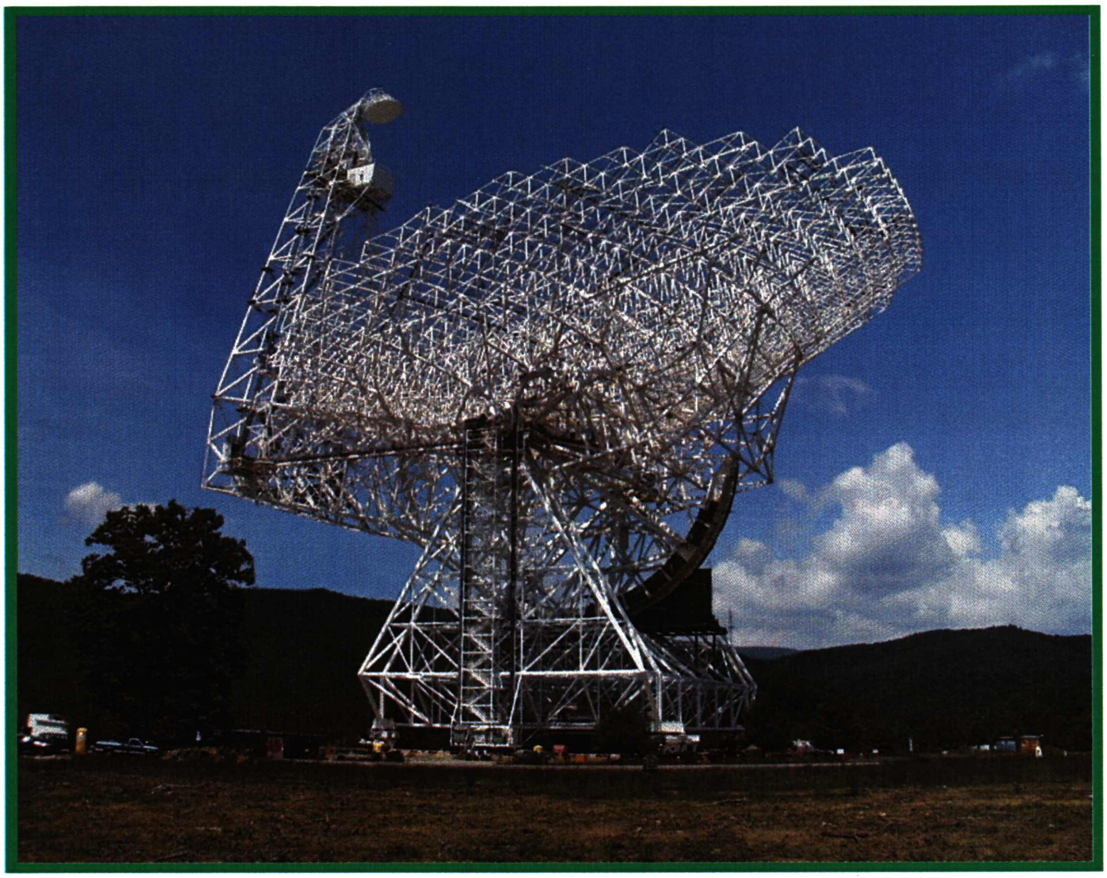

PROGRAM PLAN 2000

NATIONAL RADIO ASTRONOMY OBSERVATORY

National Radio Astronomy Observatory

Calendar Year 2000

PROGRAM PLAN

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I. MISSION STATEMENT AND INTRODUCTION

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.

Astronomy enters the new millennium charged with the potential for discovery. The prospects for understanding the structure and history of the Universe, the formation of galaxies, the origin of stars and planets, the black hole engines that drive the jets emanating from galaxy centers, to mention only a few topics, have never been better. Even as new space missions are being defined for astronomical projects, it is becoming clear that the potential for ground-based astronomy is growing. At any wavelength that penetrates the atmosphere, the mega-observatories being planned and built for ground-based observations will provide unprecedented new power in both sensitivity and angular resolution. They will dominate the astronomical science of the new millennium. The United States participation in one of these mega-facilities, the Atacama Large Millimeter Array (ALMA) is the top priority in the program of the National Radio Astronomy Observatory (NRAO.)

The year that begins the new millennium will be marked at the NRAO by a number of significant events. It will be the year that sees completion of the Green Bank Telescope (GBT) and the beginning of its operation. It will be the third and final year of the design and development phase of the Millimeter Array (MMA), now integrated into an international partnership—ALMA. It will be the year for organizing the Ultra Sensitive Array Project—the first phase of the Very Large Array (VLA) Expansion—proposal submission and review, forging of agreements with foreign partners, and construction of detailed plans. This will be the last year of the HALCA mission, signaling the end of support from NASA for activities at the NRAO in orbiting very long baseline interferometry. The year will also mark a significant turning point for the 12 Meter Telescope, as investment in new instrumentation ceases and plans are made for the eventual phase-out of operations.

In contrast to these major milestones and challenges, the Observatory budget proposed to Congress for the year 2000 continues the sequence of strained and inadequate resources. While it would be *possible* to operate the NRAO at that budget level for another year, it could only be done by continuing to neglect the future. We would be forced to continue minimal levels of investment in new instrumentation, computing capability, and maintenance. We would remain limited in making the salary schedule corrections necessary to compete effectively for new personnel. We would be hampered in implementing the modern management tools the Observatory needs to effectively conduct its programs over the long term.

This program plan does respond to the request from the Foundation for a plan *at* the Presidential request level budget. The impact of doing this without reducing operation of the NRAO telescopes is presented, as is the *increase* in budget required to both operate these facilities and provide the stewardship required for the future. Realizing the full potential of the GBT, making the Very Long Baseline Array (VLBA) more accessible to a broader range of users, providing an end-to-end data management system for all NRAO telescopes, achieving a closer relationship with and providing more support to the university community, maintaining a vibrant instrumentation program, and expanding our program of education and public outreach, all require additional funds.

Correspondingly, a budget level *below* the Presidential Request level would force consideration of a curtailment of telescope operations across the Observatory.

II. 2000 SCIENTIFIC PROGRAM

1. The Very Large Array

In 2000, we will celebrate the 20th anniversary of the VLA. This instrument begins 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 various stages of stellar evolution. Its newer capabilities at both higher (40-50 GHz) and lower (74 MHz) frequencies have opened exciting new avenues of investigation for the user community. Data produced by the NRAO VLA Sky Survey (NVSS) and the Faint Image of the Radio Sky at Twenty-centimeters (FIRST) survey are seeing wide use in diverse fields, both by itself and as a spur to additional observation and study.

Solar System

An established tool for solar research, the VLA will be used at both 74 and 330 MHz for high-resolution observations of the source regions of coronal mass ejections (CMEs) and of metric and decimetric bursts that may accompany CMEs and solar flares. These observations will be simultaneous with observations by the Mauna Loa coronagraph, the Transition Region and Coronal Explorer (TRACE) and the Solar and Heliospheric Observatory (SOHO). These observations are expected to produce new information about particle acceleration and nonthermal energy release in the solar corona, about the triggering and early evolution of CMEs, and about changes in long-lasting Type I noise storms that may be associated with the addition of coronal material in their vicinity.

Planetary studies will include a series of observations of Jupiter at 74 and 330 MHz. These observations will seek to measure variations in the planet's low-frequency flux density, and will produce information on the low-energy electron flux of the synchrotron-emitting electrons and their interaction with plasma waves and dust. An occultation of a point-like radio source (discovered by the NVSS) by Saturn's rings will provide the opportunity to learn new information about the size and spatial distribution of centimeter to meter scale ring particles. The occultation observations, at 20 and 90 cm, will be the first probe of the densest parts of the ring system which were opaque to the Voyager occultation experiments, and will help characterize the size distribution of particles larger than those probed by earlier 3.6 and 13 cm occultation experiments.

Pulsars, Novae, Supernovae, X-Ray Binaries, and Other Radio Stars

A key feature of VLA research in this area is the long history of rapid response to newly-discovered supernovae and outbursts of X-ray binaries. The VLA has contributed multifrequency 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 the compact component. Ongoing target-of-opportunity programs will continue these important contributions.

Another study will seek to resolve tantalizing questions about Supernova 1961V in NGC 1058. A nonthermal radio source at the position of this supernova, Zwicky's prototypical Type V supernova, was last observed in the 1980s, and its radio properties were similar to other known supernovae. However, the optical properties are so unusual that questions have arisen about whether the object is actually a supernova at all. Alternative explanations include an outburst of a long-period blue variable or even a hypernova The VLA observations will seek to determine the object's real nature by looking for changes in the flux density and spectral index.

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, but the details of that role still are poorly understood. The first step toward improved understanding is to measure magnetic field strengths and map their morphologies in star-forming regions. Observers will use the VLA to do this by measuring the Zeeman effect in absorption lines. One study will measure the Zeeman effect in OH absorption lines toward a continuum source in NGC 6334, a giant molecular-cloud complex and star-forming region. High-resolution observations of HI absorption lines toward a supernova remnant in the W49 star-forming complex will seek to provide information on the morphology of its magnetic fields, and in particular will determine if the magnetic field morphology changes at the SNR boundary.

The VLA will be used to study the process of high-mass star formation, which is significantly less well understood than the formation of lower-mass stars. One study will seek to increase the inventory of known high-mass protostars by detecting water-maser emission near a number of candidate objects. Water masers, emitting at 22 GHz, are thought to be good tracers for newly formed massive protostars. In another study, 7 mm observations of an ultracompact HII region may provide a valuable glimpse of a massive protostar that has only recently passed out of the hot molecular core stage to form the HII region. Another 7 mm study will seek to directly image a dusty accretion disk around a massive protostar. If successful, this would be the first direct image of an accretion disk around a massive protostar, and in addition would allow measurement of the disk's physical properties.

Following earlier observations of disks around young stellar objects in HL Tau and L1551, observers will try high-resolution studies of three more suspected disk systems. These studies are helping to characterize the properties of such disks and thus to better understand the processes of mass accretion and planet formation

Linear polarization recently was detected, using archival VLA data, in the central HII region of the nearest symbiotic binary system, R Aquarii. This unexpected finding indicates a previously unknown emission mechanism in this system, presumably shock-induced synchrotron emission. Further continuum observations of this polarized emission will seek to determine the magnetic structure of the system's jet.

Vibrationally-excited spectral lines of carbon-chain molecules will be observed in a proto-planetary nebula—the brief and rarely-seen transition between the red-giant and planetary-nebula stages of stellar evolution. These observations will show the location of the vibrationally-excited molecules in the system and allow estimation of the temperature distribution in the proto-planetary nebula.

Normal Galaxies

The VLA will continue to serve as one of the world's premier instruments for studying the center of the Milky Way. Galactic Center research will continue in the coming year, with observers using the VLA to study gas kinematics in the region near Sagittarius A*, where a 2.6-million-solar-mass black hole probably resides. Both spectral-line and continuum observations will help to improve the understanding of proper motions of gas near the black hole. The new observations, combined with previous data, will allow researchers to utilize the Galactic Center as a unique laboratory for studying the accretion process onto a black hole at scales as small as 0.1 pc. A high-sensitivity study of the Zeeman Effect on 1667 MHz OH absorption lines in the vicinity of the Galaxy's circumnuclear disk is aimed at providing unprecedented detail of the magnetic-field structure in the central few parsecs. The anticipated detail will be sufficient to constrain models and probe the effects of the magnetic field on gas dynamics, among other applications.

Moving to external galaxies, 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, extending the time base for studying flux-density variations, so far detected in two-thirds of these sources, extended to 19 years. Observations of E+A galaxies, a complex class of galaxies thought to be in a post-starburst stage, will seek to learn if instead they harbor current star formation obscured by dust, as suggested by recent evidence. A sample of compact, luminous, star-forming galaxies at low redshift will be studied as possible local analogs to the faint blue galaxies seen in greater numbers at high redshifts. This study will seek to measure properties of these galaxies such as star-formation rates, the physical conditions in the star-formation regions, and supernova rates.

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

Following the recent spectacular discovery of a large-scale radio "bubble" with complex structure surrounding M87, observers will seek to learn more about this halo by mapping its spectral index. The halo, discovered by 90 cm observations at the VLA, appears to be powered by the galaxy's central black hole, calling into question "cooling flow" models for the X-ray emission from the region. Narrowband observations at 20 cm, though technically challenging, will seek to produce spectral-index maps and to resolve further structure.

Observers will use the VLA to study radio-galaxy jets. A pair of FRI galaxies will be observed in detail to compare the results with the predictions of models of decelerating, relativistic flows based on earlier observations of jets at different orientations to the line of sight. Other observers will extend an ongoing program of detailed studies of FRII radio sources out to a redshift of 1, to test unification schemes for radio galaxies and quasars and to impose tighter constraints on models.

A pair of radio galaxies recently found to have parsec-scale symmetric jets will be observed to search for 21 cm HI absorption. Detection of circumnuclear hydrogen could indicate a circumnuclear torus and provide an important tool for testing AGN unified schemes. Another study, of HI emission in the host galaxies of low-redshift quasars, will seek further detail about the gas disruption in these host galaxies—gas disruption that supports the contention that low-redshift quasars have been "turned on" by recent galactic mergers. The new observations will seek additional information about the disruption and its role in triggering quasar activity.

The VLA will be used to study a new catalog of 52 Seyfert galaxies produced by a survey at Palomar Observatory. This is the most complete sample of Seyferts known, and multiwavelength studies of these objects will address a number of important questions about the statistical properties of radio emission in an unbiased sample of Seyferts; the possibility of correlation between radio properties and activity at other wavelengths; dependence of radio properties on Seyfert type; and how the radio structures compare to morphology at other wavelengths.

Only two objects at redshifts greater than 4 are known to show CO and dust emission. One of these will be studied with the VLA to provide the first direct measure of the gas temperature in extreme star-forming galaxies at high redshift. This information is critical to constraining galaxy formation models using submillimeter and infrared source counts.

It has been suggested that jet activity in radio galaxies may be intermittent, with recurring episodes. If so, observations at low frequency should yield detections of relic jets no longer visible at higher frequency. The 74 MHz system of the VLA will be used to study a sample of radio sources thought to be good candidates for detecting such relic emission.

The successful VLA program to detect and study the radio afterglows of gamma-ray bursts (GRBs) will be continued. The VLA made the first such detection in 1997, and since then, five GRB afterglows have been detected and studied. 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, radio afterglows have been detected in GRBs in dusty environments, a valuable point in evaluating models of GRB progenitors.

Cosmology and Large-Scale Structure

Extremely Red Galaxies (ERGs), almost undetectable at optical wavelengths, may be either very old ellipticals at redshifts greater than 2 or very dusty starburst galaxies at redshifts greater than 1. A sample of 17 ERGs will be observed by the VLA to determine which type of object they are. Either way, cosmologically useful information will be learned. If they are ellipticals, they would provide constraints on the earliest epoch of star and galaxy formation; if dusty starburst galaxies, they will contribute information on the star-formation history of the universe and to the origin of the cosmic far-infrared and millimeter-wave background.

The VLA will support ongoing efforts to refine the cosmic distance scale through the measurement of time delays in gravitational-lens systems. 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. At least four lens systems will be monitored for time delays, including the lens with the highest redshift of any known system, which could provide a distance measurement particularly valuable to the overall effort.

A very deep 1.4 GHz VLA image in a region already imaged at very high sensitivity at 8.4 GHz and in the optical, infrared, and X-ray regimes is expected to detect about 1,000 radio sources as faint as 20 microJanskys. Compared with the data from other wavelengths, this study should yield a deeper understanding of the evolution of radio emission from distant galaxies and how this relates to the global star-formation history.

