5-40	Ka	14	InP
36-50	Q	18	InP
65-90	V	45	InP
68-116	W	60	InP (3 variations)

Millimeter-Wave Receiver Development

The design and fabrication of SIS (Superconductor-Insulator-Superconductor) mixers covering parts of the frequency range 68-720 GHz are done by CDL engineers in collaboration with the Semiconductor Device Laboratory at the University of Virginia, whose ability to provide rapid turnaround of new designs is crucial to the development effort, and also with the State University of New York at Stony Brook. Mixers have been produced not only for ALMA applications, but for other radio astronomy organizations as well. The noise temperatures now being attained in laboratory receivers are only three to six times the photon temperature *hf/k*, so in many cases the dominant noise sources are external to the mixers.

Spectral line observations require only a *single sideband* response, whereas mixers have typically provided a double sideband response. At the 12 Meter Telescope, zenith system temperature was typically 60 K at 230 GHz, of which about 30 percent is due to unwanted image noise. In 1998, a sideband separating mixer design was successfully prototyped, with the Nb wafer produced by the Jet Propulsion Laboratory.

Present single-ended mixers are susceptible to LO sideband noise, which often has severe effects, increasing receiver noise temperature by as much as a factor of 2. They also require high LO power because the LO is injected by means of a directional coupler. Both of these problems can be significantly helped by development of a *balanced* SIS mixer. A balanced mixer for 211-275 GHz has been successfully developed which incorporates RF and IF quadrature hybrids and two mixers. These incorporate the same design principles and structures already proven in the image separating mixer. Development, in collaboration with the Herzberg Institute in Canada, is aimed at an alternate means of providing the hybrids: machining them into the mixer block rather than as features on an integrated circuit chip. This technique may be very useful for the lowest and highest frequency SIS bands for ALMA and will be vigorously pursued in 2001.

A 211-275 GHz mixer, incorporating *both balanced operation and sideband separation*, has been designed and began initial tests October 2000. This culmination of five years of development is expected to be the element used in the ALMA receivers for this band. In 2001, we will develop production prototypes of this mixer and evaluate consistency of process and performance.

The instantaneous IF bandwidth of present mixers is limited because of the need for an isolator between the mixer and IF amplifier. Results obtained at Owens Valley Radio Observatory have shown that it is practical to produce a mixer with an integrated IF amplifier and achieve a bandwidth of 3 GHz. A development of this type is under way to achieve an IF bandwidth of 8 GHz for use by ALMA. We have achieved 8 GHz bandwidth with good noise temperature with a 4-12 GHz IF over 211-275 GHz RF, using the InP discrete transistor amplifier described earlier. The design will be further refined in 2001 in order to achieve repeatable performance at all RF frequencies and, when combined with the balanced, sideband separating SIS mixer, will satisfy the needs of the ALMA receivers.

A single-ended "building block" mixer for the ALMA 602-720 GHz band has been designed and the wafer is being fabricated at SUNY/Stony Brook. Test apparatus has been developed and initial testing is expected in early 2001. This mixer, if successful, could by used in conjunction with the waveguide hybrids described below to produce balanced and sideband separating mixer configurations.

Emphasis on developments for ALMA strongly brings to attention the need to improve the speed at which SIS mixers can be built and tested. At present, it is possible to produce one fully tested SIS mixer in approximately two months, given all the workloads of existing personnel. For ALMA, we must achieve about two SIS mixers *per week* during the construction phase. For this reason, new techniques for assembling and automating the testing of SIS mixers must be developed, and this process which began seriously in 1998 will continue throughout 2000-2001. The improvements include fabricating test evaluation structures on the Nb wafers and placing most of the mixer testing under computer control. The present degree of success is indicated by the fact that fully testing one SIS mixer formerly needed a Ph.D. engineer for two days; this can now be done by one technician in five hours. Further improvements are expected in 2001 when fully electronically tunable LO sources become available.

Electromagnetics

Wider band amplifiers and mixers require wider band supporting elements. The CDL has designed and tested several new components with the goal of having receiver performance limited only by the bandwidth of single-mode waveguide. A new orthomode transducer (OMT) and phase shifter to convert between dual linear and dual circular polarization has been produced in quantity for the VLA K-band receivers.

This work, as well as other electromagnetic calculations, has been greatly advanced by the purchase of a commercial finite-difference time domain solver, Quickwave. For certain classes of problems, this program is many times faster than HP's HFSS. This program is now being used extensively in modeling passive devices and has saved a great deal of development time.

A new OMT for the 75-110 GHz band has been developed and is expected to be used in the ALMA receivers. Production prototypes are planned for early 2001. It appears practical to perform polarization separation in this fashion up to about 200 GHz; for higher frequencies, quasi-optical techniques will be required. However, the use of OMTs below 200 GHz will greatly simplify the optics of the ALMA receiver layout.

New feed developments have also been pursued. A new family of feeds for the VLA upgrade project is being designed in conjunction with an investigation of how best to optimize performance in the VLA asymmetrical subreflector system. These designs should be completed by the end of 2001.

In order to provide balanced and sideband separation for SIS mixers at higher frequencies, where the MMIC approach adopted for 211-275 GHz may not work well, we are developing quadrature hybrids and matched power splitters machined in split-block configurations suitable for numerically-controlled milling machines. This concept has been verified with one experimental hybrid, and several variants of this design will be produced and tested in 2001.

Digital Correlators

The 262,144-channel GBT spectrometer, which can analyze instantaneous bandwidths up to 800 MHz, was delivered to the telescope in 1998 for integrated testing. Software for operation in more of the possible modes has been written, and integrated testing is continuing in preparation for commissioning the GBT.

A duplicate of the Green Bank spectrometer was built at the MPIfR. Another duplicate was built in 1998 at the CDL for use with the Tucson 12 Meter antenna; the IF electronics were built in Tucson. A third, smaller copy was built for use by the University of Massachusetts.

In 1999, another copy was built for use as a test correlator for the prototype ALMA interferometer. This will be delivered to the VLA ALMA test site before the end of 2000.

The time-slice principle of the GBT spectrometer is being used in the ALMA correlator design. A new correlator chip is being designed by a contractor. The board-level designs, including a digital FIR filter, are expected to be essentially complete before the end of 2000, and testing will begin in 2000 and will continue through 2001. A full prototype correlator in the laboratory is expected before the end of 2002. Other selected milestones for this development appear in the following table.

Table V.2 Correlator Milestones

Milestone	Target date
Chip design complete	2000, December 31
Critical Design Review	2001, July 31
Prototype correlator delivery	2003, May 30
First quadrant to Chile	2004, June 18
Last quadrant to Chile	2006, October 06

Millimeter-Wave Local Oscillators

The LO requirements for the ALMA receivers include all-electronic wideband tunability, low amplitude and phase noise, sufficient power to drive SIS mixers, high reliability, and low cost. This precludes the use of the traditional second harmonic Gunn diode oscillators followed by frequency multipliers employing whisker-contacted diodes which are used in most millimeter receivers. ALMA has decided on a baseline plan of LO multiplier chains using YIG-tuned oscillators (YTO), amplifiers, and frequency multipliers and a photonic reference for phase-locking the YTOs using two phase-locked lasers. We have demonstrated that the phase and amplitude noise of such driver chains, using high-power MMIC amplifiers developed by JPL, are satisfactory for use in an interferometer. We expect pre-production prototypes of two such driver chains to be complete by October 2001.

New frequency multipliers have been developed in collaboration with the University of Virginia (UVA). These employ new, UVA-developed planar diodes fabricated on monolithic chips, and have been successful in 40-80, 80-160, 55-110, and 110-220 GHz frequency multipliers. These devices have a 3 dB bandwidth frequency ratio of about 1.15:1, and appear to be easily modified to achieve an even broader bandwidth with slightly less overall efficiency. These components will be used in the drivers and initial multipliers for the ALMA LO system. Pre-production prototypes which cover the desired tuning ranges for ALMA receivers for the four initial bands are expected by October 2001.

For frequencies above about 300 GHz, it is probably impractical to build efficient broadband frequency multipliers using discrete diode chips. We are therefore working on MMIC frequency multiplier designs for these critical higher frequencies, in collaboration with JPL. Triplers for 80 to 240 and 220 to 660 GHz are being designed. Prototypes may be fabricated by the University of Michigan, as well as by JPL. First prototypes of these devices are expected by June 2001.

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 expected to continue, with prototypes for 211-275 and 602-750 GHz available by June 2001.

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 by June 2001. This will be of use in both SIS mixer testing and LO multiplier development.

Adaptive Interference Excision

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. Tests of this hardware are expected in Summer 2001.

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 which are only slightly extended, a multiple-beam receiver does not achieve a significant speedup in observing compared to a single receiver. We have developed a prototype of an array feed receiver which packs planar feeds close together and achieves multiple beam synthesis by weighted combination of multiple feed outputs. This system was tested on the 140 Foot antenna 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 some time in 2001.

Technology 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 only chance to preserve an 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 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.

In 2000, 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 is for $270k, nominally for 1 October 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 is providing $270,000 for a two-year period starting 1 October 2000 The SETI Institute is supplying $144,000 in matching funds to be spent on supporting half time of two postdocs in California and consulting time from Steve Ellingson at Ohio State.

Data Management

The NRAO has launched an initiative to improve the data services and products offered to users of NRAO telescopes. This Data Management Initiative was started in the first part of 2000, following extensive discussions and consultations with the radio astronomical community and our advisory groups. This has resulted in a restructuring of Observatory-wide computing efforts around the Data Management Initiative. In this section, we discuss the mission of the Data Management Initiative, and of all scientific computing at the Observatory, the budget required to support those missions, and the likely impact of the large shortfall in the proposed budget for these areas.

The mission of the Data Management Initiative is to bring NRAO into parity with other modern observatories such as the Space Telescope Science Institute and the European Southern Observatory. Specifically, we view the following goals and commitments to our users as vital to the long-term health of the Observatory and of the radio astronomical community.

- 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.
- NRAO must take responsibility for the initial quality of data and images delivered to users. NRAO must deliver an improved scientific data product to users.
- NRAO must provide easy (web-based) access to archives of contemporary and historical images, surveys, catalogs, etc. for all NRAO telescopes.
- 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.

As we discuss below, realizing these goals within our current funding constraints is simply not possible. Computing staff and resources are currently stretched to the limit. Hence new sources of funding must be sought for this initiative. We have identified a number of possibilities. First, the Data Management goals are common with those of the ALMA and of EVLA, and so developmental efforts can be shared with the ALMA and EVLA projects. Second, we are assembling a proposal for a National Archive for Radio Astronomy, funding for which will be sought from the NSF/CISE Information Technology Research program. The goal of NARA is to establish a virtual facility dedicated to simplifying the use of radio telescopes, and to making scientifically useful archives widely available to all astronomers. NARA would provide a focal point for these developments throughout the radio astronomical community, and would also serve as a resource and point of contact for processing and archiving of radio observations. We believe that the NARA is well matched to the ITR program. The radio astronomy community and NRAO both have a strong background in the utilization of state-of-the-art computing technology for advancing science. The AIPS++ consortium, of which NRAO is a member, has devoted considerable effort to developing the technology that can be used to achieve the goals of the NARA. We will therefore use AIPS++ as a key component in our proposal, and in our planning.

The NARA is a necessary component of the Observatory's involvement in the National Virtual Observatory. The National Virtual Observatory was mentioned prominently in the recent report of the NRC Astronomy and Astrophysics Survey Committee. The NVO will link the archives of ground and space based observatories, the catalogs of multi-wavelength surveys, and the computational resources necessary to support science based on these resources. The inclusion of radio astronomy observations, both pointed and surveys, is clearly very important for the long-term scientific impact of radio astronomy. The NVO will principally be a repository for scientific results such as images and catalogs, so it is important that the NRAO commit to making an image part of the standard product from an observation.

Submission of the NARA proposal will occur in the spring of 2001. If successful, funding could start in the fall of 2001. Currently, and during the intervening time, planning for the Data Management initiative will continue. Ongoing work at the various sites will be aligned with the Data Management initiative as is possible. For example, we have started a pilot project to improve proposal handling at the GBT. Experience from this pilot project will be used in setting goals for Observatory-wide proposal handling.

If Observatory funding were to allow a reasonable start on the Data Management Initiative, the goals for 2001 would be the following:.

- Complete initial planning and design for Data Flow on NRAO telescopes.
- Develop and deploy integrated proposal handling for all NRAO telescopes.
- Develop and deploy prototype archives for VLA, VLBA, and GBT telescopes.
- Initiate development of next generation scheduling tools (including dynamic scheduling).
- Initiate development of software-based pipelines for processing VLA data.

Data Reduction and Analysis Software: AIPS, Unipops, and AIPS++

The Observatory is in the midst of a transition from our existing data analysis packages, AIPS and Unipops, to the AIPS++ package. AIPS++ has been under development by a consortium of radio observatories. The first and second releases of the AIPS++ package were made in October 1999 and June 2000. AIPS++ will be the prime data reduction and analysis package in use at the Green Bank Telescope, replacing Unipops. AIPS++ has been used extensively throughout the construction for various engineering purposes, and will be used during the commissioning phase, and for subsequent scientific observations. AIPS++ is now currently focusing on the finalization of software for the reduction of synthesis observations. In the October 2000 release, end-to-end VLA processing will be supported, and in the April 2001 release, VLBA processing will be possible. In addition to these mainstream initiatives, AIPS++ has a number of other ongoing projects that will result in new capabilities in the next year. The parallelization initiative, conducted in collaboration with the National Center for Supercomputer Applications, is proceeding well, and will result in various key synthesis imaging applications enabled for parallel computers, including those for wide-field imaging as needed for EVLA, and for mosaicing observations such as those planned for ALMA. Similarly, a visualization effort, funded by a grant from the NSF/ACR program will result in novel highly interactive reduction facilities in 2001. During the period that AIPS++ is coming up to full capability, we 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. Current staffing is inadequate in two areas: system support, and user support. As the package becomes more and more widely used, both these areas will need additional staff.

Computing Hardware

Over the past year we were again able to make only very limited progress in addressing many of the problems of our aging computing infrastructure. The level of Observatory-wide computing funding in 2000 was even further reduced from 1999, to the point where roughly one-third as much was available for such items as equipment, training, and software, compared to the 1997 and 1998 budgets. This meant that vitally needed upgrades could only be done for about 8 percent of the workstations used by NRAO's staff and visiting observers. This figure is almost identical to 1999, and is in stark contrast to the 20 percent level that was possible in each of 1997 and 1998, the level that must be permanently sustained on an annual basis to ensure that systems remain useful. If the current rate of replacement were to continue, the service lifetime of UNIX computers at the NRAO would be roughly ten years—clearly longer than it could actually be considered useable given the pace of development in the computer and software industries.

Comparatively small investments in new hardware would maintain NRAO's ability to support current facilities as well as new facilities coming on line over the next few years. Investments in software development and networking would also create opportunities for new scientific observations, loosening the computing restrictions currently faced by some advanced research efforts. Finally, continuing modest investment in NRAO's computing infrastructure would keep the NRAO one step ahead of the effects of obsolescence caused by the rapid advancements in the computing industry and diminishing availability of maintenance and support for old hardware. Budgets that do not permit such a continuous upgrade process will inevitably impact the services the NRAO can provide to its staff and user community.

System Upgrades

A replacement rate of at least 20 percent needs to be resumed and sustained in future years to allow the NRAO to continue retiring workstations which have already reached the end of their useful operational lifetimes. Upgrade or replacement is also dictated by the increasing demands on computational capability from both increased demands by NRAO users and increased observational capabilities brought about by technological advances and enhanced processing techniques. These upgrades would allow most workstations at the NRAO to be replaced or upgraded by the end of their useful lives (typically no more than four years for scientific workstations). They would also allow us to upgrade the smaller network server systems at sites such as Tucson and Green Bank. Unfortunately, this rate was not possible in 2000 due to reduced funding.

Roughly $250,000 per year should be allocated for computer hardware acquisitions/upgrades, covering desktop computers, visitor facilities, and servers, in 2001 and beyond. This level of investment will accomplish three goals:

1. Permit the NRAO to provide visiting observers with systems and storage options that are capable of handling medium to large problems.
2. Allow the NRAO to address the problems it faces with an aging computer infrastructure.
3. Provide capability for addressing high-end scientific problems that are beyond the capacities of current computing facilities at the NRAO.

If resources are constrained during 2001, the upgrade focus will remain on the first two of these goals. Continuing the recent trend of deferring resolution of infrastructure and high-end computing problems would mean that the overall return on the investment in NRAO facilities and instruments would be degraded, and the risks of major failures in computing would be increased due to the many older machines still in use.