Surveys are a proven tool of cosmology, and a series of survey projects on the VLA will complement and extend the scientific value of surveys at other wavelengths as well as provide new and possibly unexpected data. Test observations at 74 MHz will pave the way for a possible all-sky survey at this frequency The low-frequency sky is almost completely unexplored at the sensitivity and resolution believed possible with the VLA's 74 MHz system, so an all-sky survey could be very productive scientifically. Optical, IR, and Sunyaev-Zeldovich observations made in fields identified through the NVSS survey have yielded approximately 100 newly-identified distant galaxy clusters. Deeper VLA observations will allow researchers to determine the relationships between the radio activity, cluster physical status, and cosmic epoch at greater redshifts than any current cluster surveys. Other observations will complement the Chandra Deep X-Ray Survey, a survey that will be twenty times more sensitive than previous deep X-ray surveys, and the Las Campanas Near-Infrared Survey.

A sample of 17 high-redshift quasars found by the Sloan Digital Sky Survey, including the highest-redshift quasar known ($z = 5$), will be studied to address the issue of the apparent declining fraction of radio-loud quasars at high redshift and also to probe a possible new population of radio-emitting quasars at high redshift in which the host galaxy is in an extreme starburst phase. Extremely steep-spectrum radio sources identified with the NVSS and the Westerbork Survey in the Southern Hemisphere will be observed to provide good positions for optical and infrared identifications and thus enlarge the known population of radio galaxies at redshifts greater than 5. Such techniques recently discovered the most distant radio galaxy yet known, at a redshift of 5.19.

2. The Very Long Baseline Array

In the past year, the VLBA has produced some impressive and valuable scientific results, including the most accurate extragalactic distance measurement ever made; the first "movie" of gas dynamics in the atmosphere of a star other than the Sun; and demonstration of the ability to detect the Earth's motion around the Galactic Center over ten days. New capabilities such as pulsar gating and 3 mm observing 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.

To further enhance its value to the scientific community, the NRAO has begun offering new services for novice users of the VLBA, including a complete scheduling and data-calibration service for new users not familiar with VLBI techniques. Offering the routine capability to produce images with milliarcsecond resolution 10 to 100 times better than that of the Hubble Space Telescope, the VLBA is a valuable and popular tool for a wide range of astrophysical inquiries.

Solar System

In an experiment utilizing extragalactic radio sources as background sources, the VLBA will be used to study the solar wind acceleration in the region between 5 and 8 solar radii. The experiment will use phase scintillations observed with the VLBA to measure the solar-wind acceleration. This will yield new and unique information important to resolving unsolved questions about models of the origin and characteristics of the solar wind. In addition, the technique should prove valuable in the future as a tool for remote sensing of the solar wind velocity.

Pulsars, Novae, Supernovae, X-Ray Binaries, and Other Radio Stars

The VLBA pulsar gate allows researchers to do work of fundamental importance on neutron stars, supernova processes, and the interstellar medium. An already proven capability to determine parallaxes and proper motions of pulsars with subarcsecond precision will be used to measure these parameters for a number of pulsars. The resulting information about pulsar velocities will constrain core collapse processes in supernovae and binary evolution and also will contribute to understanding of phenomena such as magnetars. Accurate pulsar distances obtained by parallax methods, combined with the pulsar dispersion measures, also can provide information on the distribution of the ionized interstellar medium.

A binary system consisting of a Wolf-Rayet star plus an O star will be monitored at multiple wavelengths to measure the structural and spectral evolution of nonthermal radio emission from a region in which the strong stellar winds are interacting. The pair is approaching periastron and the ongoing observations are expected to provide information that can differentiate between competing theoretical models for the mechanism producing the nonthermal emission.

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

Following on successful 1995 observations that showed small-scale structure in the Galactic neutral hydrogen in the direction of the quasar 3C138, the quasar will again be observed to detect changes due to the shifting of the line of sight in the intervening years. This is a valuable technique for learning about structure in the ISM on scales of tens of astronomical units.

A series of VLBA observations of SiO masers in the Mira variable TX Cam have yielded a unique insight into the dynamics of a circumstellar molecular envelope. This unprecedented observational achievement has contradicted the prevailing model of these envelopes in oscillating stars and raised questions about the physics of such envelopes and of the maser action itself. In order to resolve these questions, the TX Cam monitoring program will be continued. In addition, two other late-type stars will be monitored to gain important data for comparison with the TX Cam results.

Normal Galaxies

The VLBA already has measured the proper motion of Sagittarius A*, a motion attributed to the solar system's orbital rotation around the Galactic Center. Additional observations can greatly refine the precision of these proper motion measurements and produce a number of important results. This program can resolve any (perhaps small) question about whether or not Sgr A* is actually the dynamical center of the Galaxy, as well as improve the estimate of the angular rotation rate of the Sun around the Galaxy's center. In addition, measuring the amount of peculiar motion of Sgr A* itself can constrain the mass estimates for this object and determine how much of the 2.6×10^6 solar masses imputed to the Galactic Center actually resides in Sgr A*. Further refinements in positional accuracy also may allow measurement of a trigonometric parallax for Sgr A*

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

The nearby, edge-on spiral NGC 4388 will be the subject of deep VLBA (with VLA) observations aimed at finding suspected thermal nuclear emission in its nucleus. The observers will seek to image the thermal emission, presumed to arise from an accretion disk surrounding a supermassive black hole in this Seyfert galaxy.

High-frequency polarization observations of a pair of bright quasars will seek to improve the resolution of rotation-measure images and produce a wealth of information about the densities and magnetic fields of their nuclear regions. Previous such observations have revealed high rotation measures in the inner 20 parsecs or so of such objects. The new observations will produce better information about magnetic fields closer to the cores, and will include follow-on images designed to detect possible changes over time.

Cosmology and Large-Scale Structure

The VLBA will contribute significantly to efforts to calibrate the Hubble Constant through gravitational-lens studies. The high resolution of the VLBA will be used to study lens candidates identified by other instruments to determine if, in fact, they are lenses. If confirmed, they and other lenses will be studied in detail to produce the images needed to accurately model the mass distribution of the lensing bodies. Such models are necessary for deriving distances from measurements of time delays in the systems. The large distances that can be measured by this technique are essential to reducing the errors in the cosmic distance scale.

3. The Green Bank Telescope

The GBT has several attributes that will make it a uniquely powerful scientific instrument:

- *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. This will be a powerful asset at all observing frequencies, from 250 MHz to 50 GHz, and eventually to 115 GHz. In the frequency range between 20 and 115 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 design will have very little response to emission outside the main diffraction beam. This minimizes scattering sidelobes that will greatly 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 as it comes off the telescope. 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. Spectral baseline effects caused by sidelobe response to solar radiation will also be greatly reduced.
- *Versatility, Frequency Range, and Agility* - The GBT was designed to attack a wide range of astrophysical problems. It will cover, ultimately, more than three decades of observing frequency (100 MHz to 115 GHz). Its active surface and metrology system will maintain high sensitivity and excellent pointing up to the 3 mm wavelength band. It has a wide field of view at the Gregorian focus that will give it excellent imaging properties. The receiver turret in the Gregorian cabin allows quick changes between receivers. The GBT Spectrometer is the most versatile spectral line backend yet

constructed. Its resolution and bandwidth will be a very powerful tool to wideband spectroscopy. The telescope will be equipped with backends for spectroscopy, continuum, pulsars, and VLBI and the control and data acquisition systems will support observing modes for all.

- *Location in the Quiet Zone* - The location of the GBT in the National Radio Quiet Zone 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.

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

We can anticipate some of the early uses of the facility:

- *HI, 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. Measurement of highly accurate, absolutely calibrated galactic 21cm HI profiles will no longer require heroic effort but can be done quickly and routinely. This will be of benefit to those who need to correct for galactic interstellar absorption in observation of extragalactic objects in the UV and soft X-ray, for studies of the soft X-ray background, and for comparisons of 21 cm HI spectra with spectra of other species.

The low sidelobes of the antenna will make possible the study of faint HI in the galactic halo and studies of the energetics of the ISM, which depend on very accurate measurement of the wings of galactic HI profiles. HI profiles from the GBT should have unsurpassed dynamic range and accuracy of calibration.

- *Pulsar observing*. - Pulsar observations, such as searches towards the Galactic Center, will benefit from the GBT's large collecting area, sensitive receivers, excellent sky coverage, and relatively interference-free site. Both interstellar scattering and the dispersion caused by free electrons in the interstellar medium broaden the distinctive pulses of pulsars at low frequency, making them 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 frequency coverage and agility of the GBT and the capabilities of the spectrometer will make the GBT a powerful new instrument for studies of the chemistry in interstellar and circumstellar clouds. An area where the GBT is almost certain to see use is 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 their building blocks. Long chain-carbon molecules, an important repository of interstellar carbon, may be important in interstellar dust grain theory, and in the explanation of interstellar absorption bands. There is increasing interest in interstellar molecules of biological importance as they may have influenced the formation of life on Earth. In cold, dense interstellar clouds, the rotational energy partition functions of heavy molecules causes their emission strength to peak at centimeter wavelengths. The clean beam and low standing wave response of the GBT, together with its wideband spectrometer, will allow the most sensitive studies of heavy molecules ever undertaken. The frequency range and agility will allow a number of transitions in the rotational ladder of these molecules to be observed.

- *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 high-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 VLBI Network. 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. This study has allowed a very accurate determination of the distance to the galaxy, and modified the cosmological distance scale. Presently, detailed studies of the water masers in extragalactic sources can only be carried out for the nearest galaxies because of the faintness of the maser lines. The dramatic sensitivity improvement of the GBT over currently available telescopes will extend these limits to more distant galaxies. As a single-dish instrument, the sensitivity and large bandwidth of the GBT will make it the premier telescope in searches for new water maser sources. 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. As an element in a VLBI array, the GBT will be used to study the weak maser lines in other known maser sources. The information required to determine the masses of nuclear black holes and geometric distances to these galaxies is contained in the weaker maser lines.
- *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 greatest gain. The GBT will make an enormous contribution in this field.
- *Cosmology*. The high sensitivity, excellent 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.

Much of 2000 will be devoted to commissioning the GBT, but it is anticipated that some visitor observations will begin during the year. The first observations will be at the lower frequencies, and will allow, for example, HI and OH spectroscopy and pulsar projects. Frequencies of operation approaching 50 GHz are anticipated toward the end of 2000, opening up the full range of projects mentioned above.

4. The 12 Meter Telescope

The 12 Meter Telescope continues to produce high-quality science in areas of research which are on the cutting edge of many fields of investigation. The sensitivity, flexibility, and efficiency of the 12 Meter allow investigators to engage in a diverse set of scientific pursuits, which include planetary atmospheres, cometary structure and composition, Galactic structure and star formation, astrochemistry, normal galaxies, and high-redshift galaxies.

As the only U.S. millimeter observatory which allocates all of its observing time to competitive proposals submitted by scientists from around the world, the 12 Meter Telescope has developed into a diverse and unique scientific facility. The 12 Meter Telescope offers:

- Full frequency coverage from 68 to 300 GHz with dual-channel SIS receivers.
- Reliable digital and analog spectrometers allowing spectral resolutions from 2 MHz to 6 kHz over bandwidths as large as 600 MHz.
- Heterodyne array receiver systems operating at 1 mm and 3 mm used for imaging large (>30') fields.
- An efficient on-the-fly (OTF) observing mode which allows one to image large fields quickly using facility single and array feed receivers.

Examples of the science currently done with the 12 Meter Telescope include:

- Monitoring of the weather patterns on Mars through CO absorption spectroscopy of its atmosphere. This monitoring experiment has been active for over 20 years and has added crucial information to that gathered by the Viking and Mars Global Surveyor (MGS) spacecraft. During the MGS aerobraking operations monitoring measurements done using the 12 Meter Telescope were used to track dust storm activity on Mars, thus providing an early-warning system used to correct the MGS orbit and steer it away from a potentially catastrophic encounter with a Martian dust storm.
- Spectroscopic imaging of comets. Images of a number of molecules were made of comets Hale-Bopp and Hyakutake, the first such images made at millimeter wavelengths. New insights into the structure, composition, and chemistry of comets have been derived from these measurements.
- Characterization of the physics associated with the star formation process. Spectral line measurements of the molecular emission from star formation regions at a range of evolutionary states. By using molecules as tracers of the volume density, kinetic temperature, and composition in star formation regions, a better understanding of the star formation process, from pre-stellar core to young stellar object, has been derived from these measurements. Coupled with measurements of the associated dust continuum emission from these regions, the physical evolution of the star formation process has been gleaned through these studies.
- Studies of the chemistry in our Galaxy and external galaxies. The 12 Meter Telescope has a long history of astrochemical experiments; 35 of the 120 known interstellar molecules have been discovered through observations using the 12 Meter. Astrochemical studies complement those which derive the physical characteristics of astrophysical objects. For example, an understanding of the chemical composition and evolution of star formation regions is used to support characterizations of the physical properties in these environments.

- Experiments designed to study and characterize external galaxies. Measurements of the molecular emission, specifically CO, have been used to study the physical properties of external galaxies both nearby and at the fringes of our Universe. The study of galaxies at high (>4) redshifts was born at the 12 Meter Telescope with the discovery of the first of this new class of galaxy.
- Millimeter-wave VLBI experiments which seek to image the cores of distant quasars and active galactic nuclei, study the structure of 86 GHz SiO maser emission about evolved stars, and measure details of the millimeter-wave emission from our own Galactic Center. These observations are conducted approximately four times per year in collaboration with the Coordinated Millimeter-Wave VLBI Association (CMVA). The 12 Meter Telescope forms an essential baseline for most experiments and the sensitivity of the 12 Meter makes it critical to the success of many VLBI experiments. The 12 Meter is now linked to the Kitt Peak VLBA station by fiber optics and makes use of the VLBA maser and data recorders.

III. USER FACILITIES

1. The Very Large Array

The VLA is the premier centimeter radio telescope in the world today. More than 600 scientists used the VLA for their research work in 1999 and a similar or larger number will do so in 2000. Demand for the VLA arises both from the multi-wavelength 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 complementary data provided from observations at other wavelengths. In either case, 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 wye configuration, with nine antennas on each 20 km arm of the wye. The antennas are transportable along 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, respectively. Reconfigurability provides the VLA with variable resolution at fixed frequency or fixed resolution at variable frequency.

The VLA supports eight frequency bands, remotely selectable; the six upper bands by means of subreflector rotation. The following table summarizes the parameters of the VLA receiver system.

The VLA receives two intermediate frequencies (IF), each with 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 III.1. VLA Receiving Systems

Frequency (GHz)			T_{sys} (K)	Amplifier
0.070	-	0.075	1000[1]	Bi-Polar Transistors
0.308	-	0.343	150	GaAsFET
1.34	-	1.73	33	Cryogenic HFET
4.5	-	5.0	45	Cryogenic HFET
8.0	-	8.8	31	Cryogenic HFET
14.4	-	15.4	108	Cryogenic GaAsFET
22.0	-	24.0	160[2]	Cryogenic HFET
40.0	-	50.0	95[3]	Cryogenic HFET

[1] T_{sys} includes galactic background
[2] Twelve antennas have new systems with $T_{sys}(K) = 55K$.
[3] Thirteen antennas equipped to date nineteen by year end 1999.

Future Plans

When the VLA went into operation in 1980, it gave an improvement in resolution, sensitivity, speed, and image quality of more than two orders of magnitude over existing arrays. However, as a result of technological advances during the past decade, new instrumentation is needed to keep the VLA at its current leading position among the world's radio astronomy facilities. In Section VIII of this Program Plan we describe a major new initiative to return the VLA to the leading edge of technology; the VLA Expansion Project. It amounts to a major overhaul of the entire VLA electronics system. The Expansion Project will include a new correlator, a new fiber optic data transmission system, and several new wideband receiver systems. Until major funding for the expansion is available, improvements to the VLA will be limited to yearly improvements to smaller parts of the electronics system.

Work has begun on the next generation of VLA receivers as proposed for the VLA Expansion. Twelve of the new receivers covering the full waveguide bandwidth from 18 to 26.5 GHz will be on the VLA by the end of 1999. Four new receivers will be installed in 2000. The new receivers will have provision for built-in radiometers which measure the strength of the 1.3 cm water vapor emission line. These line measurements will be used to correct phase errors in the VLA data due to atmospheric water vapor over the array. The goal is for this to lead to a routine correction that is either applied on-line or is provided to the users as part of their FITS data set. Testing and evaluation of these radiometers will be done on two receivers in 1999. Thirteen VLA antennas have been equipped with 7 mm receivers since 1995. Six new 7 mm receivers will be added to the VLA by the end of 1999 and six additional receivers will be installed in 2000. Funding is provided by an NSF MRI grant with external contributions by the Max-Planck Institute for Radioastronomie. Efforts to improve antenna pointing and surface accuracy are underway to support this initiative.

With the likelihood of increased demand for the VLA's highest-frequency systems, a critical component of the VLA operational system must be the scheduling of high-frequency observations to take advantage of the optimum weather. In 1999, the phase-monitor interferometer at the VLA was improved and made more robust; a goal for 2000 is to develop a system in which this output can be used routinely for near-real-time observing decisions by a wide variety of users. An exploration will be made of the best approach to take to dynamic scheduling of the VLA, so that good 43 GHz weather is not "wasted" on 1.4 GHz observing programs. A few crude experiments at dynamic scheduling were made in 1999, with more anticipated in 2000. Complete dynamic scheduling of the array probably cannot begin until 2001 or 2002. A particular challenge will be the incorporation of the VLA-PT link (described below) into simultaneous dynamic scheduling of the VLA and VLBA.

The VLBA Pie Town antenna is being connected as a real-time active element of the VLA, under funding through an MRI proposal to the NSF, with matching funds from AUI. This real-time link will double 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 recently completed by the Western New Mexico Telephone Company.

A single-IF demonstration interferometer was successfully used in the fourth quarter of 1998, connecting Pie Town with four VLA antennas. In the second quarter of 1999, modification of the VLA correlator was completed in order to expand the delay capabilities for all VLA antennas, enabling the operation of Pie Town with the full VLA. August 1999 saw the first images and initial scientific observations with the VLA-Pie Town link. This link will be made available in a routine manner beginning with the A-configuration scheduled for 2000 Q4. It is planned that observers will schedule PT-link observations using the same software used for VLA-only observations.

A series of tests was conducted in February and March 1998 to assess the impact of the Motorola IRIDIUM communication satellites on radio astronomy observing in the 1610–1612 MHz OH observing band. Three modified VLA antennas were used for drift scan observations while an IRIDIUM satellite was transmitting at various power levels. The out-of-band emission measured in these tests was near, but below, the interference threshold for the VLA. A remaining RFI problem for the VLA is the IRIDIUM in-band signals that disturb the VLA on-line system temperature correction. Observing at 1612 MHz is now impossible, and additional filtering to correct this problem is being investigated.

The complex samplers used at the VLA would, in principle, permit observations with continuum bandwidths up to the 100 MHz clock rate. Limited modifications to the IF system should allow observations with a 70 MHz bandwidth providing an improvement in sensitivity of about 25 percent, and smaller closure errors. Modifications on three antennas were prototyped in 1998 and have successfully demonstrated this concept. The upgrade of the full array began early in 1999. Accessing the full 100 MHz bandwidth would require extensive modifications to the IF system and is not warranted at this time.

Infrastructure

Significant infrastructure developments during 1999 and planned for 2000 include:

- Improvements to the pointing performance of VLA antennas. The six arcsecond pointing performance of one VLA antenna has spurred interest in improving pointing performance throughout the array Improved pointing performance in tandem with primary reflector surface panel readjustments (completed on 20 antennas) significantly improves antenna efficiency at the 7 mm observing wavelength. Replacement of one azimuth bearing is scheduled in 2000.
- 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. In addition, an outside testing service identified clusters of ties on the VLA track system that are the highest priority for replacement. Nearly 5,000 ties were replaced in 1998, and another 3,700 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. Track alignment, ballasting, and leveling has been completed for all of D and most of C configuration, to minimize the possibility of derailment during antenna moves. Replacement of 5,000 ties, leveling of 2.5 kilometers of track, and anchoring of three spurs is planned for 2000. Calculations show that the program must continue at the level of 5,000 ties per year for 20 years to achieve this standard
- Antenna painting. All quadrupod support legs on the VLA antennas have now been painted and two antennas were painted in 1999, to bring the total number of antennas completely painted to 16. Painting VLA antennas was initiated in 1993, beginning with antennas most obviously stained with rust before mechanical deterioration sets in. Four antennas are scheduled for painting during 2000.
- A workable fall arrest system has been designed and developed in 1999, to provide access to the VLA and VLBA antenna apex in accordance with OSHA regulations. Once the prototype has been approved

by an OSHA consultant, the fall arrest system must be installed on all 38 antennas at an estimated rate of 11 per year starting in 1999.

- A temporary manually-installed 74 MHz crossed dipole installed on every VLA antenna achieved 25 arcsecond resolution and 20 mJy sensitivity, but the dipoles cannot be left in place because of blockage at other frequency bands. Manual deployment is time-consuming and risks accident to both personnel and structure. A study of deployable dipoles initiated in 1997 and may lead to testing and acceptance of a prototype in 2000, after which deployment could begin at a rate of eight per year.
- The Visitor Center roof must be replaced and space provided at the VLA site for ALMA offices and work space in 2000. Work started in 1999 to reduce the ingress of potentially disease-bearing rodents into site buildings is expected to be completed in 2000.

Budget and Staffing

Funding at the proposed 2000 Presidential Request level would severely curtail activities in the key areas of antenna painting and track maintenance, and would delay indefinitely the planned upgrade of the VLA on-line system. This upgrade is critically needed to replace our 1987 ModComp computers, which will no longer be supported by the manufacturer after 2001. A significant delay in progress in any of the above areas could ultimately lead to lost observing time or a diminished use of the facilities.

2. The Very Long Baseline Array

Present Instrumentation

The VLBA is a dedicated instrument for very long baseline interferometry. The ten antennas are distributed about the U.S. in a configuration designed to optimize the distribution of baseline lengths and orientations (u-v coverage). 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 a future project to fill the gap in the range of baselines covered by the two instruments. The antennas are 25 meters in diameter and of an advanced design that allows good performance at 43 GHz and useful performance at 86 GHz. The antennas are designed for remote operation from the AOC. Local intervention is required only for changing tapes, regular maintenance, and fixing problems.

The VLBA is outfitted for observations in ten frequency bands as shown in Table III.2. The receivers at 1.4 GHz and above contain cooled heterostructure field effect transistor (HFET) amplifiers from the NRAO Central Development Laboratory (CDL). The receivers below 1 GHz are GaAs FETs at room temperature. The cooled receiver for each band is in a separate dewar mounted directly on the feed to minimize noise contributions from waveguides, etc. All receivers include both right and left circular polarizations. There is a dichroic/ellipsoid system that allows simultaneous observations at 2.3 and 8.4 GHz, primarily for geodesy and astrometry.

Table III.2. VLBA Receiving Systems

Frequency Range (GHz)	Typical Zenith SEFD[†] (Jy)	Typical Zenith Gain (K Jy)
0.312 - 0.342	2217	0.097
0.596 - 0.626	2218	0.090
1.35 - 1.75	295	0.093
2.15 - 2.35	325	0.094
2.15 - 2.35*	344	0.089
4.60 - 5.1	289	0.132
8.0 - 8.8	299	0.118
8.0 - 8.8*	391	0.111
12.0 - 15.4	543	0.112
21.7 - 24.1	976	0.104
41.0 - 45.0	1526	0.078
80.0 - 90.0#	4000	0.030

†System equivalent flux density
* With dichroic.
# Fort Davis, Los Alamos, Mauna Kea, and Pie Town installed.

VLBI requires highly accurate frequency standards and a wide-bandwidth recording system at each site. The VLBA sites use a hydrogen maser manufactured by Sigma Tau Corporation for the frequency standard. The recording system is based on a Metrum (formerly Honeywell) longitudinal instrumentation tape recorder that has been modified extensively by the MIT Haystack Observatory. The recorder is similar to the one used in the Mark III and Mark IV VLBI systems. There are two drives at each VLBA station to allow more than 20 hours of recording at 128 Mbits per second between required visits by station personnel for tape changes. The tapes are 16 microns thick, with about 5.4 km of tape on a 35 cm reel.

The VLBA correlator is located at the AOC in Socorro. It is able to correlate as many as eight input data channels from each of 20 antennas simultaneously. For most modes, 1,024 spectral channels can be provided for each input channel. The correlator is of a novel design, pioneered by the Nobeyama Radio Observatory in Japan, in which each bit stream is Fourier transformed to a spectrum before cross correlation (the "FX" architecture). Output data are archived on DAT tapes, while the input instrumentation tapes are recycled for more observing shortly after correlation. Users receive their correlated data in FITS format on either DAT or Exabyte tapes, typically within a few weeks of the observations.

The correlator routinely handles many modes of continuum and spectral line observations, including full-polarization data. The core of the correlator real-time code was rewritten in late 1994 and early 1995 to improve its reliability. The improved robustness has been evident in the smoothness of correlator operations since the real-time rewrite. Calibration, imaging, and self-calibration can be done in the NRAO

Astronomical Image Processing System (AIPS), and imaging and self-calibration can be done with the Caltech Difmap program. Software development for VLBI in AIPS is essentially complete. Much work has been done to make the AIPS VLBI subsystem more robust and user-friendly. Astrometric/geodetic processing is done primarily in the system developed by the Crustal Dynamics Project, now Dynamics of Solid Earth (DOSE), at NASA. The in-house computing for the VLBA is done mainly on workstations of the SUN Sparc 20, Ultra and SGI Origin 2000 classes, or on personal computers using the Linux operating system.

Present Status

The array performed astronomical observations during 55 percent of the time in 1999 Q1-Q2. A further 15–30 percent of each month was used for testing and maintenance. The peak monthly usage for astronomy was a record high in April 1999, reaching the ceiling of 70 percent estimated for a mature array. The correlator successfully handled its first program requiring 20-station correlation. The array and correlator passed an end-to-end Y2K test in 1999 Q1.

Automatic tape allocation for the VLBA antennas is now routine. This removed the burden of tape scheduling that was previously done by observers. It also enabled the recording of multiple projects per tape, which improved scheduling flexibility and was a prerequisite to begin dynamically scheduling the array in 1999. The goal of this early stage of dynamic scheduling is to exercise and debug software tools, meaning that operations cannot yet guarantee to meet the minimum observing requirements desired by observers (e.g, no rain in the southwest).

Steps were taken to enhance the user-friendliness of the VLBA and reach out to a broader U.S. user community. Dynamic scheduling and calibration transfer, mentioned above, were started. A topical session entitled "High Angular Resolution Science with the NRAO Very Long Baseline Array" was held during the June 1999 meeting of the American Astronomical Society. New announcements at that meeting included inviting U.S. graduate students to visit the Array Operations Center (AOC) for one to five months, plus offering calibration and/or imaging services for novice U.S. users. It should be noted that funding at the 2000 Presidential Request level would significantly delay the implementation of calibration and/or imaging services; it is estimated that eight new data analysts are required to sustain this service for the VLA and VLBA. These services are being implemented beginning with the October 1, 1999, proposal deadline. Finally, a feature article on the VLBA will appear in Sky & Telescope, and is currently scheduled for the December 1999 issue.

Routine observing with VSOP's HALCA satellite continued, with most of the significant scientific data processed through the VLBA correlator and relying on observations from the VLBA telescopes. Numerous problems have existed in other parts of the VSOP mission, but the VLBA has been an outstanding and consistent performer. A number of VSOP images using the VLBA were presented at the URSI General Assembly in August 1999, and a special VSOP symposium in Japan is scheduled for January 2000.

Several Ph.D. theses relying on VLBA data were completed during 1999, including two by NRAO pre-doctoral students resident in Socorro. The latter students were Michael Faison of the University of Wisconsin and Alison Peck of the New Mexico Institute of Mining and Technology.

Future Plans

Major VLBA developments in the next year fall into three major categories. These are (1) operational streamlining; (2) enhanced user friendliness; and (3) development of new capabilities.

Operations software and information-handling methods are currently undergoing major revision. A new database design and a suite of user interfaces are under construction. This new Operational Management System (OMS) will replace the current information-handling scheme, which evolved during the correlator's commissioning phase and is now a major obstacle to efficient use of both array and correlator. Some of the new OMS interfaces were tested by operations staff in 1999, and complete implementation is expected before the end of 2000. This will serve an important function in freeing operations personnel from mundane data-shuffling tasks, thus enabling them to spend more time on any special cases that require human intervention. It also will improve the robustness of the array, by providing better visibility into its performance. This system is one of the important tools that will help dynamic scheduling to become truly dynamic, and to include response of the array schedule to hardware and weather conditions on time scales of hours to days. A challenge to dynamic scheduling will be the frequent operational use of the Pie Town antenna over the real-time fiber optic link with the VLA; this operation will be routine during the VLA A-configuration session beginning in the fourth quarter of 2000.

In the area of user support, new scheduling, calibration, and/or imaging services will make it easier for astronomers who are not VLBI or radio interferometry experts to use the VLBA in conjunction with their research at other wavebands. These services also will provide an easier learning curve for graduate students who may be at institutions without resident VLBI experts. Depending on the availability of resources, this program may be expanded in late 2000. A key to efficient data analysis for users will be the inclusion of VLBA capabilities in the new AIPS++ software package, which is expected toward the end of 2000.

The correlator has distributed visibility data to observers since 1994, but it has not attached to those data the ancillary tables needed for calibration and editing. The process of automatic building such tables and attaching them to the visibility data is known as "calibration transfer." Tests in 1999 showed that the first phase of calibration transfer, including gain, system temperature, flag, and phase-calibration tables for the ten VLBA antennas, was complete. This improvement was successfully implemented for all programs correlated after 1999 Q1.

The key new capability for the VLBA in 2000-2001 will be the equipping of most antennas at 86 GHz, and the improvement of the overall system performance. Progress installing 86 GHz receiver systems is slow due to lack of funding. Four antennas have 86 GHz systems; in the third quarter of 1999, these systems were returned to the AOC for retrofitting. Improved dewars and amplifiers were installed, as well as quartz radomes; these changes should improve both nominal performance and system reliability. Testing of rail-height offsets in the pointing equations will commence soon and is expected to help at 86 GHz, by reducing the RMS pointing error from 11 arcsec to 7-8 arcsec. By the end of 2001, at least eight of the ten VLBA antennas are expected to have 86 GHz systems, with the nominal observing band expanded to cover the range from 80 to 96 GHz with funding assistance of MPIfR, Bonn. Efforts will be made to measure the subreflectors and primary antenna surfaces, with a goal of improving the typical 86 GHz aperture efficiency from about 18 percent to at least 30 percent.

A recording capability of 512 Mbits per second also should be implemented by 2001, further increasing the sensitivity for continuum sources. In mid-2001, the VLBA should have enough antennas outfitted at 86 GHz to be a reliable standalone array which can significantly advance the scientific return over the wide variety of telescopes currently observing at this frequency under the auspices of the Coordinated Millimeter VLBI Array.

Plans for a VLBA enhancement will be further developed in 2000, focusing on the scientific drivers, and a general meeting on this subject is anticipated. It is expected that these drivers will call for greatly increased bandwidth; improved short and long spacings via the VLA Expansion's A+ configuration and possible new antennas within and outside the U.S.; and enhanced frequency coverage. The bandwidth expansion requirements are similar to those of future Space VLBI missions such as VSOP-2 and ARISE, so it is hoped to take advantage of the synergistic requirements on the space and ground elements. As a first step, a design for an upgrade to a recording rate of 1 Gbit per second is planned during 2000.