Networking and Networking Upgrades

At each of its major sites the NRAO operates a complex networked computing environment. This offers numerous advantages for efficiency and flexibility in meeting the needs of computer users at the NRAO, and allows a small support staff to maintain a large number of computers. The tightly networked computing systems at the NRAO also allow the Observatory to provide significant support to its users, especially outside users. For example, the NRAO is able to provide support and documentation through the facilities of the World Wide Web. Users can access on-line documentation, download software, peruse recent NRAO preprints, newsletters, and technical memos, or download available images from the completed NRAO VLA Sky Survey (NVSS) and the ongoing Faint Images of the Radio Sky at Twenty-centimeter survey (FIRST).

The networks at the NRAO have limitations, particularly for data bandwidth between machines. A salient feature of radio astronomy is the large size of typical data sets. The network links between machines may result in bottlenecks, and can reduce the effectiveness of sharing computing resources at a site. Resolving this situation will allow increased efficiency in the use of computers at the NRAO, and allow more flexibility in meeting future computing demands.

During 2000, we have been able to resume some progress in the process of modernizing the NRAO's network infrastructure. There have been with further upgrades at Green Bank to support the demands of GBT operations, in Socorro to permit switched-Ethernet networking in the Electronics Lab, and in Tucson with new facilities to accommodate expansion due to ALMA development. A related goal is to provide high-speed links between NRAO sites, and between the NRAO and external institutions. Current network connections only allow limited access for remote observers; the pioneering efforts at the 12 Meter to provide support for remote observers should be leveraged to provide such capabilities for remote observer access for the NRAO's other instruments. Significant progress in several of these areas, including preparations for GBT remote observing support, will be possible in the near future due to the special NSF communications infrastructure grant. Videoconferencing, which was made possible as part of a special grant received in 1999 from the NSF CISE directorate, is proving beneficial in a number of areas as an aid to inter-site communication, and some improvements are planned for 2001. In addition, in June of 2000, the New Mexico Institute of Mining and Technology, with which the AOC shares its Internet connection, received a high-speed networking grant from the NSF CISE. During 2001, this grant will provide the AOC with a connection to the high-speed Abilene and vBNS+ networks, to which a number of users of NRAO telescopes and the NCSA are also connected.

Completion of the most critical improvements in the performance of the internal computer networks at the NRAO is vital. Further deferring this work will reduce the overall engineering and scientific productivity of NRAO staff and visitors.

Engineering Computing

The NRAO is pursuing several initiatives leading to development of major new observational instruments, or greatly enhanced capabilities for existing instruments. Chiefs among these efforts are the Green Bank Telescope project, the Atacama Large Millimeter Array, and the proposed EVLA. These projects, like many ongoing engineering tasks for existing instruments, are heavily dependent on the use of advanced engineering workstations to carry out various aspects of design and fabrication. If engineers at the NRAO must carry out their work using obsolete or inadequate workstations and PC's, their productivity will suffer. Improvements in this area were minimal in 2000 and will need further investment in 2001. We also need to ensure that all engineering staff has access to current releases of major software packages, to reduce the difficulty that has been encountered in exchanging information. Little progress in this area has been possible since 1998, all of it piecemeal from division or construction budgets. Approximately $50,000 should be allocated in 2001. This will allow the acquisition of both appropriate workstations and required software, in particular maintenance contracts Observatory-wide to prevent the recurrence of compatibility problems due to uncoordinated upgrade schedules.

Addressing this need will retain the productivity of NRAO's engineers, and the effectiveness of operations over the long term. Deferring this expenditure until after 2001 will reduce the productivity of our engineers and may also reduce the NRAO's ability to attract the top-level talent it needs to pursue future initiatives.

VLA On-line System Upgrade

The current VLA On-line Control System is almost at the end of its useful lifetime. The computers used in the system are 13 years old, and represent an expensive maintenance problem. In late 1999, the manufacturer agreed to a five year support contract. However, the company is no longer building computers, and its future is uncertain. It is clear that the correct decision was made in 1998: to redesign the current online system around a more modern and cost-efficient real-time environment such as that used in the VLBA, GBT, 12 Meter, and ALMA telescopes, which has considerably better performance at much lower cost.

This will reduce our dependency on an expensive proprietary architecture for which it is difficult to find experienced programmers, and make it possible to support future enhancements to instrumental capabilities more readily. While it will take much longer to implement, the advantages are numerous. It will produce a system that is easier to support, is compatible with other NRAO controls, carries much more reasonable maintenance costs, and can be designed from the outset with many of the requirements of the EVLA and other planned enhancements in mind.

The VLA On-line System redesign was begun in late 1998 and has made steady progress since. The design process is well underway, although the schedule has been affected by the need to devote manpower to ongoing support of existing telescope operations. Some of the necessary equipment for prototyping was purchased in 1999, but diminished funding this year necessitated continued deferral of the remaining items until 2001, when approximately $25,000 will be required.

Mass Data Storage

A hallmark of radio astronomy is the large volume of data that must be managed, stored and reduced. There has been a steady increase in the size of data sets produced by NRAO instruments, and in the amount of processing and analysis required. Examples of techniques that are pushing up the size of data volumes at the NRAO include mosaicing, on-the-fly imaging, interferometric spectral line observations, and new spectrometers on single-dish telescopes. Current facilities at sites for managing voluminous data sets are inadequate, with particularly lengthy delays caused by lack of data storage space and limited tape drives.

Limited deployment of higher-speed, higher-capacity tape media such as Digital Linear Tape (DLT) and similar devices such as Exabyte Mammoth was done in 1998, but it has not been possible to supplement this since. New workstations are also being purchased with an increasing amount of disk space, which reduces the need to juggle datasets but introduces a serious problem archiving the data to tape. In 2000, at the urging of the NRAO User Committee, several of the old 5 GB Exabyte and 2 GB DAT tape drives were upgraded on visitor systems at the AOC, so that a minimum of 7 GB is now typically possible. Additional upgrades will be needed for the remaining older drives. While an improvement, this does not go far enough; we need to provide the NRAO's users and visitors with new options for dealing with their data, to increase the efficiency of data processing and reduction. The greater storage capacity and transfer rates of new tape media are not only necessary to reduce the effort and time required to back up large amounts of data, but are critical for those projects which produce very large files.

In addition to storage issues related to data processing, we must also consider the requirements of archiving very large volumes of raw data. This will be particularly important for the data produced by the GBT spectrometer. The VLBA archive currently contains more than 7 terabytes of data stored on 2 gigabyte DAT tapes. The accumulated data archive of the VLA, spanning 23 years, is about 2.5 terabytes, increasing by roughly 10 percent per year; this rate will go up considerably when the proposed EVLA is implemented. Clearly, the tape media currently being used for this purpose has neither the capacity nor the longevity required for permanent archives. Alternatives will be investigated as part of the Data Management initiative.

Data Management

Deferring expenditure in data storage and handling is possible, but NRAO users will have to curtail certain types of experiments on various instruments, and continue to spend large amounts of time shuffling data instead of performing scientific analysis.

Security

Computer and network security continues to be a major concern at the Observatory. The NRAO's computer security practices must balance the need for reasonable access by users to our computing services from outside the Observatory with the need to protect those services from willful damage by unauthorized users. We continue to see increasing attempts to "probe" computers and networks from outside the NRAO (thousands of such packets every day). These probes are often used to detect vulnerabilities in our systems' configuration. There have also been a few break-ins that briefly disrupted some of the services we provide and had the potential for greater damage.

In late 1999, a Computing Security Policy was issued, with the goal of improving the security of our computers and networking across the Observatory without compromising services that are fundamental to our role as a user facility. As implementation of the policy progressed during 2000, a small change was required in the ways that users at other locations connect to NRAO systems. Because many network services contain security holes that cannot always be easily fixed, those to which access from outside of the NRAO is not essential have been blocked, to reduce our vulnerability. Although several major milestones in improving the overall level of security at the NRAO have been reached, much more work, particularly ongoing monitoring to alert us to intrusions, remains to be done.

Computing Personnel

The current level of personnel for computing support at the Observatory continues to be sufficient only to meet critical needs, and is not adequate to allow any improvement in services to our users. Lean budgets at the NRAO during the past few years have forced us to reduce personnel. As a result, the NRAO is barely able to provide essential support to its computer users, and must neglect them in certain areas. Support personnel in computing are often forced to work in crisis mode, and must neglect long term planning and enhancements in computing support. Scientific staff is often called upon for such tasks as web page development and local maintenance of important astronomical data analysis packages written outside of the NRAO.

Impact of the Request Level Budget

In this section, we describe the missions and budget requirements of the various divisions, and discuss the impact of the request (level) budget for 2001. We find overall that the missions of the divisions simply cannot be met with a flat budget.

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 activities across the Observatory. DM also is responsible for providing key technologies (e.g., AIPS++) used in achieving these goals. It is important to emphasize that the DM initiative is required just to bring Observatory services up to the level generally found in the astronomical community.

Data Management has three main subdivisions: Technology Development, Telescope Computing, and Observatory-wide Computing. The missions of these sub-divisions are as follows:

- The mission of Technology Development is to develop and maintain the software, and test and acquire the hardware needed for Data Management goals. On the software side, Technology Development includes the AIPS and AIPS++ groups, and the Data Flow group.
- The mission of Telescope Computing is to oversee and coordinate the computing required to support observing with NRAO telescopes in a way that is compatible with overall DM goals.
- The mission of Observatory-wide Computing (OWC) is to coordinate computing efforts across the Observatory, thus playing a key supporting role in the Data Management activities. OWC covers computing purchases and contracts which directly affect multiple NRAO sites by providing a centrally administered shared funding resource to supplement the site Computing budgets. It plays a particularly important role in the maintenance and improvement of NRAO's computing and networking infrastructure and facilities, computer security, staff training, and inter-site communications—vital activities which at individual sites must too often become a secondary consideration due to the overwhelming pressure of day-to-day operational concerns.

Each of the four major NRAO sites has a local Computing Division with a related mission of its own.

The mission of the Charlottesville computing division is to provide the following services to local staff (including the Director's office, Public Outreach, the NRAO Business and Personnel offices, and the CDL), AUI, and users of all NRAO facilities:

- Centralized information services, including the main NRAO web server, the nrao.edu and aui.edu electronic mail gateways, numerous mailing lists, and directory services.
- AIPS: distribution, worldwide installation and system technical support, local AIPS operational infrastructure.
- AIPS++: distribution, local operational infrastructure.
- Network (Internet, Intranet) management across the Observatory, including router configuration, setup, network monitoring, and support.
- Computer security for NRAO/CV and the NRAO network perimeter.
- Computer hardware and software installation, upgrades, and support for local staff and visitors.
- Archive services, including support for the Archive Media Transfer Facility (AMTF) as well as providing survey results (NVSS, FIRST) to the public.

Data Management

The mission of the computing division in Green Bank is to continue the development of the software for the GBT, which is scheduled to begin scientific operation in 2001. Specific areas include the control system (M&C); integration of the metrology system; data reduction capabilities initially for acceptance and commissioning, and later for regularly scheduled observations; some automatic data reduction procedures; and data storage to support retrieval for export and archive. As the GBT becomes a routine user facility, we will need to support remote observing, dynamic scheduling, and new data reduction techniques. All these are part of the core Data Management activities but local support at Green Bank is required for any development.

In addition, the site computing infrastructure must be maintained at a level where all other operational functions in Green Bank are adequately supported. These activities include general research by the astronomical staff, the NRAO Fiscal division with the payroll system, and the Management Information System accounting computers, plus support for the other operational groups such as electronics, machine shop, etc.

The mission of the Socorro Computing division is:

- To provide computing support to all divisions and visitors at NRAO-NM, and in particular to provide the computing and network infrastructure and support required to handle data from the telescopes of which the AOC is the operating center.
- To develop and maintain telescope monitor, control, and archiving software and systems for the VLA, the VLBA, and the EVLA.

The primary mission for Tucson Computing is to support the engineering staff engaged in various ALMA development activities. This entails participating in the NRAO Intranet, providing email and web access services, and maintaining a flexible networking infrastructure. In addition, there is an ongoing commitment to providing observer access to the archive of data from the 12 Meter Telescope and support for several staff engaged in non-ALMA tasks.

The table below summarizes the budgets required to meet 2001 objectives for all divisions; for comparison, the 2000 figures are included.

Table VI.1 Mission Budget Requirements 2001

	DM/TD TC	DM/OW C	CV	GB	NM	TUC	Total	2000 Total
FTEs	18	0	9 5	9	19.8	1	57 3	47.3
M&S/RE	240,000	415,000	55,000	50,000	80,000	5,000	845,000	339,000
Travel	50,000	25,000	12,000	20,000	15,000	3,000	125,000	106,000
Comp Maint	0	130,000	0	0	53,000	0	183,000	141,000

Data Management

To initiate the Data Management initiative in archiving, two small storage servers (one for Green Bank/Charlottesville and one for Socorro) must be acquired for early phases of the archiving effort (for a total of $200k). These will be augment in later years to accommodate the full archiving load.

The Data Management/Technology Development and Telescope Computing groups require some modest increases in travel funds. Year 2000 travel funding for the AIPS++ group has been a limiting factor and must be increased.

DM/OWC currently provides virtually all of the funds required to upgrade computing hardware such as staff desktop workstations, visiting observer data reduction systems, and associated peripherals. It also funds capital items at the sites. The major items in the required OWC budget for 2001 are:

- Desktop workstation upgrades: In 1999 and 2000 combined, only about 10 percent of the Observatory's desktop workstations were upgraded. In contrast, we require an annual turnover of 20 percent to limit use to the viable lifetime of five years. In 2001, we must not only resume the 20 percent level, but also make some effort to compensate for the reduced rate in previous years. A modest amount to spend on this area would be $150,000. Upgrades to auxiliary equipment such as memory, disk space, monitors, and low-end desktop backup devices require at least an additional $25,000.
- Public systems must also be upgraded, ideally every three years. Several of the Observatory's key visitor computers are already older than this, and several more are now three years old. We must upgrade at least six of these fairly high-end systems in 2001, at a minimum total cost of $40,000. In addition, both Green Bank and Socorro are in serious need of reasonably modern tape devices for visitor systems, and a total of $15,000 is budgeted for this.
- NRAO's web services require major improvements, including bringing reliability, performance, and security to acceptable levels. In 2000, a new system was purchased for installation in Charlottesville; similar systems will be needed for mirroring and local serving at the other three sites, for a total cost of $15,000. (Note: Tucson is an excellent mirroring location for improving access to the main NRAO pages.)
- VLA/VLBA: Whether or not the EVLA is funded, a major upgrade of the VLA control system must be done over the next few years. The estimated cost of items required in 2001 for this effort is $22,000. In addition, the hardware used for data archiving is in serious need of upgrading; $7,000 is required for this.
- Windows 2000: In 2001, we must begin an Observatory-wide upgrade of our PC systems to Windows 2000, which was released early this year. Roughly 350 NRAO PCs which will be affected now run older versions of Windows; these licenses must be upgraded, at a total cost of about $20,000.
- All sites have central fileservers on which many users depend. These critical systems must receive regular upgrades to perform the necessary tasks. A total of $30,000 will be needed in 2001 for this purpose in Green Bank, Socorro, and Tucson.

- NRAO engineers depend heavily on AutoCAD for circuit layout; altogether we have over 50 licenses across the Observatory. More than half of these are running a two year old version that cannot handle files created by the current version. These need to be upgraded; the estimated cost is $15,000.
- Computing security $25,000. Computing training $30,000. Miscellaneous M&S $15,000.
- The current method of providing local workstation storage for all user data is becoming difficult to sustain, primarily because of problems backing up so much data over the network. We need to investigate alternative technology such as Storage Area Networks. A pilot project, to be conducted in Charlottesville in connection with web and/or CDL database services, would cost $5,000-10,000.

Actual DM/OWC maintenance expenses in 2000 will be $98,000. The 2001 budget must allow for small increments in these contracts. Therefore $100,000 is an absolute minimum requirement. In addition, this budget should assume responsibility for engineering software contracts currently maintained by individual groups, and prevent further compatibility problems with AutoCAD by negotiating an NRAO-wide contract for future upgrades. An additional $30,000 is required for this. Note that most of this additional amount will be funded by engineering budgets if it is not covered from here.

A modest increase is also required in OWC travel to accommodate inter-site computing travel, which in the last two years was cut back because of reduced budgets.

As well as filling currently vacant positions at the AOC and Green Bank, the following additional staffing is necessary in 2001 to meet mission requirements:

Data Management

- System architect for overall Data Flow architecture, design, and implementation.
- Four FTEs to initiate design and development work on archiving, scheduling, pipelines.
- One FTE for AIPS++ system support. The AIPS++ group has been operating without a system support person for several years. An existing developer on a part-time basis has filled in this position. It is becoming an increasing problem now that we are in operational status, however, as the system support load has increased significantly. Time allocated for system support will increase in 2001; this will adversely affect development without an assigned position in this area.
- One FTE for AIPS++ user support. As use of the AIPS++ package increases, a dedicated support person is required. All developers share this duty at present. An assigned position would decrease the turn-around time for handling user queries, and would likely help significantly in extending the user base for the AIPS++ package.

Charlottesville

- Create a new position of Web Architect, to handle web service and technical issues such as CGI programming, security auditing, HTML markup, content management, web-server layout and management, and creation/deployment of new services. Currently these functions, when they are performed at all, are handled at a minimal level by several different people as time permits. This style of web management is inadequate as we continue to expand the rôle that the web plays in providing services to our user community.

- Restore 0.5 FTE in system support that was reduced in 2000; without this manpower, several major projects such as web server upgrades, computing security implementation, and directory service improvements are being seriously delayed.
- Add 0.5 FTE to assume some of the duties currently being carried out by the drastically over-committed networking engineer; this will allow him to focus on NRAO-wide networking, including support for VLBA site and ALMA Chile links, videoconferencing, traveling users, and Edgemont Road construction.

Green Bank

- All existing software engineering staff are needed for debugging and continued development of the GBT monitor and control system; an additional engineer is therefore needed to support Data Management development on other required areas such as remote observing, dynamic scheduling, pipeline data analysis, and archiving.
- A new position in computing support is required to ensure that the division can provide an acceptable level of service to in-house staff and visiting observers as the support requirements increase with the commissioning and operation of the GBT.

Socorro

- An additional software developer is sorely needed to help cover such areas as archiving software and database development and support; the current single position is not enough to cover these in addition to JOBSERVE and web development.

Tucson

- The single system administrator position is a mandatory part of site computing infrastructure and should be covered by NRAO operations, particularly as there are still non-ALMA functions being supported

Each site has an absolute minimum level of expense required for essentials such as printer supplies, tapes, components, equipment repair, etc. Some relief was available in 2000 because of Y2K stockpiling, but this will not be the case in 2001. Furthermore, Green Bank will see a significant increase in the consumables and tapes required due to commissioning of the GBT, and Charlottesville will be required to support an expanded telecommuting program for employees during construction at Edgemont Road.

Data Management

Every NRAO site also requires a relatively small budget for acquisitions and upgrades, to address minor but non-optional items such as printers, UPSs, documentation, and software to meet local needs, as well as funds for such critical purposes as advertising open positions.

Socorro is the only site that requires a local maintenance budget. The largest component, $49,000 of the total $53,000 request, is for hardware and software maintenance on the Modcomp computers which run the VLA. This is not negotiable. An additional $4,000 is needed for support on such vital software packages as the Ingres database which is required for VLBA scheduling, operation, and correlation.

Modest budgets are required at the sites to accommodate travel to training and other non-NRAO destinations.

Having described the budget required to meet the core mission of the Observatory in computing, we can now describe the impact of a flat budget. The following table shows the division of computing funds under a flat budget (for comparison, the required total is included):

Table VI.2 Proposed Budgets 2001

	DM	OWC	CV	GB	NM	TUC	Total	Total Required
FTEs	11	0	7 5	7	18.8	0	44.3	57.3
M&S/RE	30,000	100,000	50,000	30,000	60,000	0	270,000	840,000
Travel	50,000	20,000	10,000	15,000	10,000	0	55,000	125,000
Comp Maint	0	80,000	0	0	45,000	0	125,000	183,000

This division is flat in Data Management/Technology Development and Telescope Control, where the largest increase is required, and has a significant decreases from 2000 in the remaining areas:

OWC: -17% CV: -12% GB: -21% NM: -21% TUC: -100%

Of the existing sites, it is immediately apparent that the hardest hit are the two sites which support (or will support) telescopes. The proposed OWC M&S/RE budget has been cut to less than one-quarter of what it was in 1997. In addition, Tucson computing operations have been cast entirely onto the already-strapped 2001 ALMA D&D budget despite continuing general support functions. This is simply not a tenable situation.

If this proposal becomes reality, it will have a serious impact across the board, but particularly in the following areas:

- Contractual obligations for computer hardware and software maintenance in OWC and NM will not be met.

Data Management

- The Data Management initiative will be dead on arrival unless the NARA proposal to the NSF CISE/ITR program is accepted. Even then, funding would only become available in September 2001, forcing a severe scaling back of work planned for 2001.
- Green Bank will be unable to provide software development and support functions that are critical to the success of bringing the GBT into operation.
- Socorro will not be able to maintain the VLBA and maintenance-management databases that are required for everyday telescope operations;
- Charlottesville's unique ability to contribute to wide-area networking support, web serving improvements, and security implementation will have to be cut back, resulting in serious delays and reduced service levels in these and other areas.
- It will not be possible to do more than a handful of equipment upgrades, whether on desktop, visitor, or server systems. This continues the trend of the past two years, and has an increasing—and insidious—effect on the ability of all NRAO employees and visiting observers to do their work. Furthermore, failing to upgrade older systems increases the workload on the already-understaffed support groups, partly due to the higher failure rates of old hardware, and partly because multiple versions of each operating system will be required.
- It will not be possible to take more than a minimal step toward much-needed improvements in the reliability and performance of NRAO's web services to its user community.
- If EVLA funding is not received to supplement the proposed budget, the activities for VLA online replacement may have to be scaled back. This is a serious problem due to the hard deadline for expiration of the maintenance on the existing systems.
- Green Bank and Socorro will have to use almost their entire allocation in M&S on supplies and repairs. This is unacceptable.
- Engineering staff performing vital work in design and development for ALMA and the EVLA will continue to be affected by incompatibilities in software.

Education and Public Outreach

The NRAO has high U.S. and international visibility as a leader in radio astronomy research and development. Images and information about our instruments and scientific results stimulate interest both inside the scientific community and amongst the general public. The goals of our Education and Public Outreach (EPO) programs are to use this visibility and interest to improve science awareness, appreciation and education in our society, to demonstrate the value of our efforts 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.

In this section some recent highlights of the EPO program are summarized, 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 400 college teachers from around the country have participated in an NRAO-GB Chautauqua Short Course. In 2000, two Chautauqua programs were held. The program has resulted in greatly increased contact with undergraduate students, including the annual week-long Penn State Educational Research in Radio Astronomy program. In its ninth year, the program involves high school and college students, who participate in an ambitious suite of projects using the 40 foot telescope. One project conducted by the Penn State group resulted in a paper published in the *Astrophysical Journal* (537:904-908, 10 July 2000).

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 and nearly 800 teachers and college students have participated. 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 as many as 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.

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 collaborate with interested teachers to tailor an extended visit to the specific group of students. An NRAO overnight field trip for fifth grade students was featured in the April 1999 NSTA journal, Science Scope. The 40 foot telescope remains the cornerstone of the education efforts in Green Bank, and minor repairs and upgrading of the instrument were performed in 2000.

In 2000, 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, have developed an innovative multi-disciplinary astronomy project for seventh grade students. In "Our Place in the Universe," all students work in teams to conduct an in-depth investigation of a constellation. As part of their project, the students spent the night at the Observatory conducting observations with the 40 foot telescope and interviewing staff scientists. At the conclusion of their work, NRAO hosted a colloquium where student teams presented their results to their peers, parents and Observatory staff. The "Our Place in the Universe" project, honored by a Smithsonian award in 1998, will be featured in an upcoming issue of MacHome Journal.

In addition, 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 1200 children and adults have participated in extended visits since January 2000.

Community Programs

- 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 West Virginia Governor's Honors Academy, state Science Teachers Association and National Science Teachers Association (NSTA) conferences.

New Mexico

Courses for College Teachers/College Support

In cooperation with the University of Dayton, we conducted the third Socorro short course for college teachers in 2000. The course, "Interferometry in Radio Astronomy: The VLA and VLBA," was similar to the course we first offered in 1998. The short course included 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 intend to make 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, and other institutions have thus used the VLA to provide hands-on exercises with real observational data.

Directed-Study Courses for Secondary Teachers

In the summer of 2000, we hosted two secondary-school teachers in directed-study courses that are part of New Mexico Tech's Master of Science Teaching program, coordinating this with our Research Experiences for Teachers program (see below). One teacher produced a web-based virtual tour of an astronomical observing project, aimed at high-school students. The other produced a series of curriculum materials and classroom exercises built around research results from the VLA, and aimed at middle-school students. These classroom exercises will be tested and refined in this teacher's classroom during the school year, then published by NRAO and distributed to teachers nationwide. These materials are designed to assist teachers in meeting the National Science Education Standards.

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 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 school teachers, and 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. We also provide 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, Lowell Observatory, Whipple Observatory, McDonald Observatory, Apache Point Observatory, the Flandrau Science Center (Tucson) 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.

Observatory-wide Programs

Undergraduate Research Program

NRAO has sponsored a summer student program for undergraduates and graduates since 1959. For a decade the funding for this program has come from the NSF Research Experience for Undergraduates (REU) program, which has typically supported 20 students per year for approximately 12 weeks in-residence at one of the NRAO sites. In 2000 there were 25 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.

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.

We note that it was difficult to find the funding for the Co-op student program during 2000, and in 2001 it may unfortunately be necessary to downsize or discontinue the Co-op Student Program, our only engineering education effort.

Research Experiences for Teachers

In late 1999 NRAO was successful in attracting NSF funding from their "Research Experiences for Teachers" program to add six high school teachers to our summer programs at Green Bank and Socorro. An excellent program to involve the teachers both in research and in the production of educational materials that could be returned to the classrooms was created by Sue Ann Heatherly (NRAO-GB); in New Mexico, in consultation with Dave Finley, two teachers involved in the New Mexico Tech Master of Science Teaching program were involved in creating classroom materials based around VLA research. All the teachers are expected to present posters at the January AAS meeting in San Diego.

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 2000 there were five 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.

In 2000 a special program to support long term (one to four month) visits to Socorro to work on VLBA projects was announced.

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 2000 there were eight 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 over a hundred thousand people per year. At our VLA and Green Bank sites we run visitor centers to facilitate these experiences, and to provide the necessary infrastructure to support public attendance by providing a unique experience, we serve both the community interest and focus attention on NRAO. Over the next few years, we plan to improve and expand the visitor centers at both major sites, as described below.

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 more than 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 outdoor balcony on the control building, views of the electronic equipment and the control room. A free brochure guides visitors around 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, and also will become the centerpiece for a wide range of new educational outreach programs.

The Albuquerque architectural firm Stevens Mallory Pearl Campbell (SMPC) has donated its efforts to produce the initial design for a new, 20,000-square-foot visitor center at the VLA. In addition to extensive exhibit space, this facility will include an auditorium, classroom and gift shop, as well as staff office and workshop space. This new facility will allow NRAO to offer a staffed visitor center, regular guided tours, and public-education presentations. The new visitor center also will serve as the home for expanded programs for the formal educational community, including on-site science programs for K-12 students and teacher workshops aimed at integrating research and engineering aspects of the VLA into classroom curricula. Funding for the new visitor center will be sought from private corporations and foundations, individuals and appropriate government agencies. In the coming year, we will produce a suite of informative materials about this project and prepare material for proposals to funding entities. An initial design concept for a new Visitor Center at the VLA site is shown in Figs VII.1 and VII.2.

These funding efforts will support a planning project that, utilizing the expertise of professional educators and museum specialists, will include proto-typing, testing, and evaluation of new exhibits and produce detailed plans for a new suite of displays and expanded educational outreach efforts. These detailed plans then will form the basis of an implementation program to build and install the new suite of displays and to establish additional outreach partnerships to extend our educational message further throughout the Southwest.

Education and Public Outreach

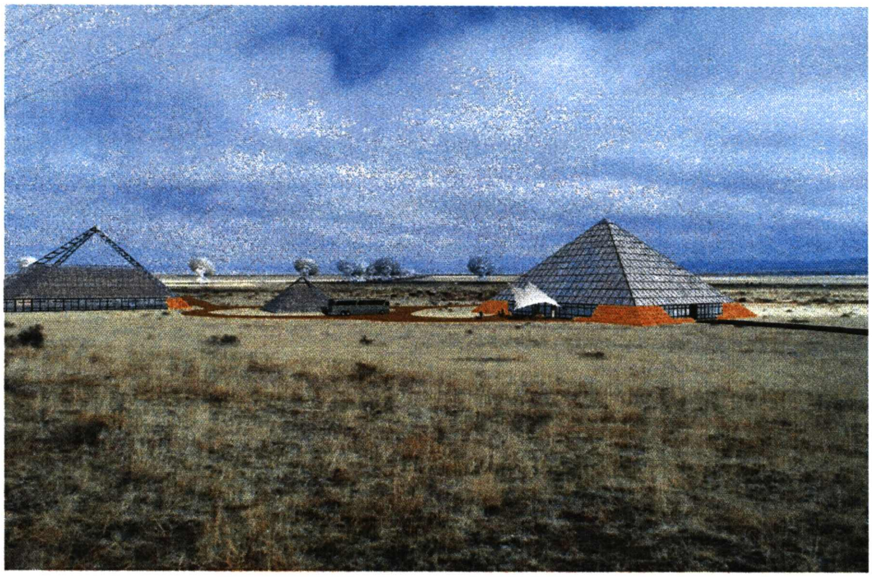


Fig. VII.1 - External view (SMPC)

Fig. VII.2. Artist's conception of VLA Center interior (SMPC).

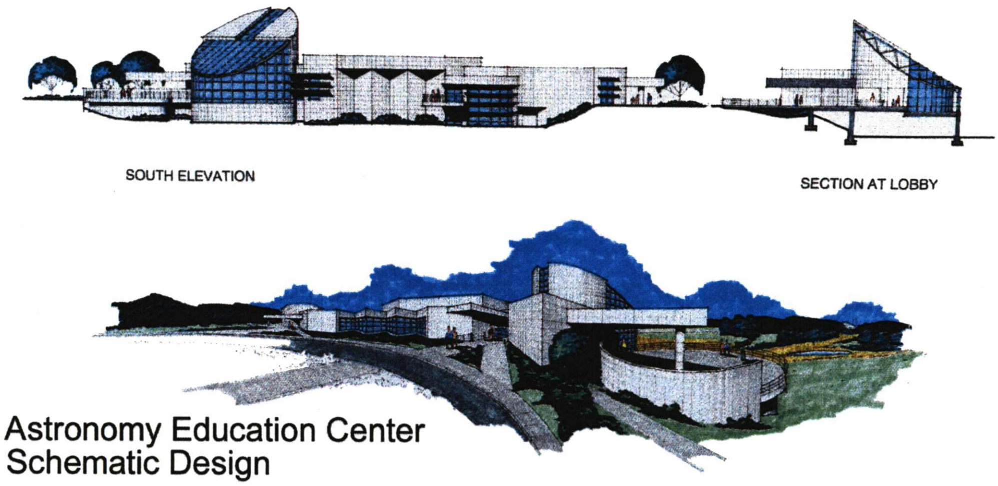


Fig. VII.3. Green Bank Astronomy Education Center (SEM)

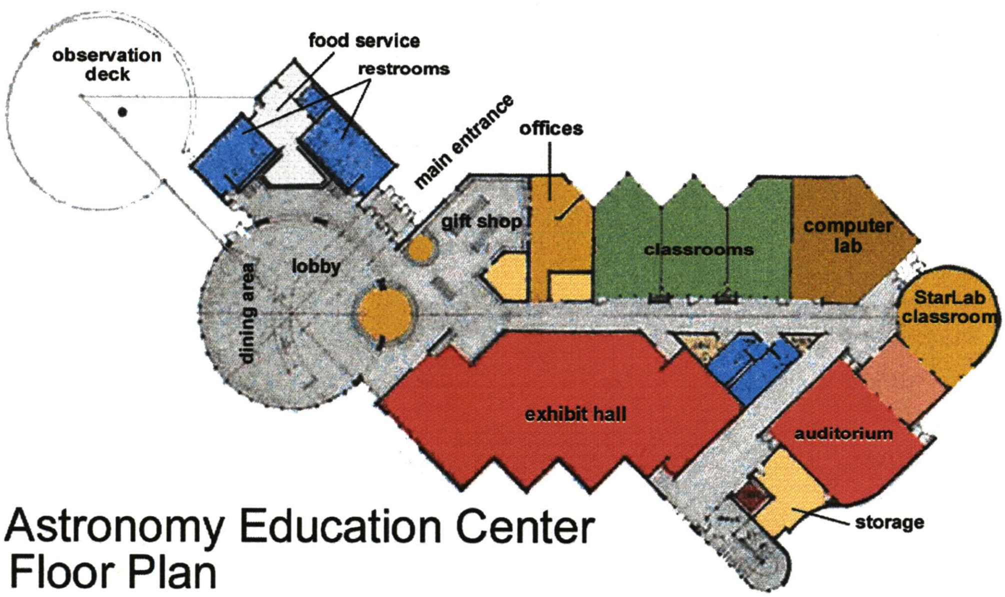


Fig. VII.4. AEC floor plan (SEM).

Education and Public Outreach

In Green Bank, NRAO is on track to open a new astronomy education and visitor's center in summer 2002. 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. Most of the design work has been completed, and we hope to bid for construction in January 2001 (Fig. VII. 3 and 4). The learning center will contain exhibit space, classrooms, auditorium, gift shop, offices and astronomical observing instruments. Funds in the amount of $3.66 million have been secured through a NASA appropriation for construction. We continue to seek additional funds from the NSF, the state of West Virginia and private foundations for the construction of the Astronomy Education Center.