A new version of CALC, the software used to compute models for the correlator, has been tested; it will be adopted for general use in early 2000. The new CALC offers improvements in nutation and in handling atmospheric propagation effects, further enhancing phase-referencing performance.

Infrastructure

Significant infrastructure developments during 1999 and planned for 2000 include:

- VLBA holography. The advent of 3 mm observing on the VLBA has led to concern about astigmatism of the subreflector surfaces and main reflector surface panels. Tests show the holographic measurements used to improve VLA observing efficiency at high frequencies will not work on the VLBA because of the long distances between antennas. Metrology systems are expensive and require ray tracing to provide a combined correction for both surfaces. A small portable "outrigger" antenna may be able to provide the necessary phase reference for VLBI holographic main reflector surface panel adjustments; a concept is planned for testing in 2000. Unfortunately, at the funding level indicated in the 2000 Presidential Request a serious effort to improve the surface efficiency of the VLBA antennas at 3 mm cannot be undertaken.
- VLBA antenna painting at the "wet" sites, namely Iowa, New Hampshire, and especially St. Croix, must be continued to maintain structural integrity.
- Drive wheel and pintle bearing replacements. An azimuth wheel drive assembly was replaced in 1998 at VLBA Brewster, after deterioration of bearings in the drive assembly was discovered. Another replacement is scheduled at St. Croix in 1999, and replacements in response to bearing failures are expected to continue at one or more per year until all 20 drives are replaced. A warped pintle bearing found in 1998 at VLBA Kitt Peak fortunately resulted in broken bolts before the bearing itself was damaged. The pintle bearing at each VLBA site is being carefully inspected to uncover any further seating problems; to date, over half have been inspected and no further problem found.
- VLBA site visits by a Socorro-based maintenance team have proved important and adequate at a three-year interval except at St. Croix. The interval for maintenance site visits to St. Croix must be reduced to one year to catch up with mechanical problems introduced by severe corrosion at that site. VLBA Site

Tech workshops conducted at the VLA site every two years are proving essential to reduce travel to VLBA sites by VLA-based maintenance personnel.

3. The Green Bank Telescope

When it begins operation during 2000, 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, and a rotating receiver turret for fast selection of receivers. The frequency coverage of the telescope is designed to cover ~100 MHz to ~50 GHz, and eventually to ~115 GHz. The combination of all these features in a 100 m diameter telescope will give the GBT unprecedented sensitivity and performance. A large number of scientific projects can be undertaken with the GBT—particularly at the higher frequencies—that simply cannot be done on any existing telescope or on any expected facility over the next few years.

Following completion of work by the contractor in early 2000, the NRAO will take receipt of the telescope and begin 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 115 GHz operation will proceed from this point in funds are made available for this purpose.

Current plans call for an initial period of commissioning lasting about 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 and by a few, experienced volunteers from the astronomical community. At the end of the initial commissioning period, some visitor observations at low frequencies will occur 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.

A final stage of commissioning would allow operation to frequencies up to 115 GHz. This would require that the active surface and telescope pointing and tracking systems be brought under closed-loop control with the laser metrology system and that high frequency receivers be built. This capability could be available within 24 months from the time NRAO receives the telescope if funds were made available.

National Radio Quiet Zone

Green Bank is situated in a 13,000 square mile region known as the National Radio Quiet Zone. By Congressional law, no transmitters can be erected in the Quiet Zone unless their emitted power falls below proscribed limits at the Green Bank 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. in 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.

Budget and Staffing

Funding at the 2000 Presidential Request level could seriously delay commissioning of the GBT. It is estimated that in addition to the staff reallocated from the 140 Foot Telescope (closed in July 1999), eight new positions are required for nominal maintenance and operations. These positions cannot be funded at the Presidential Request level. Furthermore, at that level, and outfitting materials and services would be reduced from $168k in 1999 to $35k. These cuts would have a devastating effect on GBT commissioning and operations in the year 2000, slowing progress toward the first availability of the telescope, and delaying first scientific results. In the "Mission Requirements" column in Table X.1 (Section X) we have estimated the personnel and materials and services actually required to commission the GBT in 2000.

4. 12 Meter Telescope

The 12 Meter Telescope began as the 36 Foot Telescope, the telescope responsible for the birth of millimeter-wavelength molecular astronomy. Following a period of explosive growth in this new area of astronomical research, during which most of the dozens of molecular species known to exist in the interstellar medium were first detected at the 36 Foot, the telescope's reflecting surface and surface support structure were replaced and the 36 Foot was re-christened in 1984 as the 12 Meter. Subsequently, the scientific program has evolved from one dominated by observing programs in astrochemistry to one with a broader mix of studies of molecular clouds and galactic star formation, evolved stars, astrochemistry, and external galaxies. The 12 Meter is the only millimeter-wavelength telescope in the U.S. operated full-time as a national facility. More than 150 visitors make use of the telescope annually. It offers users flexibility and the opportunity to respond quickly to new scientific developments. Low-noise receiving systems at a wide range of frequencies, currently covering all atmospheric windows from 68 GHz to 300 GHz, are maintained. Operational reliability throughout this frequency range is emphasized. Flexible spectral line and continuum back-ends allow the observer to match the instrument to the scientific goals. The development of multi-beam receivers and the on-the-fly observing technique has inaugurated a new era of high-speed source mapping on angular scales complementary to those of the millimeter-wave interferometers. The telescope control system offers great flexibility and provides a proven remote observing capability. It has also increased the efficiency and convenience of the 12 Meter Telescope; the experience gained will benefit the future ALMA operation.

Present Instrumentation: Telescope

Diameter	12 meters
Astrodome with slit	
Pointing accuracy	5 arcseconds
Aperture efficiencies	52% at 70 GHz 49% at 115 GHz 32% at 230 GHz 22 % at 300 GHz

As many as four receiver systems are mounted simultaneously at offset Cassegrain foci on the telescope. Receiver selection is by means of a rotating central mirror and can be accomplished in seconds. The receivers are configured remotely from the control room with a computer-aided tuning system.

Receivers

The NRAO tradition of providing receivers equaling or bettering any others in the world is also true at millimeter wavelengths. A closed-cycle 4.2 K system capable of holding eight SIS receivers sharing the same dewar has been developed. A complete set of state-of-the-art, dual-channel superconducting-insulator-superconducting (SIS) receivers is operational over the entire range 68–300 GHz. The arrangement of several receivers sharing the same dewar is cost effective, simplifying operations.

Table III.3. 12 Meter Receiver List

Frequency Range (GHz)	Mixer	SSB Receiver Temperature (K) Per Polarization Channel
68 - 116	SIS	60 - 90
130 - 170	SIS	120
200 - 260	SIS	200 - 400
260 - 300	SIS	400 - 500
1 mm Array Receiver:		
220 - 250	8-beam SIS	260

Note: Receiver noise is around 200 K single sideband for most of the 200-260 GHz band, increasing somewhat at the high frequency limit. All single-beam receivers have two orthogonal polarization channels. Receiver temperatures include all receiver optics.

Spectrometers

Filter-bank spectrometers are maintained so that the astronomer will have access to the proper frequency resolution for a particular astronomical observation. There is a single bank of 128 channels of 30 kHz resolution; single banks of 256 channels of 100, 250, and 500 kHz resolution; and two banks each of 256 channels of 1 MHz and 2 MHz resolution.

To enhance the telescope's spectroscopic capability and to accommodate the array receivers, a new autocorrelator is now available. Its instrumental parameters are given in Table III.4.

Table III.4 12 Meter Correlator Specification

IF Channels: 8/4/2
IF BW (Bandwidth): 800-1600 MHz
Sample Rate: 1600 MHz
Correlator Clock: 100 MHz
Usable bandwidth assumes a 75 percent efficiency factor
for analog filters.

Total BW (GHz)	Usable BW/Channel (MHz)	Lags/IF	Freq Res/IF (kHz)
8 Active Samplers			
6.4	600	1024	781.2
3.2	300	2048	195.3
1.6	150	4096	48.8
0.8	75	8192	12.2
4 Active Samplers			
3.2	600	2048	390.6
1.6	300	4096	97.6
0.8	150	8192	24.4
0.4	75	16384	6.1
2 Active Samplers			
1.6	600	4096	195.3
0.8	300	8192	48.8
0.4	150	16384	12.2
0.2	75	32768	3.0

Future Plans

Considering that ALMA is our top priority, the competition to the 12 Meter from other millimeter/submillimeter dishes on superior sites, and an increasing shift of scientific focus on higher angular resolution imaging than single dishes provide, we are planning for the phase-out of the 12 Meter. The assumption has been that we would operate the 12 Meter until interim ALMA operations began. This will be reviewed through a careful process, with community input, that weighs the scientific return against costs and the scope of Observatory activities that can be conducted with the resources available.

A New 8-Feed SIS System for 3 mm

We have begun construction of a new 8-feed multi-beam system for 3 mm, to replace the existing 3 mm system. The new system will support simultaneously dual polarizations in each of four beams on the sky, and will give substantially increased sensitivity both for point-source observations and for mapping of extended objects. Each of the eight receiver channels will have lower noise than any of our existing 3 mm receivers, by a factor of 1.7. The improvement results from a careful study of the various losses and sources of noise mainly within the receiver optics. In reasonable weather, this sensitivity improvement becomes a factor of ~2 reduction in observing time on the telescope to reach a given sensitivity. For point source observing, two of the dual polarization beams will be separated on the sky by an angle equal to the beam throw from the nutating subreflector. This makes the system a dual-polarization double-Dicke switching system, with a further factor of two gain in observing speed compared with our existing single-beam dual-polarization system. That is overall a gain in speed by a factor of ~4 for point source observations with the new system. For mapping of extended sources, all four dual-polarization beams will be used, giving an observing speed gain of approximately eight, compared to our current system. We plan to have this new 8-receiver, 3 mm system on the telescope during 2000, the last new receiver system planned for the 12 Meter.

Telescope Control, Data Acquisition, and Data Analysis Improvements

New enhancements continue to be incorporated into the telescope control system. The analog servo system that positions the telescope will be upgraded to a fully digital system. This should reduce the settling time required after telescope movement and could result in a 10 percent or more improvement in the duty cycle of most observing modes (note that 10 percent improvement in observing efficiency is equivalent to approximately 30 days of observing time in a typical season at the 12 Meter). The user interface has been enhanced to allow the observer more direct control over the telescope.

On-the-Fly Observing

The on-the-fly (OTF) observing mode has become the preferred mapping mode. With this technique, the observer makes several rapid passes over the field of interest, recording data continuously. The results are averaged to improve signal-to-noise. The gains with this mode of observing have far exceeded our original expectations. The observing efficiency is much improved, because most of the dead time required to move the telescope beam from one discrete point on the sky to the next is eliminated. A factor of nearly two in sensitivity is gained because it becomes possible to use a single off-source reference position for perhaps hundreds of on-source spectra. The ability to make a complete coverage of a given field quickly gives much higher consistency and quality in the individual data sets. In averaging the N data sets, the random noise is of course reduced by the square root of N, but for a small number of systematic defects, (e.g., the occasional bad scan due to weather or other drifts) the artifacts are reduced by a factor closer to (N). The ability to cover a field with full Nyquist sampling or better adds to the scientific value of the observations. Compared with the conventional point-by-point mapping, an increase in effective mapping speed of as much as one order of magnitude can be experienced. Comparatively large regions (e.g., one-third of a degree on a side) can be observed to a useful sensitivity limit in tens of minutes.

Naturally this observing mode produces enormous quantities of data. Special tasks have been added to the classic AIPS data reduction system to support the 12 Meter OTF mapping mode in spectral line. Further development in AIPS is taking place to support continuum OTF observing.

IV. TECHNOLOGY DEVELOPMENT

1. Electronics

In order to carry out the NRAO's mission of providing the astronomical user community with the best possible facilities for carrying out observations, research and development of equipment is required. Where possible, the NRAO takes advantage of commercially available devices or equipment developed at other institutions; but in many cases neither of these alternatives yields state-of-the-art performance in the context of practical application to radio telescopes, and so the NRAO is forced to perform leading edge engineering work. Future work will be needed in the following areas:

- Design and fabrication of HFET amplifiers;
- Design and fabrication of SIS mixers;
- Development of planar diode frequency multipliers for use in LO sources;
- Development of advanced electromagnetic structures;
- Correlators and spectrometers;
- New concepts in feed arrays;
- New concepts in interference canceling receivers.

HFET Amplifiers

History

HFET amplifier work conducted over many years has resulted in successful development of all-Indium Phosphide HFET amplifiers covering all frequencies from 18 and 115 GHz, and balanced amplifiers using GaAs devices in the range 0.3–1.2 GHz. Figure IV.1 shows the performance of the space-qualified high-frequency amplifiers developed for the Microwave Anisotropy Probe (MAP) project, compared with the theoretical performance and with the performance of NRAO SIS mixers. The highest frequency amplifier developed so far covers the band 70–115 GHz with a minimum noise temperature of 60 K, making it competitive with SIS receivers for narrow-band spectroscopy and surpassing the instantaneous performance of present NRAO SIS receivers for continuum work. This performance has been achieved with InP devices specially fabricated for the NRAO by Hughes Research Laboratories. It is predicted on theoretical grounds that there will be no significant improvement in the performance of such amplifiers with a very large investment in basic semiconductor technology.

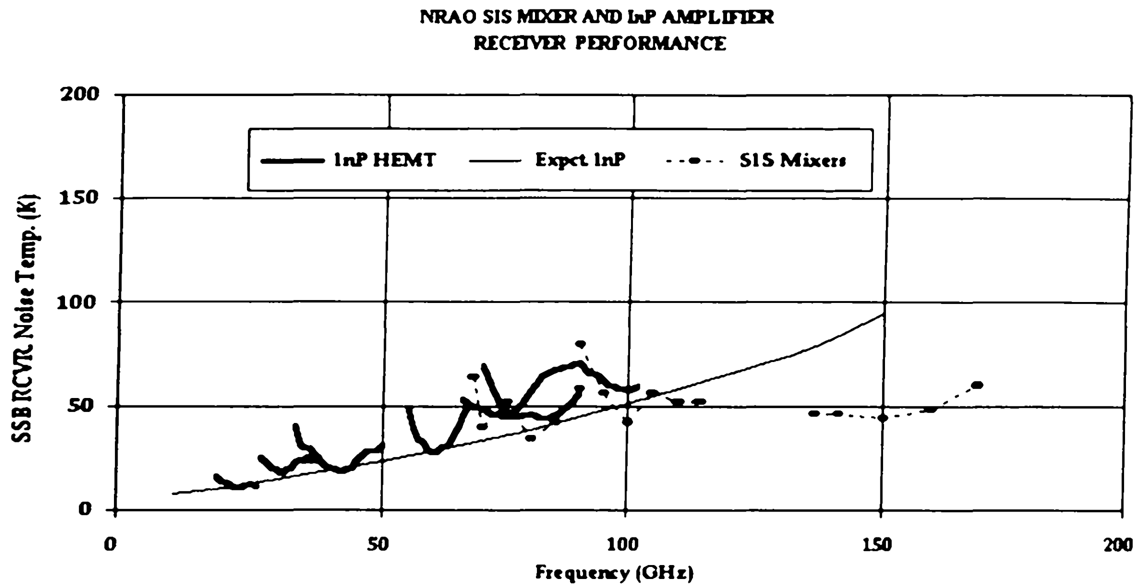

Figure IV.1. MAP HFET amplifier receivers and NRAO SIS mixer receivers. The thin solid line is the theoretical best possible performance for InP transistors.

Amplifiers for the 18–26 and 33–50 GHz bands have been incorporated into new, lower-noise receivers for the VLA and will yield dramatic improvements in sensitivity. Amplifiers covering the 85–90 GHz band have been incorporated into receivers for the VLBA, and used for VLBI observations with extremely high angular resolution. It is planned that the VLBA will be fully equipped for 86 GHz operation within the next few years.