In the fall of 1998, a Green Bank proposal to the NSF Informal Science Education Division received $1.1 million in funding. Our project, Catching the Wave, will result in interactive exhibits and new programs for tourists and school children in the West Virginia and surrounding region. Programs being developed through this project are aligned with national and state science education goals, and as such can potentially be productive enhancements to the science education of every K-12 student in the state and region. In 1999/2000, Catching the Wave exhibit ideas and program outlines were placed on the NRAO-GB education web site for review and comment. Simple exhibit prototypes were field-tested at the tour center. John Moser Productions will produce the exhibits for the Astronomy Education Center (Fig. VII.5).

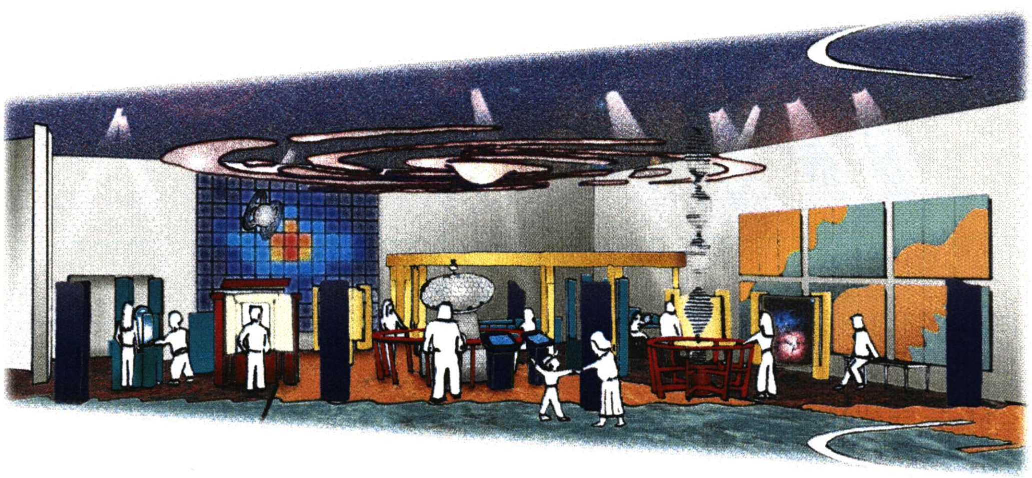


Fig VII.5. AEC exhibit concept (John Moser Productions).

Education and Public Outreach

Tours

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, we offer regularly scheduled weekend tours, often involving our REU summer students as guides. Throughout the year, by appointment, we conduct guided tours for educational and scientific groups. These include school and university classes, amateur astronomy clubs, engineering societies, and others. Typically there are more than 60 of these special tours per year, serving more than 1,500 people.

In the past year, we provided guided tours to elementary and secondary school groups from New Mexico, Arizona, Texas, and Louisiana. 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. We distribute a booklet entitled "Bringing Your Class to the VLA," that provides teachers with background information and tips on maximizing the educational value of a class visit through prior preparation and follow-up activities.

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 (direct tally) in 1999 show 25,000 visitors to the Observatory, a 14 percent increase over 1998 (a number expected to increase significantly over the next few years given interest in the GBT and the development of the Astronomy Education Center). In addition to the bus tour, visitors hear a brief talk about radio astronomy, participate in demonstrations and watch a slide show. In spring 2000, NRAO received a $17,000 grant from the West Virginia Division of Tourism in 2000. The award is being used to advertise the Green Bank tour program to regional markets and in the development of an up-to-date audiovisual show.

During the 2000 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. Local teachers were also trained in the use of the StarLab in 1999/2000; NRAO makes it available to schools at no charge. In 2000 every elementary/middle school in the county used StarLab, impacting over 600 students and parents.

Conference Displays

Maintaining a high visibility at scientific and professional meetings is an important way for us 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 has regularly run a display at the winter and summer meetings of the

American Astronomical Society (AAS). During 2000 we presented displays at both AAS meetings (Atlanta and Rochester), and in collaboration with ESO, at the IAU General Assembly in Manchester (ALMA). A visual of the joint ALMA display is shown in Fig VII.6. At both the Atlanta and Rochester AAS, the main NRAO booth was devoted to presenting GBT science and instrumental capabilities. Additional booths highlighting AIPS++ and (in Rochester) the EVLA project were also presented. During 2001 the focus of our display efforts will be GBT, EVLA, ALMA and AIPS++.

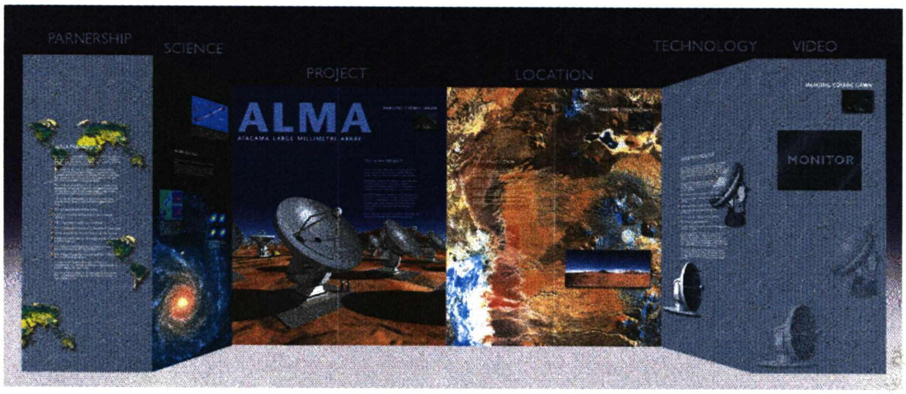


Fig. VII.6. IAU2000 ALMA Display

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 web site www.nrao.edu is now 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. During 2000 there were typically over 700 sessions per day, each browsing around ten separate pages. The total amount of data loaded from the NRAO site over a year is around 100 GB. Web site hits went up substantially around the time of the GBT dedication (the event was covered extensively in the on-line media, generating great interest).

At present, our site contains information about radio astronomy, our instruments, press releases, data products and general contact information. In response to negative comments concerning the design and utility of our site, we redesigned our web site in late 1999. We are currently planning a mirroring system around the four main NRAO sites, enabling rapid access to our site internally and from anywhere in the U.S.; we have already purchased a new central server in Charlottesville, and will implement it over the next 6-12 months.

We are currently testing a "Radio Science Depository" where interesting images and other results can be stored and indexed for access by researchers and the general public (initial response has been slow). Other potential projects for our web site include real-time displays of our instruments (previously available for the 12 Meter Telescope, in planning for the GBT). A virtual tour prototype for the GBT is underway; staff in Green Bank 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.

Publications

During 1999/2000 we have worked with the firm of Gotham Graphix (Charlottesville) to design a suite of promotional literature. Two documents, one for scientific audiences and one for the general public, are being produced for each major instrument (VLA, VLBA, GBT and ALMA), describing their scientific and technical capabilities and achievements. They are intended for distribution through visitors centers, tourism promotion outlets, to educators, and at AAS and other scientific meeting. The covers of the Green Bank documents are shown in Fig. VII.7; the documents for other sites/projects will be along similar design styles. This effort will continue in 2001.

The NRAO quarterly newsletter was redesigend during late 1999, and the new format has been used in 2000. The use of modern publishing tools has enabled the addition of science articles gathered from NRAO and the wider community, leading to a more modern product.

To celebrate two important events in the Observatory (the VLA 20th Anniversary and the GBT Dedication) site posters were produced using professional photographers (Fig. VII.7). Over the next year we plan to produce a suite of striking posters highlighting all of our sites/projects for distribution at official events, professional meetings, schools, etc.

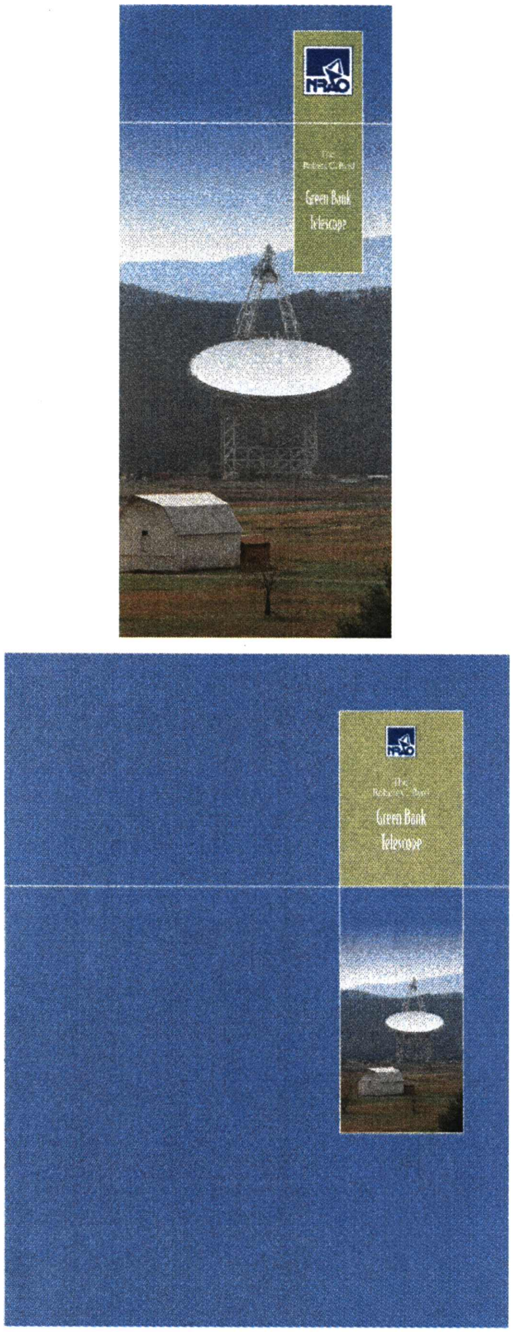


Fig. VII.7. Green Bank scientific/public brochures.

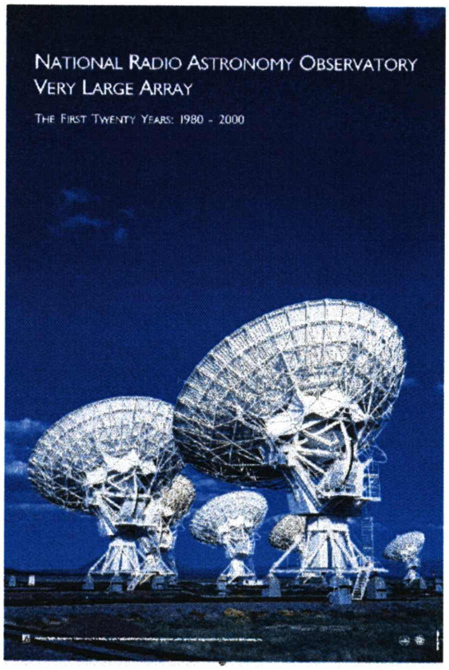


Fig. VII.8. Site posters

Education and Public Outreach

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 U.S. 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.

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 cast-off 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.

Amateur Radio Operators

NRAO is ideally positioned to use the amateur radio community, with more than 600,000 licensed operators in the U.S., 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 members present lectures to amateur radio organizations and NRAO provides displays and information about radio astronomy at amateur radio events. We also have frequent contact with national amateur radio publications, resulting in articles on NRAO scientific results and technical developments. An example is Dave Finley's feature article on the GBT, "Ham Radio and the World's Largest Fully-Steerable Antenna," in the August 2000 issue of QST, the nation's largest-circulation amateur radio magazine.

At the dedication of the Green Bank Telescope, hams assembled under the call-sign of Grote Reber (W9GFZ) and made 1,922 contacts in 51 countries.

Special Events

A big EPO event occurring during the year was the dedication of the GBT (covered elsewhere in this document). New scientific and public-level brochures were prepared for the event, and site/interview video footage was made for distribution. A 120-second video describing the GBT was created by ESI productions (Charlottesville), which was marketed to the top 50 television markets in the U.S. and placed on the web by MSNBC. Independent estimates of the coverage that the video clip received put the potential U.S. audience for this material at more than 10 million viewers. Additionally, web and print news reports have been tracked.

A celebration marking the 20th anniversary of the Very Large Array was held in Socorro on 23 August 2000, and was attended by Dr. Rita Colwell, Sen. Pete Domenici (R-NM) and

AUI and NRAO dignitaries. A goal of the meeting was to focus attention on the VLA Expansion project (EVLA), described elsewhere in this document.

Staffing

At present there are five full-time employees allocated to PR and Education at NRAO. During 2000 Helen Sim from the Australia Telescope National Facility visited for four months, assisting in general documentation production and the GBT dedication. Increased support from the NRAO occurred during 1999-2000 as our EPO efforts expanded; however to continue this we require additional funding for documentation, display and promotional purposes. In late 2000 we will be hiring a part-time education officer in NM, focusing on community relations and funding for the new Visitors Center. We will also add another EPO position in Charlottesville to begin expanding ALMA EPO efforts, and support on-going NRAO programs.

MMA (Participation in ALMA)

Overview

The Atacama Large Millimeter/Submillimeter Array (ALMA) is a revolutionary instrument in its scientific concept, its engineering design, and its organization as a global scientific endeavor. ALMA will provide scientists with precise images of galaxies in formation seen as they were twelve billion years ago; it will reveal the chemical composition of heretofore unknown stars and planets still in their formative process; and it will provide an accurate census of the size and motion of the icy fragments left over from the formation of our own solar system that are now orbiting beyond the planet Neptune. These science objectives, and many hundreds more, are made possible owing to the design concept of ALMA that combines the imaging clarity of detail provided by a 64-antenna interferometric array together with the brightness sensitivity of a single dish antenna.

The challenges of engineering the unique ALMA telescope begin with the need for the telescope to operate in the thin, dry air found only at elevations high in the Earth's atmosphere where the radiation at millimeter and submillimeter wavelengths from cosmic sources penetrates to the ground. ALMA will be sited in the Altiplano of northern Chile at an elevation of 5000 meters (16,500 feet) above sea level. The ALMA site is the highest, permanent, astronomical observing site in the world. On this remote site the 64 12-meter diameter ALMA antennas will each operate superconducting receivers that are cryogenically cooled to less than 4 degrees above absolute zero. The signals from these receivers are digitized and transmitted to a central processing facility where they are combined and processed at a rate of 1.6×10^{16} operations per second. As an engineering project, ALMA is a concert of 64 precisely-tuned mechanical structures each weighing more than 50 tons, superconducting electronics cryogenically cooled, and optical transmission of terabit data rates—all operating together, continuously, on a site more than three miles high in the Andes mountains.

ALMA is a joint endeavor of nations and science institutes worldwide. The cost and burden of building and operating ALMA will be shared among the participants. This cooperation brings to the Project a broad base of experienced people and resources. Design and Development of ALMA is organized under an agreement between the National Science Foundation and a European consortium led by European Southern Observatories. An agreement for the construction and operations phases is expected in 2001.

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 of the chemical precursors necessary for life itself.

ALMA is a radio telescope. It 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 is a synthesis telescope. It consists of more than 64 precision antennas all operating in concert to provide the imaging capability of a single antenna as large as 12,000 meters in diameter. The signals received by the superconducting receivers on each antenna are digitized and processed in a special purpose computer or signal correlator. Images of astronomical objects and cosmic phenomena are 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.

By extending the high-resolution imaging techniques of radio astronomy to millimeter and submillimeter wavelengths, ALMA will achieve an astronomical imaging capability equal in clarity of detail to the imaging capability of the Hubble Space Telescope (HST), but it will do so at wavelengths where the richness of the sky is provided by thermal emission from the cool gas and dust from which stars and all cosmic objects form. In this sense, ALMA is the appropriate scientific complement to the HST, and its successor instrument the Next Generation Space Telescope (NGST), instruments which image clearly light from stars and collections of stars such as galaxies. Together ALMA and HST (or NGST) trace the evolution of planets, stars and galaxies from their formation (ALMA), through their luminous lifetimes to their demise (HST/NGST).

The highest resolution imaging capability of ALMA comes from observations made with the ALMA antennas arranged in the most extended configuration. Lower resolution imaging of large areas on the sky is achieved by a compact configuration in which all the antennas are placed very close to one another. This *reconfigurability* gives ALMA a *zoom-lens* capability which allows scientists to tailor the imaging capabilities of the instrument to the astronomical object under study. Uniquely, ALMA is a complete imaging telescope.

ALMA's unprecedented combination of sensitivity, angular resolution and imaging fidelity at the shortest radio wavelengths for which the Earth's atmosphere is transparent 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.

ALMA is conceived and designed to be a long-lived user observatory. Its scientific impact at any time will be facilitated by the quality of its instruments and limited only by the creativity and industry of its scientist-users.

In Table VIII.1, the science requirements and flowdown technical requirements derived from joint discussions between NRAO, ESO and the scientific community are presented. Table VIII.2 shows the project scope and baseline specifications.

Table VIII.1 ALMA Science Flowdown to Technical Specifications

Science Requirement and Examples	Technical Requirements Needed to Achieve
1. High Fidelity Imaging • Imaging spatial structure within galactic disks • Imaging chemical structure within molecular clouds • Imaging protostars in star formation regions	• Reconfigurable Array • Robust Instantaneous uv-coverage, $N_{ant} > 60$ • Precision Pointing, 6% of the HPBW • Antenna Surface Accuracy RMS = 20 microns • Primary Beam Deviations < 7% • Total Power <u>and</u> Interferometric Capability • Precise (1%) Amplitude Calibration • Precise Instrumental Phase Calibration (<10 degrees rms) • Precise atmospheric phase calibration (<15 degrees rms) with compensation using both fast switching and water vapor radiometry
2. Precise Imaging at 0".1 Resolution • Ability to discriminate galaxies in deep images • Imaging protoplanets orbiting protostars • Imaging nuclear kinematics	• Interferometric baselines longer than 3 km • Precise Instrumental Phase Calibration (<10 degrees rms) • Precise atmospheric phase calibration (<15 degrees rms) with compensation using both fast switching and water vapor radiometry

MMA (Participation in ALMA)

Science Requirement and Examples	Technical Requirements Needed to Achieve
3. Routine Sub-milliJansky Continuum Sensitivity • To enable imaging of the dust continuum emission from cosmologically-distant galaxies • To enable imaging of protostars and protoplanets throughout the Milky Way • To enable astrometric observations of solar system minor planets and Kuiper-belt objects	• Array site with median atmospheric transparency < 0.05 at 225 GHz • Quantum-limited SIS receivers • Antennas with warm spillover < 5K, and aperture blockage < 3% • Antennas of aperture efficiency > 75% • Wide correlated IF bandwidth, 16 GHz • Dual polarization receivers • Array collecting area, $ND^2 > 7000\ m^2$
4. Routine Milli-Kelvin Spectral Sensitivity • Spectroscopic probes of protostellar kinematics • Spectroscopic chemical analysis of protostars, protoplanetary systems and galactic nuclei • Spectroscopic studies of galactic disks and spiral structure kinematics	• Array site with median atmospheric transparency < 0.05 at 225 GHz • Quantum-limited SIS receivers • Antennas with warm spillover < 5 K, aperture blockage < 3% • Antennas with aperture efficiency > 0.75 • Wide correlated IF bandwidth, 16 GHz • Dual polarization receivers • Array collecting area, $ND^2 > 7000\ m^2$ • Array collecting length, ND > 700 m
5. Wideband Frequency Coverage • Spectroscopic imaging of redshifted lines from cosmologically-distant galaxies • To enable comparative astrochemical studies of protostars, protoplanets and molecular clouds • To enable quantitative astrophysics of gas temperature, density and excitation	• Receiver bandwidths matched to the width of the atmospheric windows • Tunable local oscillator matched to the bandwidth of the receivers • Cryogenic capacity > 1 W at 4 K

MMA (Participation in ALMA)

Science Requirement and Examples	Technical Requirements Needed to Achieve
6. Wide Field Imaging, Mosaicing • Imaging galactic disks • Imaging the astrophysical context of star formation regions • Imaging surveys of large angular regions • Searches for dusty and luminous protogalaxies • Searches for minor planets in the solar system • Solar astrophysics	• Compact array configuration, filling factor > 0.5 • Instantaneous uv-coverage that fills more than half the uv-cells, $N_{ant} > 60$ • Precision pointing, 6% of HPBW • Antenna surface accuracy 20 microns • Total power <u>and</u> interferometric capability • Precise amplitude calibration, 1% • Precise Instrumental Phase Calibration (< 10 degrees rms) • Correlator dump time 10 msec • Capability to handle data rates > 100 Mbyte/sec
7. Submillimeter Receiving System • Measurement of the spectral energy distribution of high redshift galaxies • Chemical spectroscopy using CI and atomic hydrides • Determination of the CII and NII abundance in galaxies as a function of cosmological epoch	• Array site with median atmospheric transparency < 0.05 at 225 GHz • Quantum-limited SIS receivers • Antennas with warm spillover < 5 K, aperture blockage <3% • Antennas with aperture efficiency > 0.75 • Precise Instrumental Phase Calibration (<10 degrees rms) • Precise atmospheric phase calibration (<15 degrees rms) with compensation using both fast switching and water vapor radiometry
8. Full Polarization Capability • Measurement of the magnetic field direction from polarized emission of dust • Measurement of the magnetic field strength from molecular Zeeman-effect observations • Measurement of the magnetic field structure in solar active regions	• Measure all Stokes parameters simultaneously • Cross correlate to determine Stokes V • Calibration of linear gains to < 1%
9. System Flexibility • To enable VLBI observations • To enable pulsar observations • For differential astrometry • For solar astronomy	• Ability to phase the array for VLBI • Sum port on the correlator for external processing • Sub-arraying, 4 subarrays simultaneously • Optics designed for solar observations

Table VIII.2: Baseline 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

The Joint U.S. - European ALMA Project

The Atacama Large Millimeter Array Project was created by the U.S. National Science Foundation and the European Coordinating Committee (ECC) from an agreed merger of the U.S. Millimeter Array (MMA) Project and the European Large Southern Array (LSA) Project. The ALMA Project is founded by means of a Memorandum of Understanding (MOU)[1] signed June 1999 by the NSF and the ECC. The agreement expressed in the MOU is for the Design and Development phase (*Phase 1*), which ends December 31, 2001; however both sides also express their intention to complete and sign an agreement for ALMA construction (*Phase 2*) within the period agreed for Phase 1.

[1] Memorandum of Understanding concerning the design and development phase of a large aperture millimeter/submillimeter array, to be known as the Atacama Large Millimeter Array (ALMA), June 1999.

MMA (Participation in ALMA)

The U.S. side of the ALMA project is led by the National Radio Astronomy Observatory (NRAO), which is operated by Associated Universities, Inc. (AUI) under a cooperative agreement with the NSF[2]. The European side of the project is a collaboration between the European Southern Observatory (ESO), the Centre National de la Recherche Scientifique (CNRS), the Max-Planck-Gesellschaft (MPG), the Netherlands Foundation for Research in Astronomy (NFRA) and Nederlandse Onderzoekschool Voor Astronomie (NOVA), the United Kingdom Particle Physics and Astronomy Research Council (PPARC), the Swedish Natural Sciences Research Council (NFR), and the Spanish Instituto Geografico Nacional (IGN) and Oficina de Ciencia y Tecnologia (OCYT).

Project Development

The U.S. Millimeter Array Project

Planning for the Millimeter Array began at the National Radio Astronomy Observatory (NRAO) in 1982. A series of community science workshops sponsored by the NRAO were held in the decade of the 1980s that served to define the scientific requirements and technical specifications for the MMA. The result of these workshops became the basis for the MMA Proposal[3] submitted by Associated Universities, Inc., (AUI) to the NSF for the design, construction and operation of the MMA.

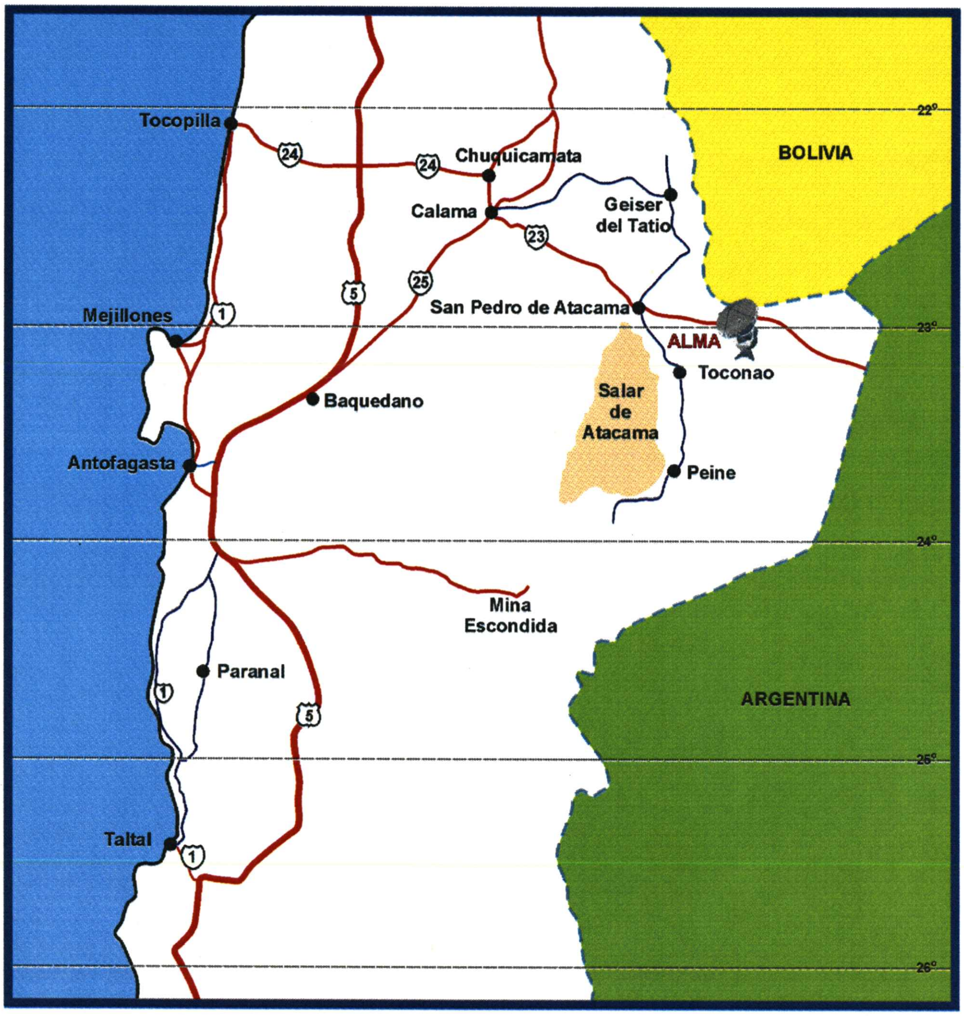
The Millimeter Array Project proposed by AUI in 1990 was an array of 40 antennas each of 8 meters diameter equipped with receivers covering all the atmospheric windows at millimeter wavelengths, specifically to a highest frequency of 350 GHz. The MMA proposed then was optimized for precision imaging which is achieved by having a sufficient number of antennas—or more precisely, a sufficient number of interferometers, pairs of antennas—to fill the uv-plane quickly and completely. The figure of merit for precision interferometric imaging is ND, the product of the number of antennas in the interferometric array, N, and their diameter D. For the MMA proposed by AUI in 1990 this figure of merit, ND = 320.

Identifying a suitable site for the MMA was a major undertaking that occupied the decade 1985 to 1995. Remotely operated atmospheric testing equipment was built and operated at four potential MMA sites. These sites were: the Magdalena mountains near Socorro, NM; the White Mountains near Springerville, AZ; Mauna Kea on the island of Hawaii and the Altiplano in northern Chile. The testing equipment continuously monitored the atmospheric transparency of the site and provided meteorological data. Summer incursions of moist gulf

[2]Cooperative Agreement No. AST9223814 between the National Science Foundation, Arlington, VA 22230 and Associated Universities, Inc., Washington, D.C. 20036.

[3]"The Millimeter Array," proposal submitted to the National Science Foundation by Associated Universities, Inc., July 1990.

air make the sites in the continental United States unusable for the scientific objectives of the MMA many months of each year. The site in Hawaii is greatly superior to the continental U.S. because the steady trade winds maintain a nearly constant climate year round. But the flat area required for the MMA is not available on Mauna Kea. The



identification of a truly excellent, and large site in the Chilean Altiplano proved ideal for the MMA and led to its recommendation to the NSF[4]. A map of northern Chile showing location of the site is presented above.

[4]"Recommended Site for the Millimeter Array," submitted by Associated Universities, Inc. to the NSF May 1998.

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The exceptionally dry conditions on the Chilean site meant that the sensitivity of the MMA would not be limited by atmospheric emission and that the full scientific gain of quantum limited receivers could be realized on that site. It also meant that the submillimeter atmospheric windows were also transparent from that site, unlike the case for the other potential sites studied for the MMA. Recognizing this, the scientific Millimeter Array Advisory Committee (MAC) recommended in 1995 that an observing capability in at least one of the submillimeter windows become part of the baseline MMA project. That committee report is available on the web at http://www.mma.nrao.edu/committees/. This recommendation is an addition to the scope of the array proposed by AUI, but it was recognized to be extremely desirable scientifically and it exploits fully the potential of the site. With this addition, the scope of the MMA Project was complete.

The Large Southern Array Project

Since 1991 European astronomers met and discussed concepts for a large millimeter-wavelength array for the southern hemisphere, the *Large Southern Array*. The LSA concept emphasized very high sensitivity achieved through large collecting area, 10,000 m^2, at millimeter wavelengths. In addition, an array configuration as large as 10 km in extent was specified in order to achieve angular resolution of 0\".1 at millimeter wavelengths, and the array required a high quality site at an elevation above 3000 meters.

In order to refine the LSA concept, and to explore possible sites to investigate the technology required, the Institute de Radio Astronomie Millimetrique (IRAM), the European Southern Observatory (ESO), the Onsala Space Observatory (OSO) and the Netherlands Foundation for Research in Astronomy (NFRA) agreed to pool their resources in a joint European study. A Memorandum of Understanding to this end was signed in April 1995, with the goal of producing a report within two years which could be discussed by the community and serve as the basis for further studies. Technical design and site studies followed culminating in a report[5] that was submitted to the sponsoring institutions.

The Merged US-European ALMA Project

In 1997 representatives of the MMA and LSA project teams met and agreed on the desirability of merging these two projects into a single project of larger scope. The merged project was to emphasize both the precision imaging requirement of the U.S. scientists with the requirement of the European group for spectroscopic imaging of molecular gas in cosmologically-distant galaxies. The latter scientific requirement has as its figure of merit the product ND^2 and, for fixed cost, favors an array of a small number of large antennas: the European group favored antennas of 15-16 meters diameter. Clearly, to merge the two projects a compromise is required on the antenna diameter between the eight meters proposed by the U.S. group and the 15-16 meters favored by the Europeans. While this discussion was in progress the MMA scientific advisory committee, the MAC, encouraged the MMA Project to focus design studies on an antenna larger than 8 m in hopes of securing the merger by compromising with the European project. This recommendation

[5]"LSA: Large Southern Array Combined Report," April 1997.

from the 1997 MAC meeting is also available on the web at the same URL as noted above. The MMA Project heeded this recommendation and 12 m diameter was adopted as the baseline specification for the combined U.S.-European Project provided that the design of that antenna would maintain its performance in the submillimeter. With this change to the U.S. specification, and the agreement of the U.S. and European communities on the science goals for the merged array, it became feasible for the NSF and the ECC to conclude the MOU for Phase 1 of the combined, "Atacama Large Millimeter Array," Project.

Realization of ALMA in two Phases

Recognizing that the scale of the U.S. Millimeter Array Project set it apart from many NSF initiatives and projects, the NSF and AUI agreed that it was desirable to structure the MMA project in two phases: A design and development, or prototyping, phase to be followed by review and separate approval for the construction phase. Funding for the design and development work in the U.S. began in 1998 . The ALMA Coordinating Committee (ACC) adopted this same two-phase structure for the U.S.-European ALMA Project and this is now codified in the ALMA MOU. The ALMA Phase 1 extends to the end of December 2001.

ALMA Design and Development Project

The goals and deliverables of the ALMA Design and Development (Phase 1) Project as specified in Article 6 of the MOU are two, namely:

- The objective of Phase 1 is to completely define the work to be carried out in Phase 2 and its cost and to negotiate the Agreement for its implementation. The definition shall include scientific and technical requirements, proposed technical and management approaches, a Work Breakdown Structure (WBS) and the cost estimate and schedule for Phase 2, as derived from this WBS.
- The project shall show in Phase 1 both the feasibility of the proposed technical approach to meet the requirements, and the reliability of the cost estimate and schedule, by performance measurements on prototype components, and subsystems, such as prototype antenna(s).

This work is underway both in Europe and in the U.S. Specific plans for CY2001 in the context of this NRAO Program Plan are summarized below.

ALMA Construction Phase Plans

ALMA construction is planned to begin in 2002 upon completion of the design and development phase of the project. An abbreviated, but otherwise complete, WBS for the construction phase of the ALMA Project has been created jointly by the European and U.S. ALMA Project teams.