We expect that ALMA will use these amplifiers for phase calibration and scientific observations at frequencies between 30 and 90 GHz, and possibly up to 115 GHz.

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

We expect over the next few years to phase out the use of GaAs devices except perhaps at the very lowest frequencies and to convert almost entirely to InP devices. To our knowledge, InP devices have never been used successfully below 18 GHz; however, there does not appear to be any fundamental reason why this cannot be accomplished. Accordingly, we have designed a completely InP amplifier for the 4–12 GHz band, and expect it possibly to be useful up to 18 GHz; this may be used as an intermediate frequency amplifier for ALMA or in its own right as a front-end low-noise amplifier in ultra-wideband receivers.

At the low frequency end of the spectrum, we have developed balanced amplifiers using Lange couplers fabricated on printed circuit boards. These amplifiers have a noise temperature of 2–3 K and will be used initially in the low-frequency GBT receivers. This technology can certainly be used above 1 GHz, perhaps as high as 2 GHz with the present technique and even higher in the future. The advantage of a balanced amplifier over a single-ended design is twofold: first, the input match can be made very good so that generation of circular polarization from linear polarization can be achieved in the RF; and second, the third-order intercept point is higher and thus intermodulation distortion caused by in-band interference is reduced. Current designs work very well up to 1.2 GHz.

Future Plans

For the VLA, VLBA, and GBT, we will fabricate new HFET amplifiers both to improve the performance at currently available frequencies, and to extend performance to cover all the atmospheric windows available and justified by antenna performance up to 115 GHz. We expect that most of these amplifiers will be built using the discrete device technology (MIC) which we employ at present. We have carefully followed the recent development in integrated amplifiers-on-a-chip (MMIC) which have opened the possibility of reducing production costs. However, we note that the development costs of such MMIC circuits is very high, and the savings to be found in using MMIC devices is primarily in the area of reduced technician labor. If MMIC devices designed by other amplifier engineers become sufficiently refined, we expect to adopt them for NRAO use.

Development of InP amplifiers operating as low in frequency as 1 GHz will be attempted in an effort to reduce system temperature as much as possible; however, near and below this frequency the portion of the contribution to system temperature from the existing GaAs devices is minor and may not justify the effort.

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

SIS Mixers

History

Superconductor-Insulator-Superconductor (SIS) mixers fabricated of niobium have been made for the NRAO by the University of Virginia Semiconductor Devices Laboratory and by the Jet Propulsion Laboratory.

The most recent devices produced and tested are of a new tunerless design which so far has been shown to work well from 210–280 GHz. Using this fundamental mixer design, we designed a single-chip image separating mixer which was fabricated at JPL and demonstrated less than 60K receiver noise temperature (single sideband). The layout of this mixer is shown in Figure IV.2, and its performance is shown in Figure IV.3. The performance of this prototype nearly meets the goals of the project, which is >10 dB image rejection—enough to virtually eliminate the system noise contribution from the atmospheric noise in the rejected sideband.

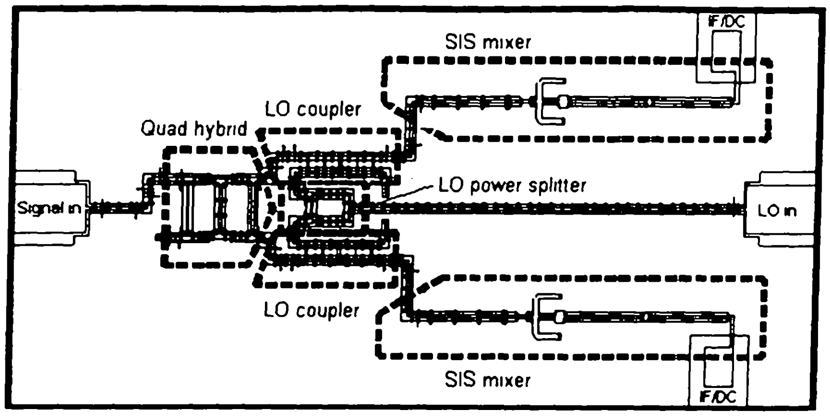

Figure IV.2. Layout of sideband-separating mixer chip

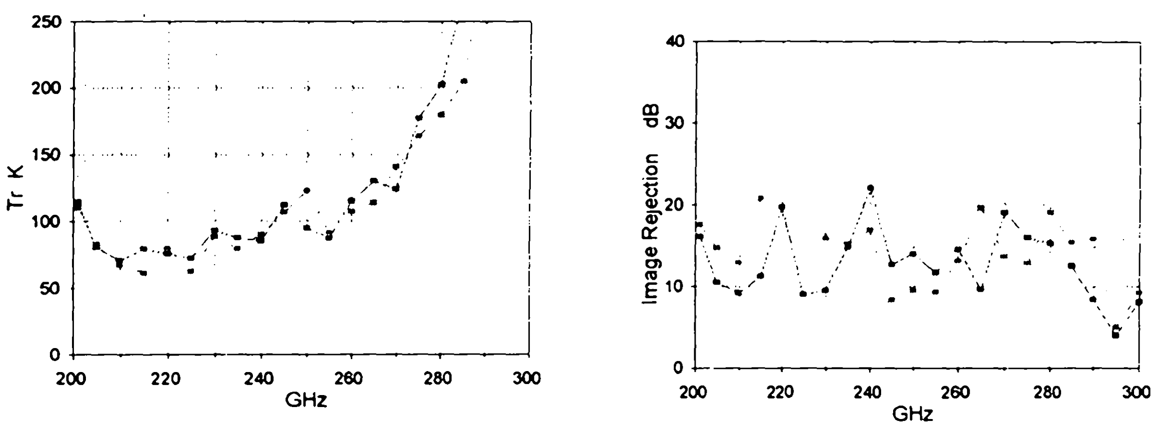

Figure IV.3. Single sideband noise temperature and image rejection of the sideband-separating mixer prototype.

A second new design was for a single-chip balanced, tunerless mixer. Such a design will reject LO noise and make it possible to eliminate a directional coupler for the LO signal, thus dramatically reducing the LO power requirement, with significant cost savings. A prototype was fabricated and tested, and the performance of a prototype is shown in Figure IV.4. The device shown is tuned slightly high but demonstrates the success of the principle.

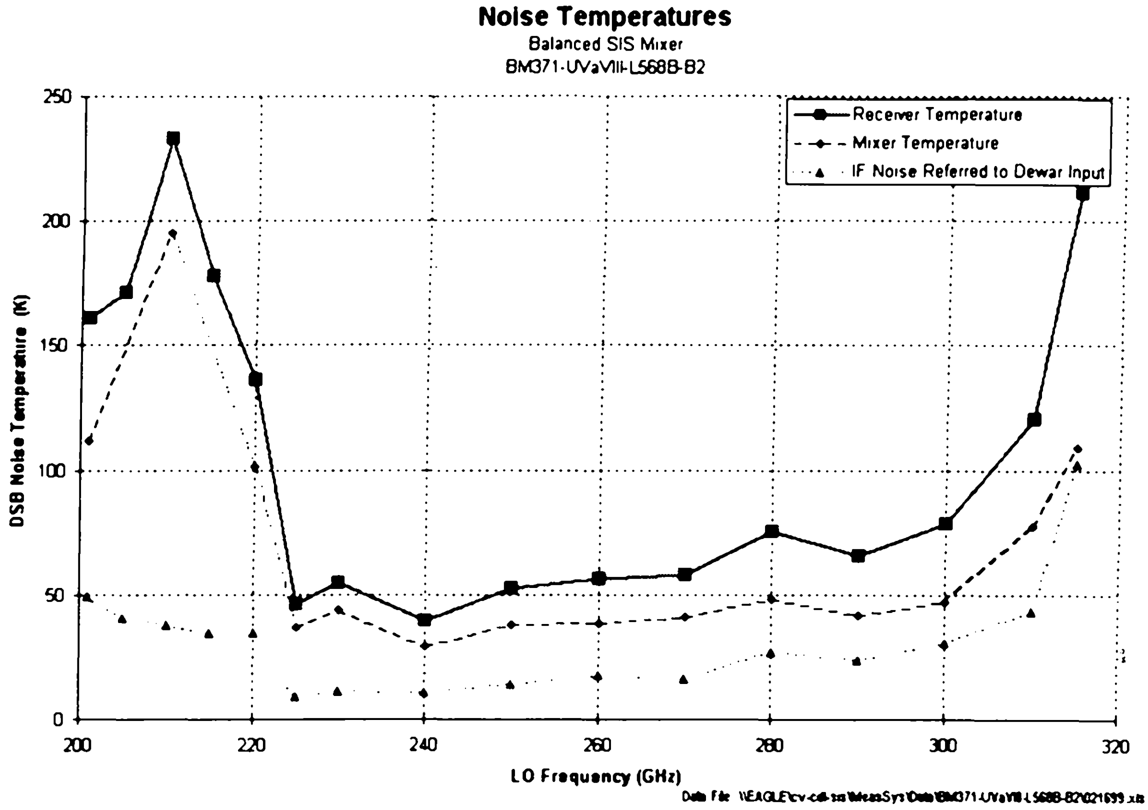

Figure IV.4. Noise temperature of balanced mixer prototype

Both the image-separating and balanced prototype mixers are designed with very low output capacitance so that the bandwidth of the intermediate frequency (IF) signal can be increased over that which is currently available.

Future Plans

A new development project is the inclusion of an integrated IF amplifier within the mixer body. This technique has been successfully pioneered by Caltech (with design assistance from the NRAO) in order to achieve a bandwidth of ~4 GHz (as opposed to less than 2 GHz for other current designs). In cooperation with JPL, we have undertaken the design of an MMIC IF amplifier for the intended MMA IF range of 4–12 GHz. In a parallel effort, the design knowledge gained in the course of the development of the 4–12 GHz HFET amplifier described previously is expected to result in the capability of using a wideband IF amplifier employing discrete transistors.

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

At frequencies above about 350 GHz, it may be that the transmission line losses on the MMIC chips become large enough to contribute significantly to system noise. We have already investigated the possibility of fabricating image-separating, balanced mixers using single-mixer chips mounted in a structure which employs waveguide couplers to achieve the same ends as the couplers on the MMIC chips. Prototypes of such couplers for 211-275 GHz have been successfully manufactured, and work in this area is planned for higher frequencies.

For the ALMA project, fabrication and test of large quantities of SIS mixers is required; this has not been accomplished previously anywhere. Accordingly, much effort will be spent on quality control, automated test procedures, and device reproducibility in order to make such a large manufacturing effort feasible.

Electromagnetic Studies

History

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

For the GBT, new feeds were developed for all GBT observing frequencies. For the VLA, feeds were developed for the new, low-noise receivers.

The NRAO recently developed a new orthomode transducer and a new phase shifter for the 18–26 GHz band which when combined show excellent performance as a full waveguide band polarizer. This is about twice the bandwidth of any other polarizer for this band. These developments are directly related to expansion of the VLA to achieve complete frequency coverage and have been incorporated into the new 18–26 GHz receivers. Along with an InP HFET amplifier, this resulted in a noise temperature at the zenith of about 50K, a factor of 3 improvement over the old system. The phase shifter is now being fabricated using electroforming, which gives excellent repeatability.

New computer modeling software has been used to evaluate the design of phase shifters and design new ones for the 2--40 GHz and 12–18 GHz bands. A prototype for 26–40 GHz has been successfully fabricated.

For the 12 Meter telescope and particularly for ALMA, the NRAO has developed feeds, diplexers, couplers, quasi-optical components, and vacuum windows for the millimeter regime. These elements are critical for wideband performance. A vacuum window using a PTFE-crystalline quartz-PTFE sandwich was fabricated and tested, and shows great promise for extending the interval of time before refrigerators must be shut down due to leakage.

Future Plans

New orthomode transducers have been designed for frequencies up to 110 GHz; these will be tested and will serve as prototypes for new, wideband receiver use. Complete polarizers will be developed for the 12–18 and 26–40 GHz bands.

New wideband, low-loss feeds will be developed for the VLA. This includes Cassegrain feeds for frequencies above 1.2 GHz and prime focus feeds below 1.2 GHz.

We will continue to research new window materials and construction techniques to achieve minimum RF loss combined with acceptable gas leakage. In particular, a 5-layer window should yield less than 0.08 dB loss across an entire waveguide band and have zero gas leakage.

LO Systems

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

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

Second, we are investigating the possibility of an LO system in which the signal is generated in a photomixer by beating together two infrared lasers operating in CW mode at slightly different frequencies. A demonstration system using a low-frequency photomixer to generate either a beat tone up to 60 GHz has been successfully phase-locked to an external reference and has shown the required phase stability. The principal obstacles to using such a system in the mm and sub-mm bands are that photodiodes that operate efficiently at frequencies up to 900 GHz are difficult to design and fabricate, and that no good means has yet been demonstrated for coupling sufficient energy out of the photodiode at the frequencies of interest. We have contracted with the photomixer and microwave groups at UCLA to design a structure which will permit three key processes: (1) efficient coupling of the laser energy into a photodiode element, (2) operating the photodiode element at the required power level without destroying it, and (3) coupling the resultant RF energy out through a waveguide. The RF power level required depends on the success of the balanced

SIS mixer, which we expect to have relatively low LO power requirements. While the development effort for such a system is large, the potential savings in implementation cost and reliability are also large.

Digital Electronics

History

The NRAO has designed many auto- and cross-correlators for single-dish and interferometric use. These include numerous spectrometers of increasing complexity, culminating in the successful design of instruments for the GBT and the 12 Meter Telescope. The GBT spectrometer uses a custom correlator chip containing 1,024 correlating elements (multiply & add). It performs 2.6×10^{13} calculations per second. Cross-correlators for the VLA and VLBA have been in regular use for many years.

Expected Developments

A crucial element of ALMA is the correlator. As part of the ALMA conceptual design, we have considered various correlator architectures which could meet ALMA needs, and settled on a conceptual design for a lag correlator which requires the minimum number of interconnecting cables. It will require the development of a new correlator chip with 4,096 lags, a factor of 4 greater than the chip used in the GBT spectrometer. The total calculation rate will be 5.2×10^{15} multiply-and-add operations per second. We are building a GBT spectrometer copy (configured as a cross-correlator) for first ALMA use with two antennas. A prototype of the final correlator is intended to be ready in 2003.

In conjunction with the correlator development, we have decided upon the use of a digital FIR filter in place of analog baseband filters, to cut costs and eliminate the uncontrollable systematic errors inherent in an analog filtering system. We will build a prototype of such a filter and test it extensively.

Feed Arrays

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 2.2 beamwidths. Thus, for mapping radio sources which are only slightly extended, a multiple-beam receiver does not achieve a significant speedup in observing compared to a single receiver. We have developed a prototype of an array feed receiver which packs planar feeds close together and achieves multiple beam synthesis by weighted combination of multiple feed outputs. This system was tested on the 140 Foot Telescope and showed that multiple beams with good beam shape and efficiency can be synthesized from appropriately phased linear combinations of the basic feed elements. An advanced version of the receiver including cooled amplifiers is under development, and this effort is expected to continue. We will also investigate the use of bolometer arrays at the highest frequencies for single-dish use.

Interference Rejection

As the number of radio transmitters increases, radio astronomy becomes increasingly difficult. This is particularly bad in the case of satellite-borne transmitters, which cannot be avoided by placing radio telescopes in remote locations. We will fight radio frequency interference by a variety of means, and we expect that this effort will continue to expand in the future.

Any technological means of observing in the presence of RFI requires that the receiver be highly linear in its response, even in the presence of strong interfering signals. We will advance the state-of-the-art in this regard, paying close attention to both linearity and gain.