The remote, overseas site for ALMA creates the need to organize the construction project around integration facilities in the U.S. and Europe and to ship to the site only completed, functioning, and tested hardware. This is to minimize costly overseas construction staff. For the ALMA construction project the initial system integration, and all the testing and evaluation of the two prototype antennas (one provided by the European side of the Project and the other by the U.S. side) will be done at the NRAO VLA site near Socorro, NM, where office/laboratory facilities and crafts specialists are available . In Chile, the first two years

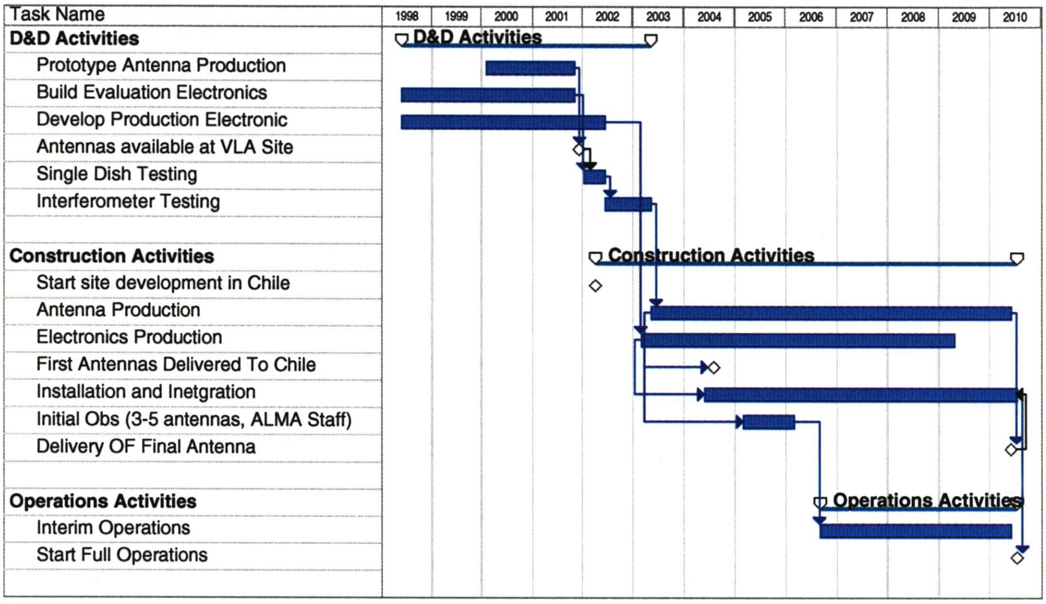

Figure VIII.1 ALMA top level schedule in both the Design and Development and Construction phases.

of the construction project will emphasize development of the initial phase of the site civil works. This includes not only construction on the array site of the first roads, power generation and distribution system and buildings, but it also includes the initial phase of construction of the Operations Support Facility (OSF) in the nearby village of San Pedro de Atacama. Only in the third year of the ALMA construction project is the contract let for the production suite of antennas. Once the first antennas arrive in Chile the system integration task will relocate to Chile. One important part of the system integration is testing and commissioning of the newly arriving hardware. That will be done by involving the European and U.S. scientific community in the testing process of the array; a process that will gradually and naturally evolve into interim scientific operations of ALMA.

Program Plan for Design and Development: Plans for CY2001

The design and development phase activities have progressed at a rapid pace in spite of the need to integrate European involvement in all areas. Close and effective collaboration is now occurring throughout the development tasks. We have now held more than a dozen major design reviews jointly with the Europeans. Additionally, the Japanese are now invited to participate in these reviews as well.

MMA (Participation in ALMA)

The MMA project documentation is in the process of being converted to ALMA documentation. The MMA Project book has become The ALMA Test Interferometer Project Book and the ALMA Project Book. The former can be found at http://www.tuc.nrao.edu/~demerson/almapbk/test_int/, while the later can be found at http://www.tuc.nrao.edu/~demerson/almapbk/construc/ . These documents represent the current agreements between the U.S. and European teams on all areas of the project.

Two contracts have been let for prototype antenna procurements, one on the U.S. and one on the European side. An engineering concept of the prototype antenna being built by Vertex Antenna Systems, LLC., is shown in Figure VIII.2. The two antenna procurements

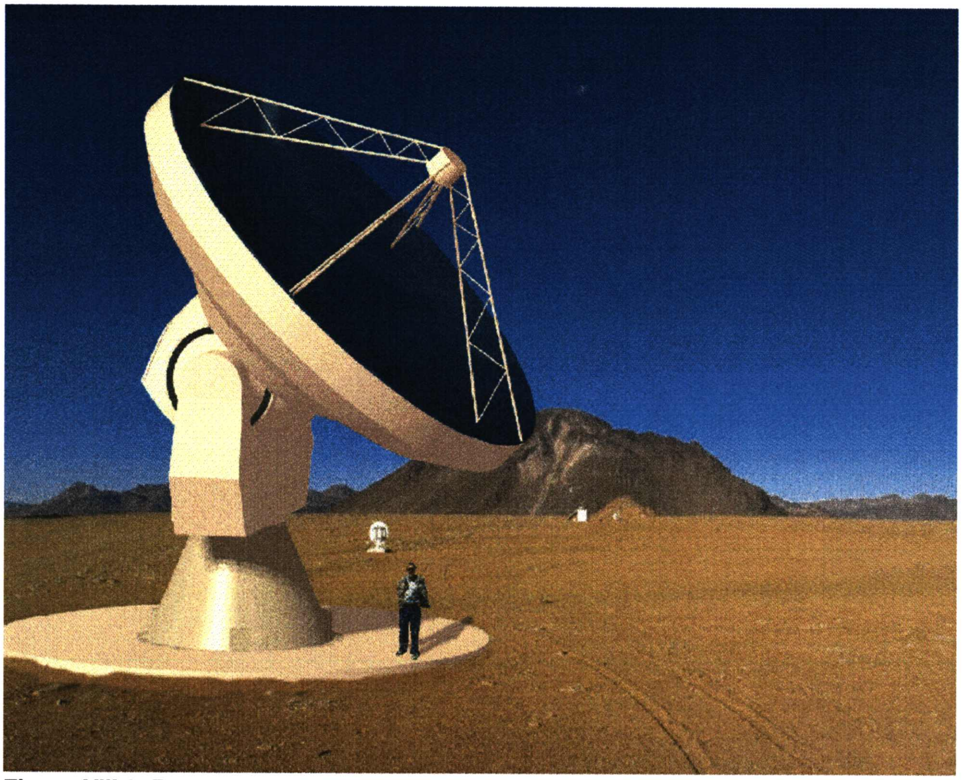

Figure VIII.2 Prototype antenna being built by Vertex Antenna Systems, LLC.

are for different designs that each meet a common set of requirements and a nearly identical set of detailed Interface Control Documents (ICDs). The ICDs were carefully coordinated to insure that each antenna will have compatible mechanical, electrical and control interfaces. Both antennas are scheduled to be erected at the VLA site by November 2001. It is anticipated that the design providing the best overall performance, as determined by the testing to be carried out at the VLA site, will be selected for production for all sixty four antennas.

Work is in progress for the electronics necessary to carry out the testing of these two

antennas. Test receivers are being fabricated at the Tucson lab. ESO has provided funding to build the receiver for their antenna. IF electronics for the test receivers are being fabricated in Socorro. A test correlator has been completed at the CDL and is ready for shipment to the VLA site.

A major design decision for ALMA this year was to distribute the LO reference photonically. This novel concept uses the difference frequency between two phase locked lasers as the millimeter wave reference for the local oscillator. These lasers, located centrally, are combined and fed via optical fiber to each of the antennas. The technique has been successfully demonstrated in the lab. The demonstration included line length correction to maintain phase matching independent of thermally induced changes in fiber characteristics. This elegant solution will save significant production costs.

CY2001 will be the fourth year of design and development for the ALMA Project. The planned budget, broken down by WBS level one element is shown in Table VIII.3. Table VIII.4 shows the project totals.

TABLE VIII.3: CY2001 Budget By WBS Element ($k)

WBS Element	Labor	Travel	Contracts	Materials and Services
Administration	907	87	0	460
Site Development	0	15	0	9
Antenna	303	40	75	120
SIS Mixers	776	10	414	174
Receivers	748	50	0	150
LO Multipliers	299	15	0	135
LO Photonics	387	20	0	263
LO Reference & Back-end	655	20	0	510
Correlator	378	10	0	52
Computing	706	57	0	57
System Integration	469	40	0	199
Calibration & Imaging	199	20	0	30
TOTALS	**$5,827**	**$382**	**$489**	**$2,159**

TABLE VIII.4: CY2001 Totals ($k)

Labor (70.8 FTEs)	$5,827
Travel	382
Material & Services	2,159
Contracts	489
Management Fee	180
COST	**$9,037**
Contingency	268
Adjustments:	
ESO Reimbursements	(255)
Carryover	(100)
SUB TOTAL	**$8,950**
NSF Committee Functions (Held by NSF)	50
TOTAL	**$9,000**

MMA (Participation in ALMA)

As shown in the above Tables VIII.3 and VIII.4, planning for a fourth year of design and development for ALMA is based on an assumed $3M augmentation of the $6M contained in the President's request. This augmentation follows the recommendation of the MMAOC that the MMA design and development program continue at its present pace. Funding at the augmented level will assure that we maintain the momentum created during the previous three years.

As this fourth year of design and develop is expected to lead directly to the construction phase in 2002 there are a number of critical activities planned. These activities include:

1. Two prototype antennas of different designs, one supplied by the U.S. and one by Europe, will be delivered to the VLA site for evaluation. Testing starting in 2001 and completed in 2002 will lead to the selection of a single design to replicate for the 64 antennas required for ALMA.

2. Construction of test interferometer hardware and software will be completed during 2001. These systems include evaluation receivers for each of the prototype antennas, complete LO and IF systems, fiber optic IF data transmission, holography beacon and receiver, antenna nutators, and monitor and control software. A correlator and digitizers for the test interferometer were previously completed and are available. This hardware will support the testing required to verify the performance of the prototype antennas that will lead to selecting a best design. Additionally, the test interferometer will become a test bed for pre-production prototypes of ALMA hardware.

3. A CDR of the front-end subsystem is scheduled for early in 2001. Following the CDR, detailed design and prototyping of the cryogenics, frequency cartridges and optics will proceed rapidly to engineering prototypes later in the year.

4. Prototyping of the IF and fiber-optic back-end will accelerate in 2001.

5. The design of the custom correlator chip will be completed early in 2001. Fabrication of prototype quantities will allow construction and testing of prototype circuit boards to verify performance.

6. Tests of ALMA monitor and control software will be carried out using the 12 Meter Telescope at Kitt Peak. These tests, performed by agreement with the University of Arizona, will provide early validation of the telescope control software. This will significantly reduce risk later in the program.

Other activities that are part of the CY2001 budget are intended to address specific risk mitigation efforts, improve coordination of technical tasks with our international partners and involve our university collaborators. These activities include:

1. Maintain Foundries For SIS Fabrication
   The ability to produce SIS junctions in sufficient quantity on the ALMA schedule is

a key risk area. It is prudent to maintain two university based fabrication programs and the ALMA budget accommodates this.

2. Local Oscillator Industrial Partnership
We have an opportunity to join an exciting development program being carried out jointly by JPL and TRW (for the NASA/FIRST Project) to produce MMIC power amplifiers that are directly applicable to the ALMA LO multiplier chains. These amplifiers will provide higher power output compared to existing designs adding needed power margin.

3. University Studies
The ALMA project has received excellent contributions from our university collaborators. In CY2001, there are a number of areas where university assistance is planned for independent analyses and complimentary design tasks.

4. Increase Travel
As we have begun to ramp up the level of interactions with our European partners, it has become clear that we need to plan for periodic extended working visits. Exchanging technical workers for up to three week periods will provide great opportunities to resolve problems rapidly as well as solidify teaming relationships. Additional travel to Japan is anticipated to complete the planning for the Japanese enhancements to the ALMA baseline program.

5. Build Second 4K Test Dewar
The development schedule for SIS mixers and multiplier chains is limited by the availability of a single test dewar. Significant scheduling flexibility could be gained by building a second 4k dewar system. This will also reduce the schedule risk of any unanticipated down-time due to hardware failure of the existing test dewar.

6. Direct Photonic LO Demonstration
The rapidly advancing state-of-the-art in photo-mixers provides an opportunity to reduce the costs of the LO system compared to our baseline plans. A development program at Cal Tech could produce a photo-mixer with sufficient power output to directly meet the receiver LO requirements, eliminating the need for multipliers. We need to fund this demonstration now if the results are to be available prior to freezing the receiver design.

New Initiatives

VLA Expansion

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 which spans the entire breadth of modern astronomy. Yet the VLA's productivity is only a fraction of its potential. 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, and would dramatically increase the scientific productivity of the instrument.

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 much more powerful on-line computing will enable much 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:

1. The continuum sensitivity will increase an order of magnitude or more in several bands.
2. Continuous frequency coverage from 300 MHz to 50 GHz will be obtained.
3. The bandwidth that is transmitted from the antennas, and processed by the correlator, will increase by a factor of 80.
4. The maximum number of spectral channels available, and the maximum frequency resolution, will increase by a factor of over 500.
5. The resolving power will improve tenfold.
6. 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:

1. Measuring the three-dimensional structure of the magnetic field of the Sun.
2. Using the scattering of radio waves to map the changing structure of the dynamic heliosphere.
3. Measuring the rotation speeds of asteroids.
4. Observing ambipolar diffusion and thermal jet motions in young stellar objects.

5. Measuring three-dimensional motions of ionized gas and stars in the center of the Galaxy.
6. Mapping out the magnetic fields in individual galaxy clusters.
7. Conducting unbiased searches for redshifted atomic and molecular absorption lines.
8. Looking through the enshrouding dust to image the formation of high-redshift galaxies.
9. Disentangling starburst from black hole activity in the early universe.
10. 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. And, we can expect that, as with the original VLA, it is likely that the most important discoveries to be made will be those which cannot now be anticipated.

The VLA Expansion Project comprises two major phases:

Phase I: 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:

1 A new correlator, able to support 40 or more antennas, to process broadband signals and to provide vastly improved resolution and flexibility for spectral line work.
2 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.
3 New online computers, operating software and archiving, to enable more powerful and flexible interaction between the telescope and the operators and observers.
4. 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 lower frequencies. 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 which would be re-directed to support the project, and from contributions from foreign partners.

Phase II: The New Mexico Array

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

1. Adding up to eight additional new antennas 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.
2. Adding fiber optic links between the VLA and the inner VLBA antennas, and between the VLA and the additional new antennas.

In addition to this, Phase II *may* include other enhancements:

1. Possible implementation of an improved low frequency capability which will provide frequency coverage from 300 MHz to 1 GHz.
2. 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 (Ultrasensitive Array)

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. Current funding will not allow either project to be completed this year, and it is hoped that these ongoing projects will be completed with new project funds.

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 IX.1 summarizes the proposed new and upgraded VLA Cassegrain observing bands.

Table IX.1 Proposed VLA 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 IX.2 compares the continuum sensitivity of the current instrument with the expected performance of the VLA Expansion. We assume a maximum useable 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' integration, summing over two orthogonal polarizations with the listed instantaneous bandwidths, and with "natural" weighting.

Table IX.2. VLA Point-Source Sensitivity

Wavelength (cm)	Effective BW (GHz)	Expanded VLA T_{sys} (K)	Expanded VLA δS (μJy)	Current VLA (1998) T_{sys} (K)	Current VLA (1998) 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	5.7
11	1.5	29	1.1	-	-
6	3	31	0.82	42	6.4
3.6	3.0	34	0.95	35	5.3
2	4.0	39	1.0	110	20
1.3	6.0	55-70	1.2	160	37
0.9	8.0	45	1.1	-	-
0.7	5.0	66	2.4	90	60
0.6	3	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 HIA Canadian correlator design group at the DRAO is preparing a proposal to fund and build the Expanded VLA correlator. A preliminary proposal has been reviewed by the NRAO, and is now being revised to incorporate suggestions by NRAO staff. It is expected that this proposal will be submitted this fall to the Canadian NRC for consideration for funding. Discussions between the HIA and the NRAO, and between the NSF and the NRC are ongoing. It is our goal that this critical component of the VLA Expansion Project will be started in 2001.

New Initiatives

High Angular Resolution - The New Mexico Array

There is a serious gap in u-v coverage between the 35 km longest baseline of the VLA and the ~ 200 km shortest baseline of the VLBA. We plan to bridge this gap by combining the VLA with nearby VLBA stations, and by adding up to eight new antennas located at distances of ~ 50 to 300 km from the VLA. The proposed new 40-station correlator would be able to independently correlate various subsets of these antennas, giving astronomers an unprecedented flexibility in selection of sensitivity and resolution. These flexible subarrays will (a) increase the resolution of the VLA at all frequencies and enlarge the range of resolutions over which it has scaled-array capability, (b) improve the dynamic range, field of view and extended source sensitivity of the VLBA, and (c) provide the VLBA with a scaled-array capability.

Early studies have indicated that eight outrigger antennas would enable good u-v sampling over the 35–500 km baseline range for the entire visible sky. However, detailed studies to estimate the quality of imaging as a function of number of outrigger antennas, as well as their location, must be undertaken to understand the trade-off between cost and imaging versatility.

The New Mexico Array is the key element of Phase II of the VLA Expansion Project. Detailed studies, and preparation of a complete proposal, are now being started.

Decadal Committee Recommendation

A presentation of the VLA Expansion Project to the radio panel of the Decadal Committee was made in February, 1999. In May of 2000, the Committee released its recommendations for funding in astronomy over the new decade, and gave a very favorable recommendation for the VLA Expansion Project. The project was listed among the top four overall, and was 2nd in ground-based projects. This high recommendation is critically important for acquiring funding for this project.

Anticipated Activity for 2001 and 2002

The planned expenditures for the EVLA project for the next two years are shown in Table IX.3. The table presumes the project will begin early in 2001, and that new NSF funds for this project will be at the $5M level for the first three years. The overall project budget given in the EVLA Phase I proposal calls for a nine-year duration, with a total cost in new funding from the NSF of $49.9M. An alternate plan, with completion in seven years at a total cost $2.3M less, is possible and is preferable to the NRAO, but will require higher yearly expenditures. The displayed table assumes that the EVLA correlator will be built by the correlator group of the HIA (Herzberg Institute for Astrophysics), at the DRAO site in Penticton, B.C. Planning for this correlator is now well advanced, but actual construction of the correlator awaits approval of the project by both parties.

The EVLA project budget presented in the Table IX.3 assumes a contribution by existing staff of $1.2M for 2001, and $1.1M for 2002 (indicated as "Redirected Operations Effort"). Other activities in support of the EVLA Project will include development of the Phase II proposal, and further development of the details of the Phase I proposal.

Table IX.3 EVLA M&S Budget

	2001 ($k)	2002 ($k)
Project Management	$340	$280
Management, planning		
Office Equipment & Supplies		
Advisory Comm support		
Staff Travel & Relocation		
System Integration & Testing	$320	$325
Production, test and lab equipment		
Civil Construction	$745	$695
FO cable, trench and install (200 kft)		
FO cable (550 kft)		
FO manholes, conduit, piers		
Antenna Mechanical	$105	$200
Feed cone, ant mech, HVAC, electrical		
NRE, feed cone (mech eng)		
Cassegrain Receivers	$690	$370
Design & develop new cassegrain systems		
Complete 22 GHz receiver		
Complete 43 GHz receiver		
Feeds	$20	$0
Local Oscillator System	$560	$420
H-maser Frequency Standard & Rb		
LO Prototyping		
Fiber Optic System Prototyping	$205	$350
IF System Prototyping	$150	$320
Computing / Monitor-Control	$150	$150
M/C & Computing Hardware		
Other M&S		
Sub-Total M&S	**$3,285**	**$3,110**
Contingency (15%)	$493	$467
Sub-Total M&S	**$3,778**	**$3,577**
Sub-Total Wages & Benefits	$1,323	$1,826
Total M&S and Wages & Benefits	**$5,101**	**$5,403**
AUI fee 2%	$102	$108
Redirected Operations Effort	**(1,200)**	**(1,100)**
Total	**$4,003**	**$4,411**

Notes: Wages are based on a generic algorithm. The main tasks in 2001 and 2002 will be:

1. Install the fiber optic cable.
2. Develop and prototype the Monitor / Control system.
3. Continue the VLA on-line software rebuild.
4. Design and prototype LO/IF and Data Transmission systems.
5. Complete VLA K and Q-band receivers.
6. Purchase necessary test equipment.

We also will begin to hire additional project staff with the expectation at the project will have funding in the coming years.

New Initiatives

Green Bank Telescope High Frequency & Focal Plane Array Programs

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

The *Day 1* suite of instruments will 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 as regards telescope 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 have been detected in line emission at redshifts greater than ~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 GBT working group has recommended a family of instrument systems for the 3 mm band. The group recommended that the first system to be built be a 68-115 GHz, dual-beam, dual-polarization system, divided into two frequency bands, 68-95 GHz and 90-115 GHz. The low frequency module (68-95 GHz) would be a correlation-type receiver with excellent continuum and spectroscopic performance and would be built first. The high frequency module would be contained in the same cryostat, but would be a total power receiver aimed at spectroscopy. Plans for the first 3 mm module are now complete. If resources are available, work on this receiver will begin in early 2001. The construction of this receiver will take two years.

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 spectroscopy and continuum work in the 3 mm band. Especially exciting is the possibility of placing a large-format bolometer camera (up to several thousand pixels) on the GBT. The exquisite 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. Efforts are underway to form a collaboration for the development and construction of a large-format bolometer camera. 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 sinuous feeds that fully sample 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. A prototype beam-forming array has been tested successfully. A four-year program has been designed for the development and production of a 19-beam L-Band (21 cm) array with competitive noise performance. If resources are available, this program will commence in early 2001.

GBT High Frequency Mission Requirements

The table IX.4 provides an estimate of the staffing levels required to undertake the program described above. The staff positions listed are additional staff needed beyond the resident Green Bank staff. There are currently 4.5 FTEs working in the Metrology Group not shown in this table who would continue on the project. At least one engineer and two technicians from the resident staff would also be available for work on the instrumentation development program. The final year of the chart represents the steady state in which the staff is refining and maintaining the hardware and software already developed.

Table IX.4 GBT 3 mm Development Program
(Additional Staffing Requirements)

Task	Position	Staff in FTEs CY2001	CY2002	CY2003	CY2004	CY2005
Metrology Program (additional positions)						
	Scientists	0.5	0.5	0.5	0.5	0.5
	Technicians	1	1	1	1	0.5
Atmospheric monitoring						
	Engineers	0.1	0.1	0.1	0 1	0.1
	Scientists	0.25	0.25	0.1	0.1	0.1
Instrumentation Development (additional positions)						
	Engineers	1	2	3	3	2
	Technicians	3	3	3	3	2
	Scientists	1	1	1	1	1
Dynamic Scheduling						
	Scientists	1	0.5	0.5	0.5	0.5
	Programmers	1	1	1	0.5	0.25
Totals		**8.85**	**9.35**	**10.2**	**9.7**	**6.95**

Budget Requirements

An estimate of the budget required for the 3 mm development program is given inTableIX.5. Only the 68-115 GHz dual-beam receiver have had engineering studies performed; the remaining costs are rough guesses. Staffing costs are based on the previous table.

Table IX.5. GBT 3 mm Development Program *(Budget)*

Task	Cost in k$ CY2001	CY2002	CY2003	CY2004	CY2005	Sum
Metrology System						
Staff	78	78	78	78	55	**367**
Materials	25	10	10	10	10	**65**
Atmospheric Monitoring						
Staff	24	24	14	14	14	**91**
Materials	10	10	5	5	5	**35**
Dynamic Scheduling						
Staff	124	91	91	62	47	**414**
Materials	10	5	5	5	5	**30**
Instrumentation Development						
Staff	280	358	436	436	312	**1820**
68-115 GHz Dual Beam Rx	119	75				**194**
User-built 3 mm instruments		30	40			**70**
85-115 GHz Focal Plane Array		50	450	100		**600**
Spectrometer Upgrade		200	200	100		**500**
Wideband, Multi-input spectrometer			250	100	50	**400**
GBT 3CAM Bolometer Camera	150	150	1000	1300	400	**3000**
Totals	**$819**	**$1,081**	**$2,579**	**$2,210**	**$899**	**$6,688**

New Initiatives

Grants to Data Analysis

In our Mission Requirements Budget we have included a new program called Student User Support. It would be the first such program for NSF if approved and funded. What are its goals? All NASA missions provide an opportunity to apply for funding along with observing time. We are convinced that NSF should take steps in this direction. The Policy Panel of the Astronomy and Astrophysics Survey Committee has recommended this for ground-based facilities and the Committee itself has endorsed this recommendation in their report "Astronomy and Astrophysics in the New Millennium". We propose to introduce such a program with a *first step* which will address the most pressing need in the user community—better funding for university researchers—in the most productive way—tying those funds to programs that involve graduate students—working on dissertation research.

In 1999, 70 students from U.S. universities used NRAO telescopes in support of their PhD dissertations. We believe a significant program of support for university groups, tied to student observing programs, can be constructed at an annual cost of $2,000,000. As the funding available for user support grows, we propose to extend it next to all university-based users.

Non-NSF Research

Green Bank 85-3 Pulsar Station

One antenna element of the original Green Bank Interferometer known as 85-3 is used as a pulsar monitoring station. This modest program is done through a collaboration between NRAO and university groups at UC Berkeley and Princeton. The program monitors a list of pulsar sources daily to detect changes in the pulsars or the intervening interstellar medium. A considerable number of important and unique results have been obtained from this program that could not be detected without close monitoring. Support for this program is also problematic, however, given the tight budget for priority Green Bank activities. Efforts are underway by the university PI to obtain external funding for the 85-3 pulsar program. If these efforts are ultimately unsuccessful, 85-3 operations will also be suspended.

NRAO Space VLBI Earth Station

Under a contract with NASA, NRAO operates a 13.7 m antenna at Green Bank that serves as one of the primary earth stations for the HALCA/VSOP space VLBI observatory. This has been an extremely efficient and cost-effective operation that has a better than 99 percent valid recording rate. Support for the station through 2001 is currently under discussion at NASA. It is likely that if support for HALCA continues, it will be at a significantly reduced level. The NRAO Earth Station will be available to participate in possible future missions such as RadioAstron, ARISE, and other space observatory projects.

Routine Space VLBI observing with VSOP's HALCA satellite continued in 2000. Given a functional satellite, VLBA observing and correlation with HALCA will continue throughout 2001, albeit at a somewhat reduced level due to funding cuts and satellite constraints. The proposed ARISE (Advanced Radio Interferometry between Space and Earth) mission, which would orbit a 25 meter radio telescope with capabilities similar to the ground VLBA antennas, was recommended by the astronomy decadal survey committee in 2000. In 2001, further development of the technical aspects of ARISE will take place, and details of possible international collaborations will be explored further.

2001 Preliminary Request-Level Financial Plan

Table XI.1 NSF Funding by Function/Site
($ in 000's)

Operational Functions	FTE	Salaries & Benefits	Materials, Services, & Equipment	Travel	Total Budget at NSF Request Level
Observatory Wide Activities	102.3	$7,274	$2,954	$498	$10,726
MMA-ALMA (U.S) *	68.0	5,700	180	0	5,880
GBT Operations	99.9	6,313	860	100	7,273
VLA/VLBA Operations	198.8	11,993	3,481	210	15,684
CDL Revenue & Common Cost Recovery			(540)		(540)
Management Fee			770		770
Total NSF	**469**	**$31,280**	**$7,705**	**$808**	**$39,793**

Source of Funds for Total at NSF Request Level

Operations-new NSF funds	*$32,530*
REU-new NSF funds	*100*
MRI Carryover	*299*
CISE Carryover	*194*
*MMA Particip in ALMA (U S) **	*6,000*
NSF Informal Educ. Carryover	*670*
TOTAL	*$39,793*

Table XI.2. Non-NSF Funding
($ in 000's)

Funding Source	FTE	Salaries & Benefits	Materials & Services	Travel	Total Request Level Budget
NASA OVLBI	7 3	$352	$516	$20	$888
NASA Educ. Ctr.	0.0	0	3,279	0	3,279
ILL/NCSA	3.0	214	34	2	250
Total Non-NSF	**10.3**	**$566**	**$3,829**	**$22**	**$4,417**

Table XI.3. NSF Funds (Request Level Budget) by Budget Category
($ in 000's)

	New NSF Funds	Uncommitted Carryover of 2000 Funds	Total Available for Commitment at Request Level	Commitments Carried Over from 2000 Funds	Available for Expenditure at Request Level
Personnel Compensation	$19,483		$19,483		$19,483
Personnel Benefits	5,845		5,845		5,845
Travel	781		781		781
Materials & Services	6,185		6,185	700	6,885
Management Fee (Ops)	650		650		650
Common Cost Recovery	(415)		(415)		(415)
CDL Device Revenue	(125)		(125)		(125)
Res & Oper Equipment	226		226		226
Total NSF Operations	**$32,630**	**$0**	**$32,630**	**$700**	**$33,330**
MMA-ALMA (U.S.)*	$5,880	$0	$5,880	$6,000	$11,880
Management Fee (MMA)	120		120		120
MRI	0	299	299	0	299
CISE	0	194	194	0	194
Education (RC & CTW)	0	670	670	0	670
Total NSF	**$38,630**	**$1,163**	**$39,793**	**$6,700**	**$46,493**

* The budget for ALMA shown in these tables is that of the NSF/Presidential request, that is, $6M. As explained in Section IX, "MMA (Participation in ALMA)," this amount is not adequate to accomplish the tasks for a fourth year of design and development. The required amount is $9M shown in Section IX and also shown under Mission Requirements in Section XIII, "Organizational Plan."

Organizational Plan

		Budget at NSF Request Level		Mission Requirements Budget		
		FTE	Totals	FTE	Totals	
1	Observatory Wide Functions & Programs					
1.1	Director's Office	6 3	984	6.3	984	
1 2	Administration					
1.2.1	Business & MIS	5.3	1,532	5 3	1,532	
1.2.2	Fiscal	11 8	707	11 8	707	
1.2.3	Safety & Environment	2.0	177	2 0	177	
	Total Administration	19.1	$2,416	19.1	$2,416	
1.3	Human Resources					
1.3.1	Human Resources	6.0	396	6.0	396	
	Total Human Resources	6 0	$396	6 0	$396	
1 4	Research Support					
1.4 1	User Support Programs	1.2	130	1 2	130	
1.4.2	Staff Science Support	1.0	281	1 0	281	
1.4 3	Data Analysis Grants			0 0	2,000	(1)
	Total Research Support	2.2	$411	2 2	$2,411	
1.5	Education					
1 5 1	REU Program	3 4	224	5.4	266	(2)
1.5 2	RARE CATS/CTW	0.7	670	0.7	670	
1.5.3	Postdoctoral Program	12 0	613	12.0	613	
1.5.4	Student Program	3 5	246	3 5	246	
1.5 5	Library	2 7	458	2.7	518	(3)
	Total Education	22 3	$2,211	24.3	$2,313	
1.6	Public Outreach					
1 6 1	Public Relations	4 8	345	4 8	510	(4)
1.6 2	GB Visitors Center & Tour Program	0 8	40	0.8	40	
1 6 3	VLA Visitors Center & Tour Program	0.0	5	0.0	5	
1.6 4	NASA - Education & Science Center	0 0	3,279	0.0	7,279	(5)
	Total Public Outreach	5 6	$3,669	5.6	$7,834	
1.7	Data Management					
1.7.1	Data Management	4 3	544	11.3	894	(6)
1.7.2	Observatory Wide Computing	0.0	200	0 0	350	(7)
1.7.3	Observatory Communications	1 0	94	1.0	94	
1.7.4	CV Computing Support	4 5	445	6.5	545	(8)
1.7.5	AIPS	1.0	103	1.0	103	

		Budget at NSF Request Level		Mission Requirements Budget		
1.7 6	AIPS ++	7.0	534	7.0	534	
1.7.7	ILL-NCSA	3 0	250	3 0	250	
1 7 8	NSF/CISE	2 0	194	2 0	194	
	Total Data Management	22 8	$2,364	31.8	$2,964	
1.8	Technology Development					
1.8.1	Electronics - CDL	21.0	1,578	21.0	1,578	
	Total Technology Development	21.0	$1,578	21.0	1,578	
1 9	Equipment					
1.9.1	Instrumentation		226		1,583	(9)
1 9 2	Operating Equipment		0		0	
	Total Equipment		$226		$1,583	
	Total NSF Obs Wide Functions & Programs	99.6	9,862	110.6	14,130	
	Total Non-NSF Obs Wide Functions & Programs	5 7	4,393	5.7	8,393	
	TOTAL OBS WIDE FUNCTIONS & PROGRAMS	105 3	$14,255	116 3	$22,483	
2	MMA/ALMA (US)	68.0	$5,880	70.8	$8,820	(10)
3	GBT Operations					
3.1	Management & Administration					
3 1.1	Site Director's Office	2 0	359	2 0	510	(11)
3.1 2	Business Office	4.0	251	4.0	251	
3.1.3	Visitor's Residence & Cafeteria	8.0	237	8 0	237	
	Total Management & Administration	14.0	$847	14 0	$998	
3 2	Computing	9 0	823	11 0	948	(12)
3 3	Electronics	26.0	2,130	29 0	2,730	(13)
3 4	Plant Maintenance	17.0	710	18.5	860	(13)
3.5	Scientific Support	11 9	1,199	13.3	1,649	(13)
3.6	Telescope Operations	12.0	838	14 0	1,423	(13)
3.7	Mechanical Engineering	9 0	536	9.0	536	
3 8	NSF-MRI	1.0	190	1.0	190	
3.9	NASA - OVLBI Earth Station	3.6	400	3.6	400	
	Total NSF GBT Operations	99 9	7,273	109.8	9,334	
	Total Non-NSF Green Bank	3.6	400	3.6	400	
	TOTAL GBT OPERATIONS	103.5	$7,673	113.4	$9,734	