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

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 spaceborne transmitters to minimize RFI effects on our observations. To this end, the NRAO will continue to participate in regulatory committee deliberations and publicize the need to preserve spectrum space for astronomical research. We will also pursue technological improvements, such as the use of balanced amplifiers in the crowded low frequency spectrum and the use of HFET amplifiers instead of the more RFI-susceptible SIS mixers at frequencies below 100 GHz. Tests of the interference to the protected radio astronomy band around the 1612 OH line from the Motorola Iridium system have been conducted. This work will continue in an effort to eliminate the effects of harmful interference due to such low-earth-orbit systems.

Failure to attract NSF MRI funding, and the lack of funds in the NRAO Research Equipment (RE) budget based on the 2000 Presidential Request level for NRAO, means that RFI research within NRAO is essentially at a standstill until alternate funding can be identified.

2. AIPS++ Project

AIPS++ is an international collaboration between a consortium composed of NRAO, the Australia Telescope National Facility, the Berkekey-Illinois-Maryland Array, and the Netherlands Foundation for Research in Astronomy. The goal is to develop a new package for the analysis of radio astronomical observations. The new package is designed to have greatly expanded capabilities compared to existing packages. These capabilities are needed for the new generation of telescopes such as the GBT and ALMA, as well as for the continuing development of the VLA and the VLBA. AIPS++ is an ambitious project, the package itself is composed of over 1.5 millions lines of C++ and Glish code, developed by a globally distributed team of about 25 people using the Internet for communications and code distribution. In addition to the post-processing capabilities conventionally found in such packages, AIPS++ has facilities to aid real-time observing using radio telescopes. This latter capability is essential for the GBT and for ALMA, and is also expected to be used at the VLA.

The most important milestone for the AIPS++ Project in 1999 is the first public release of the package. AIPS++ has been in use at the various consortium sites since 1995, and has been in selected testing by various astronomers since 1997. A pre-release CDROM was issued to a number of testers in August 1999, and has been in testing and revision since. The revised version will be issued in October 1999 as the first public release of AIPS++. The CDROM, available for both Linux and Solaris operating systems, will be shipped to over 200 astronomers who have signed up to receive the release. Subsequent major releases are planned on a six month interval, though minor updates and patches will also be available on a shorter time-scale over the Internet.

Now that this very significant milestone has been passed, we can now proceed on a number of fronts:

- We expect to spend a considerable effort on publicizing the package and educating new users. The first effort at this consists of a series of tutorials held at the Array Operations Center in August and September 1999.
- In reaction to the impressions of the first wave of users, we will continue to fine-tune various aspects of the system, such as the user interface, and the presentation of documentation.
- The commissioning of the GBT will be aided by the use of AIPS++-based tools for engineering work, the initial commissioning, and the first scientific observations. This continues work that has been proceeding at Green Bank since 1995.
- AIPS++ will contribute to the development of ALMA in two major ways in 2000. First, we will provide simulation software in early 2000 that will be used to answer key design questions for the array. Second, we will provide software for holographic measurements of the prototype array antennas. In addition, we will continue our longer-term support of ALMA by the development of the necessary mosaicing and real-time observing capabilities that are crucial to the success of ALMA.
- We will continue to develop a few key the capabilities of AIPS++. By the end of 2000, we expect that VLA and VLBA observers will be able to reduce a typical observation completely within the package, from filling the data to making publication quality plots.
- We expect that the VLA upgrade will make substantial use of AIPS++ for the management of the end-to-end data flow, as well as for real-time imaging, and post-observing reduction.
- For the VLBA, the goal is to provide intelligent scripts for automated processing of VLBA data all the way to images. We expect to have this complete by 2001, and so work on this will start in 2000.
- Some non-consortium groups are using the package. For example, the Hertzberg Institute of Astrophysics is using AIPS++ for the ACSIS focal plane correlator that it is designing for the James Clerk Maxwell Telescope.

Finally, the consortium is considering how to expand. This issue arises because of the interest of other radio astronomical centers in joining the consortium. We expect to accrete one or more new consortium members in 2000.

V. DATA MANAGEMENT

Observatory-wide Computing

Computing facilities at the NRAO provide vital functions both for NRAO operations and for the scientific research conducted by NRAO users and visitors. Besides the obvious necessity for computer control of the systems which comprise a radio telescope, the use of computers and data reduction systems are essential to translate most of the raw data from radio telescopes into the imagery and other products which lead to scientific results. Significant processing is required before scientific analysis can even begin. In radio astronomy, computer analysis is fundamental to the process, not merely a useful adjunct to scientific analysis.

Computing systems at NRAO must satisfy strong demands in the face of constrained budgets. Over the past year the NRAO was able to make very limited progress in addressing many of the problems of its aging computing infrastructure. The drastically reduced level of Observatory-wide Computing funding in 1999, compared to the previous two years, meant that vitally needed upgrades could only be done for approximately 6 percent of the workstations used by NRAO's staff and visiting observers. This is in stark contrast to 20 percent in each of 1997 and 1998, which is the level that must be permanently sustained on an annual basis to ensure that systems remain useful. The projection for 2000, based on the Presidential Request level, represents a severe cut in our ability to maintain NRAO's computing infrastructure.

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 NRAO computing systems 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 which do not permit such a continuous upgrade process will inevitably impact the services the NRAO can provide to its staff and user community.

Essentially no improvements can be made to local site networking from the anticipated operating budget. However, in March 1999 the NRAO received a special grant from the NSF CISE directorate. This grant will permit significant enhancements to the NRAO Intranet in support of video-teleconferencing, as well as to Internet connections and other equipment at Green Bank in support of remote observing.

The main focus in a year with such tight budget constraints has to be support of the telescopes and observing. Much of the 1999 funds therefore went to items related to the VLA real-time system rewrite, associated training, and improvements to visitor facilities at Green Bank. Limited improvements in other key areas were made during 1999, primarily the purchase of large-format printers in Green Bank and Socorro for scientific and engineering use, as well as reasonably modern projection equipment, capable of interfacing with computers for scientific and technical presentations, in Green Bank, Tucson, and Charlottesville.

NRAO's partnership with the National Computational Science Alliance (NCSA - formerly the National Center for Supercomputing Applications) is in full swing. This partnership will help the NRAO and the NCSA build a connection and infrastructure which will open the doors at the NCSA to the radio astronomy community. Certain kinds of problems in radio astronomy, such as wide field imaging, pulsar searching, and analysis of large spectral-line data cubes, can require computing resources beyond what the NRAO, and most other research institutions, can provide. The NCSA collaboration focuses on implementing parallelization techniques in selected AIPS++ tasks which, combined with improved access to NCSA's facilities, we hope will allow radio astronomers to take advantage of powerful parallel architectures.

NRAO's program to assess, test, and correct software and hardware bugs related to the change of century on January 1, 2000, has made excellent progress. Following tests and upgrades of some key software, it now appears that critical functions at the Observatory, such as financial and telescope operations, will be largely unaffected. Nonetheless, contingency plans for supplies and operations are being developed to cope with potential disruptions in the early part of the new year.

For 2000, the following initiatives and efforts are priorities for computing facilities, equipment, and support.

Year 2000 Preparations

When clocks tick over from the year 1999 to the year 2000 only a few months from now, many current computer systems, software, and smart hardware containing embedded microprocessors may malfunction if not updated or replaced before that time. The simple convention of using two digits for the year instead of four has created a pervasive time bomb ticking away inside of much of the software and hardware used today. The effects of the so-called "Millennium Bug" may be widespread, and serious for organizations which are unprepared. It has become clear that substantial efforts are required to correct Year 2000 (Y2K) problems.

The assessment phase of NRAO's preparations was completed almost two years ago; testing and repair has been ongoing since then. Several key tests, including those of Fiscal computing, VLA, VLBA, and 12 Meter Telescope operations, with the date set to 2000, have been carried out successfully. A few final tests will be performed in late 1999 (primarily those involving the GBT). The primary fileserver at the AOC, which was seven years old, could not be made Y2K-compliant and was replaced in early 1999. No other critical systems appear to have such serious Y2K compliance problems.

Y2K vulnerabilities at NRAO break down into the following areas:

- Fiscal, Payroll, and Personnel: These are critical to NRAO's continued operation. All major components are believed to be Y2K compliant; detailed testing has verified this estimation. We have also evaluated our dependencies on outside services in these areas, and believe that no major problems will be encountered.
- Telescope Operations: Detailed testing revealed only a few small errors in the real-time control systems and data processing software, all of which have now been repaired. The 140 Foot Telescope in Green Bank will cease operations before the end of 1999. Portions of the GBT monitor and control software will be tested in late 1999; the code has been designed to be Y2K-compliant.
- Embedded PC's Many of our most complex electronics systems use embedded PC's and chips which may not be Y2K compliant. While most of these do not rely on the date to perform their tasks, further testing may be required to see which systems are affected, and where updates or replacement might be needed.

- Communications: Only minor problems exist in our own telephone, intranet, and Internet-related equipment; remediation is already underway and will be completed by late 1999. As with our business systems, there is a potential for problems in outside services, and contingency plans are being developed in case important communications services are unavailable or crippled in the first part of 2000.
- Utilities and Other Key Outside Requirements: Our planning will include possible disruptions in power delivery to NRAO sites, as well as other services such as water, fuel, shipping, mail, and emergency services.

Detailed assessment and testing of PC systems and evaluation of third-party software was begun in mid-1999; only limited testing of the latter can be performed. At this time, it appears unlikely that Y2K fixes at NRAO will require substantial resources from the Research Equipment budget in 1999 and 2000. Some 1999 funds were used to permit the sites to do moderate overstocking of essential computer supplies such as toner and removable storage media, to protect against shipping and supply problems in late 1999 and early 2000.

The current status of NRAO's Y2K efforts, as well as useful related information, can be accessed through the Internet at http://www.cv.nrao.edu/y2k/.

System Upgrades

During each of 1997 and 1998, approximately one-fifth of the workstations at NRAO were upgraded to more capable systems. At least this level of replacement needs to be maintained in future years to allow NRAO to continue retiring workstations which have already reached the end of their useful operational lifetimes. Upgrade or replacement is also required by the increasing demands on computational capability at NRAO 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 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 was not possible in 1999 due to reduced funding.

Without this level of effort, the NRAO risks following a path leading to the situation of the late 1980's, where use of observational facilities was restricted solely to prevent overloading of data reduction capabilities. Roughly $250,000 will be required for hardware acquisition in 2000. This level of investment will accomplish three goals:

- Reduce difficulties faced by users getting time on workstations at the NRAO which are capable of handling medium to large problems.
- Allow the NRAO to address the problems it faces with an aging computer infrastructure.
- Provide capability for addressing high-end scientific problems which are beyond the capacities of current computing facilities at the NRAO.

If resources are constrained during 2000, the upgrade focus will remain on the first of these goals. Resolving the infrastructure and high-end computing problems could in principle be deferred, but 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. This level of effort should be continued indefinitely to keep scientific research at NRAO at astronomy's leading edge.

While the NRAO must provide AIPS support for a broad range of UNIX systems, we must also be careful not to strain our resources by attempting to maintain too much diversity. Improvements in performance on very inexpensive Intel hardware running Linux continue, maintaining its favorable price/performance margin over the more traditional UNIX platforms at the NRAO. While Linux cannot replace all other UNIX systems in our installations—it does not have support for large files, and some of the commercial software we require is not available—it is an extremely attractive and cost-effective platform for many purposes, and is likely to remain so.

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 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 to its users through the Internet (NRAO's home page http://www.nrao.edu/). Users can access on-line documentation, download software, peruse recent NRAO preprints, newsletters, and technical memos, or download available images from the completed NVSS and the ongoing FIRST survey.

The networks at 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 NRAO, and allow more flexibility in meeting future computing demands.

For the past few years, we have been able to make progress in the process of modernizing NRAO's network infrastructure. This process was deferred during 1999 due to budget constraints. It must resume in 2000 with further upgrades at Green Bank to support the demands of GBT operations; in Charlottesville to prepare for the merging of the Ivy Road and Edgemont Road facilities; and in Tucson with new facilities to accommodate expansion due to MMA development. A related goal is to provide high speed links between NRAO sites, and between 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 enhanced and expanded to provide such capabilities for remote observer access for 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.

The estimated cost for completing the most critical improvements in the performance of the internal computer networks at the NRAO will be \$150,000 in 2000. 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. Chief among these efforts are the Green Bank Telescope project, ALMA, and the proposed VLA upgrade. 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 are faced with carrying out their work using obsolete or inadequate workstations and PCs, their productivity will suffer. Improvements in this area were minimal in 1999 and will need further investment in 2000. Special efforts are also being made to ensure that all engineering staff have access to current releases of major software packages, to reduce the difficulty that has been encountered in exchanging information. Little progress in this area was possible in 1999; the estimated cost of these undertakings during 2000 will be approximately $50,000. This will allow the acquisition of both appropriate workstations and required software.

Addressing this need will maintain the productivity of NRAO's engineers, and the effectiveness of NRAO's operations over the long term. Deferring this expenditure until after 2000 will reduce the productivity of NRAO engineers and may also reduce 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 nearly 12 years old, and represent an expensive maintenance problem. After being informed by the manufacturer of these computers, in the spring of 1998, that support can be guaranteed only for approximately two more years, the NRAO decided to redesign the current online system with the intention of basing the new system on a more modem and cost-efficient hardware platform such as that used in the VLBA, GBT, and 12 Meter 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 instrumentational capabilities more readily. While it will take much longer to implement, it will produce a system that is easier to support, is compatible with other NRAO control systems for which we have considerable in-house expertise as well as a larger pool of potential applicants, carries much more reasonable maintenance costs, and can be designed from the start with many of the requirements of the VLA Upgrade and other planned enhancements in mind.

The VLA On-line System redesign was begun in late 1998 and has made good progress in 1999. The design process is well underway, real-time software development group members have received training they needed to make effective use of modem equipment and software technologies, and some of the necessary equipment for prototyping will be purchased toward the end of 1999. Diminished funding this year necessitated deferral of the remaining items until 2000, when approximately $25,000 will be required. Further deferral of this effort in 2000 may seriously delay implementation of the new system.

Mass Data Storage

A hallmark of radio astronomy is the large volume of data which 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 which are pushing up the size of data volumes at NRAO include mosaicing with the VLA, on-the-fly imaging at the 12 Meter, interferometric spectral line observations, and new spectrometers for the GBT and the 12 Meter. 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. The NSF CISE grant will permit improvements to the online data storage facilities at both the GBT and the 12 Meter to reduce the constraints on remote observing imposed by inadequate disk space.

During 1998 we began limited deployment of higher-speed, higher-capacity tape media such as Digital Linear Tape (DLT) and similar devices such as Exabyte Mammoth. New workstations are also being purchased with an increasing amount of disk space. This will provide NRAO's users and visitors with new options for dealing with their data, and should increase the efficiency of data processing and reduction at NRAO. The greater storage capacity of the new tape media is critical for those projects which produce files larger than 2 gigabytes, since these files cannot be split up to fit in the 5 gigabyte capacity of earlier media.

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 and 12 Meter spectrometers. The VLBA archive currently contains more than 4 terabytes of data, stored on 2 gigabyte DAT tapes. The accumulated data archive of the VLA, spanning 22 years, is over 2 terabytes, increasing by about 10 percent per year; this rate will go up considerably when the proposed VLA Upgrade is implemented. Clearly, the tape media currently being used for this purpose have neither the capacity nor the longevity required for permanent archives. Alternatives will need to be investigated.

No high-performance tape drives were purchased during 1999. This is particularly a problem at the AOC, where few of the tape drives available to visiting observers can store more than 5 GB. A desirable level of expenditure for data storage and handling facilities at NRAO during 2000 would be $100,000. This would allow significant enhancement of current facilities and add new capabilities for especially large scientific problems. Individual tape systems with the required capacity and transfer rates are somewhat costly, and adding enough drives to create a useful capability at NRAO requires significant resources. Deferring this expenditure 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. There are no funds allocated in the 2000 Presidential Request level budget for these facilities.

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. In recent months, we have seen a considerable increase in the "probing" of computers and networks from outside the NRAO. These probes are often used to detect vulnerabilities in our systems' configuration.

There have also been a few break-ins which briefly disrupted some of the services we provide to non-NRAO sites and had the potential for greater damage.

During 1999, the Computing Council and a group of NRAO technical staff began to develop ways to improve the security of the computers and networking without compromising services that are fundamental to our role as a user facility. It is likely that, beginning in late 1999, some changes may be required in the ways that users at other locations connect to NRAO systems. As many network services contain security holes which cannot always be easily fixed, those to which access from outside of the NRAO is not essential may in future be blocked, to reduce our vulnerability. We expect to have firewalls in place at all NRAO sites in early 2000.

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 pursue advanced developments in computing. A consequence is that NRAO is not maximizing the scientific return from our observing facilities. Unfortunately, lean budgets at NRAO during the past few years have led to reduced personnel, particularly in software development. As a result, 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 are sometimes called upon for such tasks as web page development and local maintenance of important astronomical data analysis packages written outside of NRAO.

During 2000 NRAO should move to address critical shortages in certain areas of computing support. Particular needs for support and programming personnel exist at all four of the NRAO sites. The initial Design and Development phase of the MMA, which extends through mid-2001, is in reasonable shape with funding for 5.5 full-time employees. But significant software challenges face our plans to get the VLBA and the GBT fully operational, and to modernize the VLA control systems. Increased personnel for software development for the VLBA would dramatically enhance the observational capabilities and operational effectiveness of the VLBA, while additional personnel for the GBT would reduce the time required to bring the GBT laser ranging system into full operation. No new positions are currently budgeted for FY2000.

AIPS

The Astronomical Imaging Processing System (AIPS) continues to be the primary software package for reducing radio-astronomical data within NRAO and world-wide. The 15OCT98 version of AIPS has been distributed to over 300 sites, running Solaris, Linux, DEC Alpha, HP and SGI versions. The number of AIPS installations has grown over the last year. The majority of AIPS distributions are now received by ftp (82%), although a CD ROM distribution is now available, and is growing rapidly in popularity. The TST versions of AIPS (currently 31DEC99) are currently distributed automatically to sites throughout the U.S., Europe, and Japan. Supporting the VLA, VLBA, and Space-VLBI is driving the core of AIPS development at present. There are currently ~4.5 full-time equivalent employees in the AIPS group, performing both user support and application development.

During 2000 it is planned that staff will begin to transition to AIPS++ from AIPS, and that development in AIPS will be reduced to distribution and bug-fixes.

VI. EDUCATION PROGRAM 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 attract and train students in radio astronomy, and to advertise the capabilities of our facilities to the astronomical and scientific community.

In the past our approach to EPO has been a combination of Observatory-wide programs (such as the REU summer program, press releases, AAS displays) and site-specific efforts (e.g. the Green Bank education programs, Project ASTRO in New Mexico, and the site visitor centers). In 1999 an effort to centralize and improve our EPO effort was begun with the appointment of an Assistant Director (Beasley) and a Public Information Officer (Johnson) in Charlottesville. In this section some recent highlights of the EPO program are summarized, and our plans and ongoing developments described.

1. Education

Green Bank

In 1999, 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 7th grade students. In 1999, 7th grade students spent the night at the Observatory conducting observations with the 40 Foot Telescope and interviewing staff scientists.

Beginning in 1988, the Observatory has hosted three-day workshops each spring for science faculty of undergraduate colleges. Approximately 350 college teachers from around the country have participated in an NRAO-GB "Chautauqua Short Course." In 1999, two Chautauqua programs were held in Green Bank. The program has resulted in greatly increased contact with undergraduate students. Other resident courses in 1999 included the annual meeting of the Society of Amateur Radio Astronomers, and the eighth annual Penn State Educational "Research in Radio Astronomy" program.

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. The cornerstone of the experience is a set of open-ended research projects that groups of teachers must perform on the 40 Foot transit telescope. Observatory staff give advice, but not assistance, and the teachers get concrete experience in science research. Teachers then develop research projects for their classroom students. In one form or another, the program has been in operation since 1987 and more than 750 teachers and college students have participated. Glenville State College continues to offer the program to its students using its own funding. Our current NSF-funded teacher enhancement program adds a second year "Technology Institute," using the Apple Computers, 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.

In addition, organizations ranging from the National Youth Science Camp to college astronomy clubs make extended visits to use the 40 Foot. 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 800 children and adults have participated in extended visits since January 1999.

Other education efforts in Green Bank include:

- Mentor programs for about half a dozen students from area high schools who spend part of each week on site working on scientific and engineering projects for their senior theses.
- Career awareness tours for the Pocahontas County High School freshman class.
- After school "science-for-fun" program for local elementary school children.
- The Regional Science Bowl for high school students continues to be held at NRAO.
- A monthly radio show featuring astronomy and the Observatory.
- An NRAO-GB education web site to promote our educational programs.
- Presentations at the West Virginia Science Teachers Association and National Science Teachers Association (NSTA) annual conferences.

VLA

In cooperation with the University of Dayton, the NRAO conducted a Chautauqua Short Course in Socorro for college teachers in 1999. The course, "Interferometry in Radio Astronomy: The VLA and VLBA," was similar to the course we first offered in 1998. Twenty-five teachers from 14 states attended the short course, which 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. Both the 1998 and 1999 sessions of this course were extremely well-received by the participants, and we intend to make this a permanent part of the Socorro educational program.

- 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.
- Observing Time for Astronomy Classes: 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.
- 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.

- Project ASTRO: 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.

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 on average 20 students per year for approximately 12 weeks in-residence at one of the NRAO sites. In 1999 there were 22 summer students working on both scientific and technical projects.

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. Some recent papers are listed below. 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 at the 2000 Presidential Request level of funding for NRAO it may unfortunately be necessary to downsize or discontinue the Co-op Student program, our only engineering education effort.

Graduate Education

Over the last decade the trend in astronomical research towards multi-wavelength problem-oriented astronomy has left U.S. colleges increasingly unable to guide student research in certain areas of astronomy. 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 1999 there were eight students, with three departing late 1999. 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 1999 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 1999 there were eight Jansky Research Associates in residence.

2. Public Relations

Visitor Centers

The VLA Visitor Center remains a popular destination for tourists. More than 24,000 visitors signed an unattended guest book in 1998, and the total for 1999 will be similar. 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.

We plan to completely redesign the educational displays at the VLA Visitor Center to provide an updated treatment of astronomy and NRAO's role, and to incorporate more modern and effective techniques for stimulating learning. An application for an NSF Informal Science Education planning grant was unsuccessful, but, based on reviewers' comments and additional consultations, we are forming additional partnerships with regional science-education institutions to strengthen our proposal. We will again seek a planning grant to develop inquiry-based exhibits and programs that will more effectively convey the basic concepts of astronomy and radio observations to our diverse visitor population.

Such a grant 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.

In the fall of 1998, a Green Bank proposal to the NSF Informal Science Education Division was funded in the amount of $1.1 million. 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 will be 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, 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. We narrowed our search for exhibit design firms and will select one by end of September 1999. During the next nine months exhibits will be designed and tested at the Visitors Center. Fabrication and installation will take place the following year.

In the future, we envision year-round educational programs for the general public and students in Green Bank. In fall, 1998, an architectural firm was hired to help plan the concept for a new science learning center. Conceptual design work has been completed. The learning center will contain exhibit space, classrooms, auditorium, gift shop, offices, and a rooftop optical observatory. The cost estimate for the center as designed and associated site work is approximately $3 million. We are seeking funds from the NSF, the state of West Virginia and private foundations for the construction of the Science Learning Center.

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, using 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. In 1998, there were 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 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) between January and August of this year show 17,500 visitors to the Observatory, a 6 percent increase over tallies for the same months in 1998. In addition to the bus tour, visitors hear a brief talk about radio astronomy, participate in demonstrations and watch a slide show.

During the 1999 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. About 130 visitors participated in these events. A portable planetarium (Star Lab) was purchased this summer and has been used in the special program series. We plan to use the Star Lab in outreach events at local K-12 schools during the academic year.

Conference Displays

NRAO has regularly run a display at the winter and summer meetings of the American Astronomical Society (AAS). During 1999 a new 20-foot display was purchased from Skyline Displays. This display will also be used at conferences and trade shows, including representing radio astronomy at the World ITU conference in April 2000. (Images from a recent AAS display are shown in Figures VI.1 and VI.2.)

At the Chicago AAS meeting a session devoted to presenting results from the first five years of VLBA observations was successfully held. Science results and tutorials on how to use the instrument were combined, and the all-day session was well-attended.

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 http://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 1999 there was an average of 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.

Figure VI.1


THE MILLIMETER ARRAY
THE 12-METER TELESCOPE
Reaching to The Faint Radio-Emitting Universe
The Parent Instrument of Millimeter-Wavelength Molecular Astronomy
Subarcsecond Imaging of Thermal Objects at Millimeter, Submillimeter and Far-IR Wavelengths

Figure VI.2

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 are currently undertaking a redesign which should be completed late 1999. We are also implementing a mirroring system around the four main NRAO sites, enabling rapid access to our site internally and from anywhere in the U.S.

We are currently designing a "Radio Science Depository" where interesting images and other results can be stored and indexed for access by researchers and the general public. Other potential projects for our web-site include real-time displays of our instruments (already available for the 12 Meter Telescope, in planning for the GBT), and possibly "virtual tours," i.e. web-based exploration of our sites/instruments.

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.

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 article, "Gamma-Ray Burst Briefly Affects Propagation," in the ARRL Letter for October 2, 1998.

Budget and Staffing

At present these are five full-time employees allocated to PR and Education at NRAO. There is no separate allocation of materials and services funds for these efforts; most funding comes from NSF Education grants or from the Director's Office. To expand our PR efforts in 2000 we require at least an additional $50k over the Presidential Request level for display and promotional purposes, however even at the Presidential Request level it may be difficult to maintain our Education Public Outreach program during 2000 at the level achieved in 1999.

VII. MMA (Participation in ALMA)

The Millimeter Array (MMA) is a synthesis telescope designed to bring to millimeter and submillimeter astronomy the aperture synthesis techniques of radio astronomy for high angular resolution imaging. The MMA will image at 1 millimeter wavelength with the same 0.″1 angular resolution achieved by the Hubble Space Telescope (HST) at visible wavelengths. It will provide scientific insight at millimeter/submillimeter wavelengths that is complimentary to that of the HST and its successor instrument, the Next Generation Space Telescope. The MMA was proposed to the National Science Foundation (NSF) by Associated Universities, Inc., in 1990 as the next major scientific initiative of U.S. radio astronomy. An initial phase of design and prototyping funded by the NSF was begun at the NRAO for the MMA in 1998. In 1999, the NSF and a collaboration of European institutions agreed to merge the MMA Project with the European Large Southern Array (LSA), a project of scientific scope similar to that of the MMA. The combined U.S.-European instrument is the Atacama Large Millimeter Array (ALMA). ALMA is an equal partnership between the U.S. and Europe and has as a design goal the construction of an array of 64 antennas each of 12 meters diameter and each equipped with receiving systems for all the atmospheric windows between 30 and 950 GHz. ALMA will be built in the Chilean Altiplano on a site reserved for science by the Republic of Chile. The NRAO is responsible for the U.S. participation in ALMA.

Project Status

The year of this Program Plan, the year 2000, is the third and final year planned for the Design and Development (D&D) phase of the Millimeter Array (MMA) Project. In the preceding two years, three of the four primary milestones for the D&D effort were achieved; these are:

- Recommendation to the NSF of an international partnership in the Project. On June 10, 1999, the NSF signed a Memorandum of Understanding with a confederation of five European institutions for the joint design and development of the Atacama Large Millimeter Array (ALMA). The ALMA Project will subsume the MMA and the similar European project known as the Large Southern Array.
- Provision to the NSF of a thorough cost estimate for the construction of the MMA that could be audited. That estimate, and the NSF audit process, were completed in July 1999.
- Receipt of bids from antenna contractors for fabrication of a prototype antenna that meets the MMA specifications and is within the budget envelope specified for the Project. Bids were received from four antenna contractors on June 30, 1999, a date that had been planned as defining the critical path for the D&D project. With NSF permission it is expected that the contract for the prototype antenna can be signed early in the fourth quarter of 1999.

The fourth major milestone, permission from the Republic of Chile to make use of the Chajnantor site in the Chilean Altiplano, is no longer the sole province of the MMA Project. As agreed by the NSF and the European ALMA partners, the ALMA partnership will approach the government of Chile for use of the site. At the same time the Republic of Chile has been extremely welcoming to the MMA/ALMA Project.

As we begin year 2000 the MMA Project emphasis is on making the transition to the construction phase of the project, and on the evolution of the U.S. MMA Project to the international ALMA partnership.

Organization of the MMA Project

The organization of the MMA Project during the initial three-year Design and Development phase is illustrated in Figure VII.1 This organization is based on the Work Breakdown Structure (WBS) for the tasks in the D&D phase. The numbers in the organizational boxes shown refer to all the major tasks of the WBS (see below). The D&D WBS is structured by MMA systems, not necessarily by location of the individuals doing the work; for this reason the same responsible manager, or MMA Division Head, appears in more than one box. In 2000, this organizational structure will be redefined in cooperation with the European group for the purpose of the U.S. participation in the ALMA project.

The MMA Division Heads are the heart of the Project. Each of these individuals is responsible for a major technical system. In the Design and Development phase of the project their efforts are directed toward design and evaluation of technical options; in the construction phase of the project they are responsible for the quantity production of their respective systems. The MMA Division Heads meet weekly by teleconference. They all report to the Project Manager who has the responsibility to chair their meetings and resolve disputes.

The Work Breakdown Structure is the defining article for the Project. It consists of the list of tasks to be accomplished in the Design and Development phase and a time-ordered list of subtasks structured to meet the goals. Resources, funds and personnel, are assigned at the subtask level appropriate to the requirements of that subtask. The MMA D&D WBS Gantt Chart for all tasks and subtasks is nearly 50 pages long; it is available in electronic form on the MMA web pages. Also available is a dictionary for each WBS task and subtask that defines the nature of the task and the resources to be assigned to that task. An abbreviated version of that Gantt Chart, selected at level 2 (i.e., a tabulation of the eleven WBS categories and one level down in detail in each of those categories) is included in Table VII.1. This chart illustrates progress being made and the effort remaining on the level 1 and 2 tasks. In all these areas there is, of course, much finer subtasking detail which can be found via the MMA web pages.

The Project requirements and the technical specifications designed to meet those requirements are detailed in the MMA Project Book. The Project Book is maintained by the MMA System Engineer as an electronic document that is revised as major project decisions are made. The Project Book is the fundamental project reference; it is always up-to-date and always available on-line. A companion document, the MMA Management Plan summarizes the management structure of the project and includes the project technical baseline, the detailed project tasking, personnel assignment, budget and procedures by which the project makes changes to the baseline. The Management Plan is also available via electronic access on the MMA web pages.

the construction phase in 2001 with approximately this level of personnel. Thereafter additions to the staff will be made in those areas that become the responsibility of the U.S. ALMA Project through negotiation within the framework of the ALMA partnership. The MMA Design and Development phase budget and staffing by level-1 WBS category is given in Figure VII.2. Detailed Project cost accounting is given to the NSF monthly.

In Section X of this document the Presidential Budget Request level for ALMA development is indicated as \$8m, with 53 full-time employees. To meet organization goals, we estimate that \$11.66M are required; this increase is comprised of the additional costs incurred changing the prototype antenna diameter from 10 to 12 meters (necessary to secure international collaboration as stipulated by the NSF), and four new positions to meet expanded project management requirements.