		Budget at NSF Request Level		Mission Requirements Budget	
4	VLA/VLBA Operations				
4 1	Management & Administration	19.4	3,055	19.4	3,055
4.2	Array Operations	23.8	1,175	23 8	1,475 (14)
4 3.	Computing Support	18 8	1,467	19 3	1,567 (15)
4.4	Electronics	64 0	4,375	64.0	4,975 (14)
4.5	Engineering Services	48.5	3,367	48 5	4,567 (14)
4 6	Scientific Support	19.8	1,665	19.8	1,665
4.7	VLA Expansion Project				
4.7 1	Planning Group	3.3	471	11 3	3,901 (16)
4 7.2	NSF MRI - Pie Town Link	1.0	100	1.0	100
4.7.3	NSF MRI - VLA Q-Band Receivers-MPI	0 2	9	0.2	9
	Total VLA Expansion Project	4.5	$580	12.5	$4,010
4 8	NASA - OVLBI Science	3.7	488	3.7	488
	Total NSF VLA/VLBA Operations	198 8	$15,684	207.3	$21,314
	Total Non-NSF Socorro	3 7	488	3.7	488
	TOTAL VLA/VLBA OPERATIONS	202 5	$16,172	211 0	$21,802
5	CDL Device Revenue & CCR				
5 1	CDL Device Revenue		(125)		(125)
5 2	CCR		(415)		(415)
	TOTAL REVENUE & CCR		($540)		($540)
6	Management Fee		$770		$1,074
	Grand Total	**479.3**	**$44,210**	**511.5**	**$63,373**
	SUMMARY:				
1	*Central Functions & Programs*	*105.3*	*14,255*	*116.3*	*22,483*
2	*ALMA (USA)*	*68.0*	*5,880*	*70.8*	*8,820*
3	*Green Bank & GBT Operations*	*103.5*	*7,673*	*113.4*	*9,734*
4	*Socorro & VLA/VLBA Operations*	*202.5*	*16,172*	*211.0*	*21,802*
5	*CDL Device Revenue & CCR*	*0 0*	*(540)*	*0.0*	*(540)*
6	*Management Fee*	*0.0*	*770*	*0.0*	*1,074*
	Grand Total	*479.3*	*$44,210*	*511.5*	*$63,373*

Organizational Plan

	Budget at NSF Request Level		Mission Requirements Budget	
Income (I) & Carryover (C/O)				
NSF Ops (I)	368 9	30,699	396 3	40,595
NSF REU (I)	3 4	224	5 4	266
NSF-MRI & CISE (C/O)	4.2	493	4.2	493
NSF-Educ (I & C/O)	24.5	2,377	24 5	4,602
NSF MMA (I)	68.0	6,000	70.8	9,000
Other Projects (Non-NSF) (I)	10.3	4,417	10 3	8,417
Grand Total	479.3	$44,210	511.5	$63,373

Notes:

(1) Data Analysis Grants - see *New Initiatives* section.

(2) Increase number of co-op students.

(3) Provide for additional journal subscriptions and publication charges.

(4) To increase the educational product development and public outreach effort.

(5) Additional funds to support the Astronomy Education Center development in Green Bank.

(6) Staff increase to initiate design and development work on archiving, scheduling and pipelines.

(7) Funds are required to upgrade workstations, including public; upgrade PC systems to Windows 2000; upgrade file servers and provide additional training.

(8) Additional system support for web server upgrades and computer security implementation as well as network support.

(9) Instrumentation and research equipment are nearing obsolescence and a concerted effort to replace and upgrade this equipment is vital.
Examples are: noise measurement equipment, quasi-optical testing equipment, RF equipment for various gigahertz, electronic test equipment and initiation of the 3 CAM Bolometer Array.

(10) To bring ALMA budget tc required 2001 level. The major activities include pre-production prototypes of major subsystems, complete preparations for test of prototype antennas, maintain foundries for SIS production, participate in development program with JPL and TRW to produce MMIC power amplifiers, procure prototype correlator chips, build second 4K test dewar and direct photonic LO demonstration.

(11) Increase in utility costs related to the GBT.

(12) To provide data management development and computing support staff at an appropriate level.

(13) Additional staff to accelerate the scientific development of the GBT, as well as the basic maintenance of the antenna. Coupled with this is the continued outfitting. GBT development will require staff for instrument development, technical staff, a frequency coordinator, and project scientist. Annual preventative maintenance should be addressed.

(14) We have a long range plan to replace VLBA masers, increase VLA railroad tie replacement, accelerate our antenna painting, bearing replacement and transporter upgrades. We plan to install a new fall arrest system on the VLBA & VLA, as well as a chemical storage facility at the VLA.

(15) An additional software developer is necessary in archiving software and data base development.

(16) Begin the EVLA project - see *New Initiatives* section.

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.

Four 3 mm (W-band) receivers, covering the 80-90 GHz range, had been installed on VLBA antennas between 1996 and 1999. Each of these systems is unique, and there are no spares. Difficulty in maintaining them in an operational state has indicated several areas requiring redesign. Replacement of some components made it possible to keep three of these receivers operational (at the Fort Davis, Los Alamos, and Pie Town stations) since April 2000. Four new, redesigned receivers will be built during 2000-2001, with funds provided by the Max-Planck-Institut fur Radioastronomie in Bonn, Germany. These will cover an expanded frequency range, from 80-96 GHz, a percentage bandwidth comparable to lower-frequency VLBA receivers, to increase the number of methanol maser transitions which can be observed and the redshift range over which CO can be observed in absorption. The first two new systems, and the fourth old receiver, partially retrofitted, are to be installed by the end of 2000 at North Liberty, Kitt Peak, and Owens Valley. The remaining two new receivers are scheduled for installation at Hancock and Mauna Kea by the end of 2001.

Both the main- and sub-reflector surfaces of the VLBA antennas have faults which will limit the aperture efficiency at 3 mm wavelength. These are known very approximately from VLBI holography, but this technique has been shown to be limited by differential atmospheric fluctuations. Several alternatives were considered for more precise surface measurements, sufficient to allow readjustment of the surfaces. A local (i.e., non-VLBI) holography system was selected as the best approach under the existing funding and staffing constraints. This system will observe a 12 GHz geostationary communications satellite beacon, and use a special feed optically coincident with the 3 mm feed location. It will also be possible to reposition the holography feed diametrically opposite the 3 mm position on the feed ring, to allow separation of the main- and sub-reflector figures. An extremely low-cost implementation, using as much as possible of each VLBA station's equipment, is under development, with completion planned for the end of 2000.

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 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 a 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 about 20 such objects will be carried out to determine whether they are faint radio sources, in accord with the known radio/[O III] relation for Seyferts. If so, this will help confirm the identification of a significant population of the "missing" type 2 quasars.

VLA observations of Seyfert galaxies from the Palomar Bright Galaxy spectroscopic survey have been carried out, with imaging and data analysis complete for all target sources. It appears that the radio luminosity function of Seyferts in the vicinity of 10^{20} W/Hz will be increased by about 1.5 orders of magnitude. Statistical analysis of the sample, its relation to galaxy properties at other wavelengths, and a study of the differences between Seyfert 1 and 2 galaxies will be completed in the next year. VLA imaging of more than 200 H II galaxies from the same Palomar sample will be carried out, to investigate the incidence of weak active galactic nuclei in such objects. If many are seen, this may bridge much of the final gap of 1-2 orders of magnitude between the luminosity functions of Seyfert galaxies and of normal spiral galaxies.

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 which 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 a survey for radio continuum sources in the inner regions of 374 UGC galaxies; probing the mass accretion rates of nearby quiescent ellipticals; imaging the inner parsec of NGC 4395, the least luminous Seyfert 1 nucleus; and measuring proper motions in the FR I radio galaxy M84. In addition, a new technique will be used to conduct a VLBA survey of 100 FIRST sources in the NOAO deep wide field J1432+3416.

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 lightyear. The movie of jet kinematics (now 7 epochs over 5 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 towards 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 which 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 also contributing 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 are being 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. Over the next year, the remainder of the new data will be acquired, calibrated, and imaged. Analysis will begin on the comparative properties of the sample.

The VLA was used to map a sample of three edge-on *superthin* spiral galaxies in the HI 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 Gyrs since merging.

Past studies have repeatedly demonstrated that the copious amounts of cold atomic gas found at large radii in disk galaxies give rise to extensive gaseous tidal features. Twentyone 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 recently discovered 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 selected galaxies from a sample of apparently isolated spirals whose integrated H I profile is known with high precision. The goal of the mapping program is to evaluate the reason why half of the sample galaxies show asymmetry in their H I profiles. The fraction of galaxies showing interaction in progress appears to be small, and to improve the statistics data from other H I mapping programs will be used as appropriate. For those objects where the asymmetry arises within the galaxy itself the study will address the lifetime of the perturbation which is manifested in the profile asymmetry.

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 H I structure in distant Galactic material can be probed using a background source with rapid structural changes. During outbursts of the microquasar GRS 1915+105, the proper motion of the approaching component is ~250 AU (23 mas) per day. Using the VLA at 21 cm during such an outburst, the time-variable H I absorption along the changing line of sight has been measured. The detections and upper-limits on the opacity variation, on scales of ~100-1600 AU, are consistent with extrapolation of the power-law index of 2.75 for the power-spectrum of H I fluctuations on scales from 4 pc to 0.02 pc. The existence of small-scale 10-100 AU variations in the ISM is already established from pulsar, VLBA, MERLIN, and VLA observations. The new approach is complementary to techniques using extragalactic sources and nearby pulsars, but demands rapid response to radio flares from Galactic transients occurring a few times per year.

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 which, 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} α 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 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 which 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 sigma) 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

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 c′ the jet and water masers which 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).

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 GBI, VLA, and VLBA, the X-ray satellite RXTE, and UKIRT (infra-red). The disk/jet coupling, jet evolution on AU-scales, and milliarcsecond astrometry will be investigated

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 min during minor X-ray/radio outbursts, and re-establishes within 18 hrs 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. A first epoch of VLBA astrometry in May 2000 located the compact core to within 1 mas, and proper-motion measurements will continue in 2001. Imaging of the weak (5 mJy) core is proceeding. Future work on this and other new X-ray transients will image the flat-spectrum radio cores of accreting black holes, expected to be compact synchrotron jets.

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. The analysis of 12 M data will continue through the coming years to determine the kinetic temperature evolution of Comet Hale-Bopp from images of the HCN, CO, H_2CO, HCO^+, and CH_3OH emission from this remarkable visitor.

Astrometry, Geodesy, and Geophysics

Two enhancements to the Jodrell Bank VLA Astrometric Survey (JVAS) will be completed: (a) a search for 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 added 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 sub-millimeter wavelength radiotelescopes 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 up-grade 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.

Space VLBI groups at Green Bank, Charlottesville, and Socorro, have been active participants in the Japanese-led VLBI Space Observatory Program (VSOP) mission. New facilities and capabilities were developed for Space VLBI at both prior to the launch of the mission's spacecraft HALCA, on 1997 February 12. Both then contributed extensively to in-orbit checkout through about July 1997, and subsequently have been vital elements of the VSOP scientific program.

The NRAO OVLBI Earth Station project in Green Bank is one of five ground tracking stations supporting the mission. It provides an uplink phase reference to the spacecraft, and records the astronomical data downlinked from HALCA onto VLBI tapes. From the two-way phase link, it also measures timing offsets used in correlating the VLBI observations and for orbit determination.

The NRAO Space VLBI project, based at the Array Operations Center in Socorro, operates the VLBA as the ground-based component of the VSOP ground-space interferometer system, or as the core of a larger, global ground array. As much as 30 percent of scheduled VLBA observing time has been assigned to peer-reviewed VSOP observations. The VLBA correlator processes essentially all the VSOP observations recorded on VLBA-compatible tapes, corresponding to about 75 percent of the mission's total throughput.

Reduced NASA funding in 2000, as well as the failure of some vital spacecraft components, led to a significantly reduced observing schedule for VSOP on the VLBA. It is anticipated that VSOP support will continue, at a further reduced rate, through the end of the mission in 2001.

The VLBA was designed to be upgradable for operation at 3 mm wavelength. Efforts toward realizing this capability were started in several areas in 1999 and 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, by mid 2000. It is anticipated that the 512 Mbps capability will become available on the VLBA by early 2001. A study of the feasibility and cost for a final upgrade, to the VLBA recording system's planned maximum capacity of 1 Gbps, will be completed by 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 Academy of Sciences 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; FASR.

A. J. Beasley - Radio interferometry, VLBI observing techniques; Assistant Director for Program Development.

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; VLA scientific support.

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

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; GBT Project Scientist.

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: 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; 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; Chair, Jansky Selection Committee.

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 - Starburst galaxies and scientific visualization; Head - ALMA Computing.

M. A. Gordon - CO, galactic structure, gas-rich galaxies, and interstellar medium; ALMA site development.

W. M. Goss - Galactic line studies, pulsars, and nearby galaxies; Assistant Director, Socorro Operations.

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; telescope use statistics.

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

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

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; Deputy Assistant Director, Data Management.

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

L. J. King - Antenna structural/mechanical analysis, design, and optimization; GBT Antenna Engineer.

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

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.

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.

J. M. McMullin - Astronomical software systems; AIPS++ development.

A. H. Minter - Interstellar turbulence and space VLBI; Space VLBI scientific support.

G. Moellenbrock - VLBI Polarization, AGN, interferometry calibration and imaging algorithms; space-VLBI tracking support and AIPS++ synthesis development.

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

P. J. Napier - Antenna and instrumentation systems for radio astronomy; ALMA antennas.

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

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; Head-Green Bank Computing.

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

M. S. Roberts - Extragalactic studies, 21 cm neutral hydrogen research.

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

F. Schwab - Mathematical consulting, 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; Deputy AD for Socorro Operations.

G. A. 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.

J. M. Uson - Clusters of galaxies and cosmology; GBT scientific support.

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.

A. H. 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; Head - Socorro Array and Correlator Operations.

Q. F. Yin - Normal galaxies and imaging techniques; NVSS and GBT Calibrator Project.

M. S. Yun - Extragalactic radio sources and star formation; ALMA scientific support.

J. A. Zensus - Extragalactic radio sources, VLBI; VLBA 3 mm receiver project; joint appointment with MPIfR.

APPENDIX C - NRAO COMMITTEES

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
R. Todd Clancy, University of Colorado
Imke de Pater, University of California, Berkeley
Christopher G. De Pree, Agnes Scott College
Jason Glenn, University of Colorado
Lincoln J. Greenhill, Center for Astrophysics
Carl E. Heiles, University of California, Berkeley
Paul T. P. Ho, Smithsonian Astrophysical Observatory
Jeffrey D. Kenney, Yale University
Elizabeth A. Lada, University of Florida
T. Joseph W. Lazio, Naval Research Laboratory
Colin Lonsdale, MIT Haystack Observatory
David J. Nice, Princeton University
Christopher P. O'Dea, Space Telescope Science Institute
Patrick Palmer, University of Chicago
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
Farhad Yusef Zadeh, Northwestern University

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:

Donald Backer, University of California
Edward B. Churchwell, University of Wisconsin
James M. Cordes, Cornell University
Neal Evans, University of Texas
Lee Mundy, University of Maryland
Thomas Phillips, California Institute of Technology

Mark Reid, MPIfR
F. Peter Schloerb, University of Massachusetts
Jean Turner, University of California, Los Angeles

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 Tucson in 1998, in Socorro in 1999, and in Green Bank in 2000. The current membership of the Committee is:

Thomas Bania, Boston University
Geoffrey A. Blake, California Institute of Technology
Lincoln J. Greenhill, Harvard-Smithsonian, CfA
Karl M. Menten, Max-Planck Institut fur 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

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
Pierre Cox, Institut d'Astrophysique Spatiale
Dick Crutcher, University of Illinois
Darrel Emerson (ex officio), National Radio Astronomy Observatory
Neal Evans, University of Texas
Stephane Guilloteau (ex officio), IRAM
Mark Gurwell, Harvard-Smithsonian Center for Astrophysics
Karl Menten, Max-Planck Institut für Radioastronomie
John Richer, MRAO, University of Cambridge
Nicholas Scoville, California Institute of Technology
Peter Shaver (ex officio), European Southern Observatory
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
Min Yun, National Radio Astronomy Observatory

Active Observers
Leonardo Bronfman, University of Chile
Yasuo Fukui, Nagoya University
Tetsuo Hasegawa, University of Tokyo
Masahiko Hayashi, Subaru Telescope, NAOJ
Ryohei Kawabe, Nobeyama, NAOJ
Naomasa Nakai, Nobeyama, NAOJ

Organization Chart