Figure VII.2

ALMA US Task Scheduling

File: ProjPlan19990805.mpp
View: ALMA US Tasks (Level 1 and 2)
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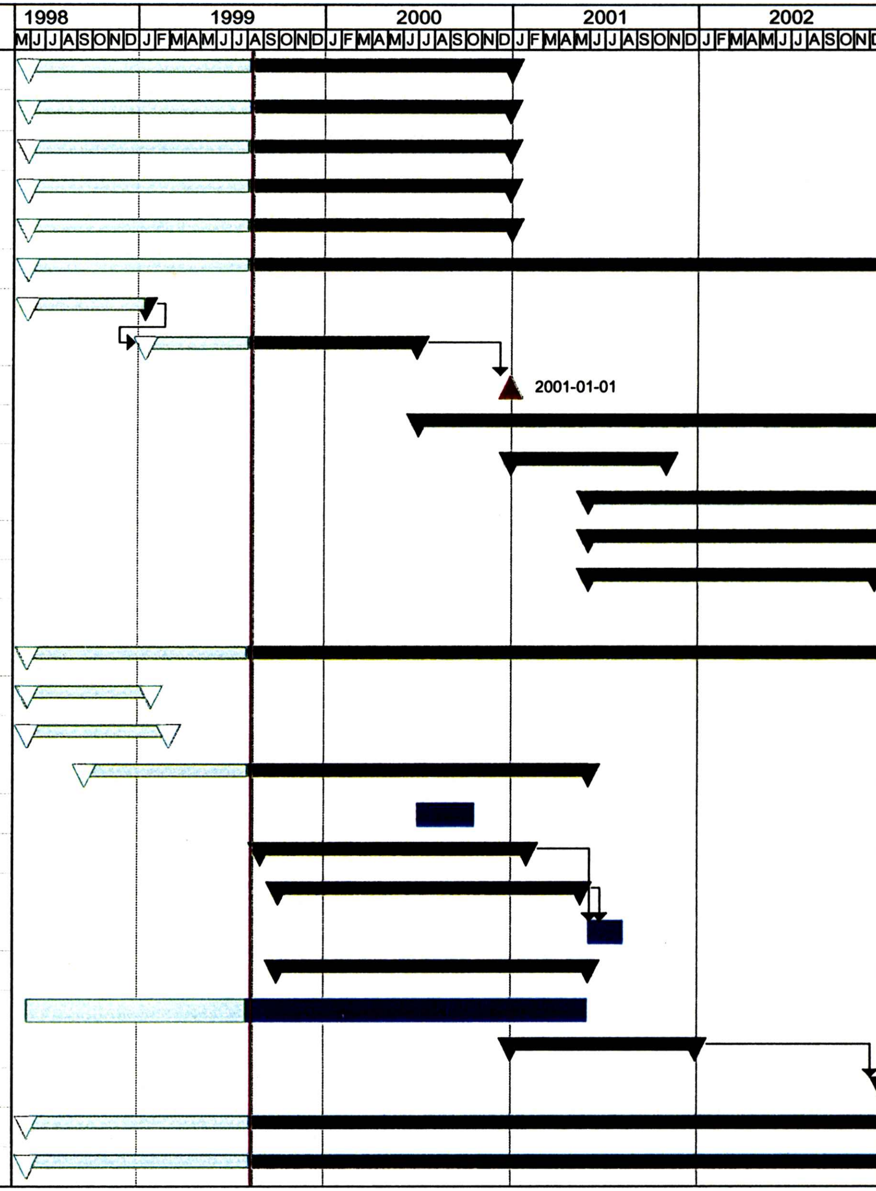
WBS (f)	Task	Start	Finish	Duration	Work
1	**Administration**	1998-06-01	2001-01-01	135.2w	617.73w
1.1	Management	1998-06-01	2000-12-29	135w	463.62w
1.2	Facilities	1998-06-01	2000-12-29	135w	26.13w
1.3	Agreements in Chile	1998-06-01	2000-12-29	135w	66.57w
1.4	Partnerships	1998-06-01	2001-01-01	135.2w	61.41w
2	**Site Development**	1998-06-01	2007-12-28	500w	137.8w
2.1	Prepare Initial Development Plan	1998-06-01	1999-01-15	33w	39.8w
2.2	Revise Development Plan	1999-01-18	2000-06-30	76w	98w
2.5	**Start Facilities Construction Process in Chile**	2001-01-01	2001-01-01	0w	0w
2.10	Maintain Site Access Rights	2000-07-03	2007-12-28	391w	0w
2.15	Prepare for Site Development	2001-01-01	2001-10-31	43.6w	0w
2.20	Develop Array Site	2001-06-01	2004-03-15	145.4w	0w
2.25	Develop Operations Support Facility	2001-06-01	2004-03-15	145.4w	0w
2.30	Develop OSF/Array Link	2001-06-01	2002-12-13	80.2w	0w
2.40	Prepare for Instrument Assembly	2003-09-01	2004-08-31	52.4w	0w
3	**Antenna**	1998-06-01	2002-12-30	239.2w	687.79w
3.1	In-house designs	1998-06-01	1999-01-29	35w	140w
3.2	Specifications	1998-06-01	1999-03-05	40w	29w
3.3	Procurement of Prototype Antenna	1998-09-22	2001-06-01	140.8w	287.94w
3.4	Foundation	2000-07-04	2000-10-23	80d	4w
3.5	Apex	1999-08-30	2001-01-31	74.6w	36w
3.6	Metrology	1999-10-04	2001-05-17	84.6w	113w
3.7	Antenna Evaluation and Enhancement	2001-06-04	2001-08-10	50d	15w
3.8	Transporter	1999-10-01	2001-06-01	87.2w	17w
3.9	Internal Antenna Interface Support	1998-06-01	2001-06-01	157w	7.85w
3.15	Procurement of Antenna #2	2001-01-01	2001-12-28	52w	38w
3.20	Production Antennas	2002-12-30	2002-12-30	0.2w	0w
4	**Receivers**	1998-06-01	2007-04-27	465w	2,523.38w
4.1	SIS Mixers	1998-06-01	2004-02-18	298.6w	1,519.72w

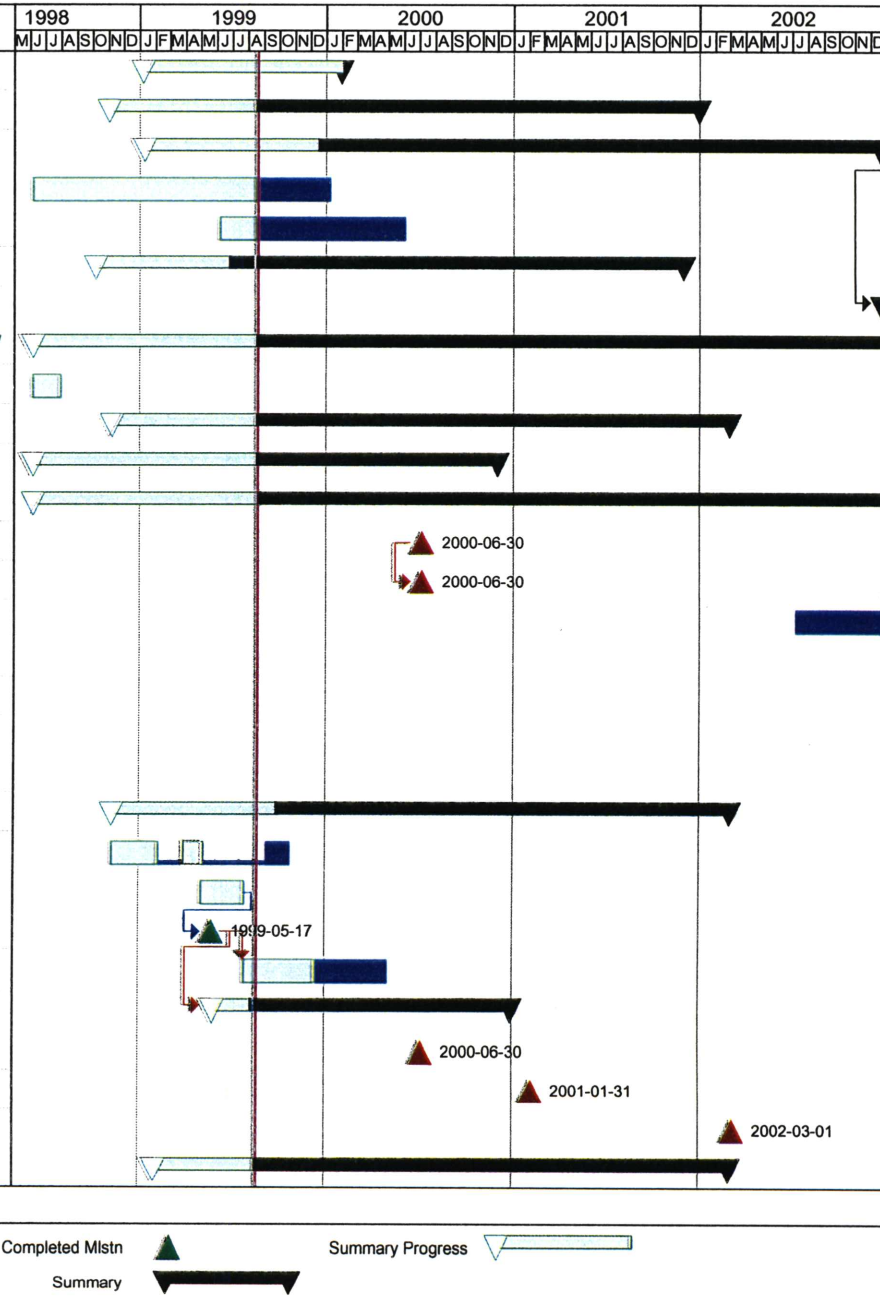


Milestones: **bold type**
Summary Tasks: underline

Task · Split · Progress · Milestone · Completed Mlstn · Summary · Summary Progress

ALMA US Task Scheduling

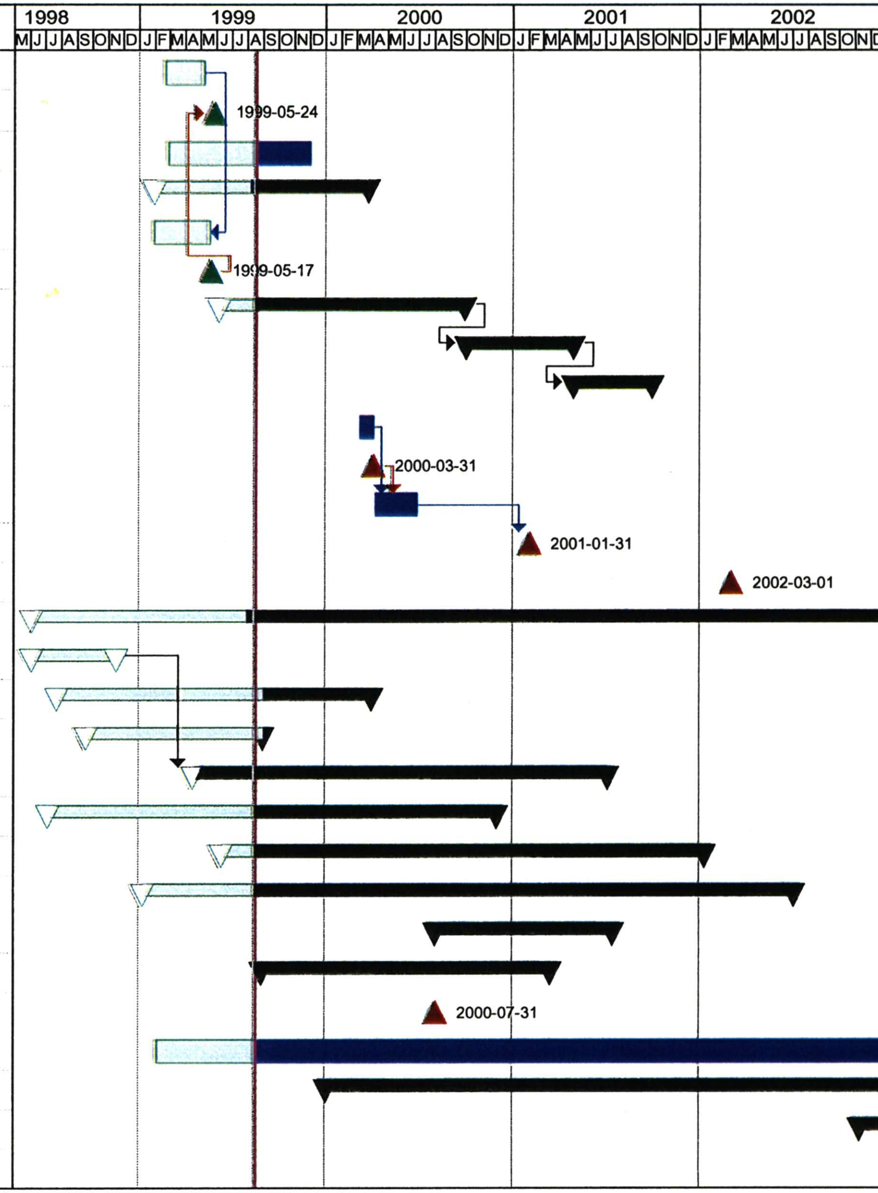
WBS (f)	Task	Start	Finish	Duration	Work
4.2	HFET Amplifiers	1999-01-01	2000-01-31	56.4w	6w
4.3	Antenna Evaluation Receivers	1998-10-27	2001-12-31	166w	369w
4.4	MMA Production Receiver Design and Prototy	1999-01-04	2002-12-20	207w	441.66w
4.5	Lab / Test Equipment	1998-06-01	1999-12-31	83w	7.8w
4.6	Test & Calibration System	1999-05-31	2000-05-26	52w	15.6w
4.10	Cryogenics Development	1998-10-01	2001-11-30	165.4w	163.6w
4.15	MMA Production Receivers	2002-12-23	2007-04-27	227w	0w
5	LO System	1998-06-01	2007-03-09	458w	1,125.97w
5.1	Specifications and Conceptual Design	1998-06-01	1998-07-24	8w	0w
5.2	LO Reference	1998-11-02	2002-03-01	173.8w	608w
5.3	Multiplier Chain LO	1998-06-01	2000-12-01	131w	324.47w
5.4	Photonic LO	1998-06-01	2006-03-24	408w	174.5w
5.5	CDR: LO System	2000-06-30	2000-06-30	0d	0w
5.6	Decision: Multiplier Chain or Photonic LO	2000-06-30	2000-06-30	0d	0w
5.7	LO Final Design	2002-07-01	2002-12-27	26w	19w
5.8	Production Review: LO	2003-02-28	2003-02-28	0w	0w
5.9	LO Manufacturing	2003-03-03	2004-06-04	66w	0w
5.10	LO On site systems integration	2004-06-07	2006-03-10	92w	0w
5.11	Continued Support	2006-03-13	2007-03-09	52w	0w
6	IF System	1998-11-02	2002-03-01	173.8w	191w
6.1	IF System Specifications	1998-11-02	1999-10-15	26.2w	13w
6.2	Preliminary System Design	1999-04-26	1999-07-19	12w	16w
6.3	PDR: IF System	1999-05-17	1999-05-17	0d	0w
6.4	Lab / Test Equipment	1999-07-19	2000-04-24	40w	4w
6.5	IF Bench Prototype	1999-05-19	2000-12-29	84.6w	158w
6.10	CDR: IF System	2000-06-30	2000-06-30	0d	0w
6.15	Deliver (Bench) Prototype IF System	2001-01-31	2001-01-31	0d	0w
6.20	Deliver IF Field Prototypes to Test Interferomet	2002-03-01	2002-03-01	0w	0w
7	FO System	1999-01-25	2002-03-01	161.8w	431w



Milestones: **bold type**
Summary Tasks: underline

ALMA US Task Scheduling

WBS (f)	Task	Start	Finish	Duration	Work
7.1	FO System Specification	1999-02-16	1999-05-03	11w	11w
7.13	**Decision: Analog/Digital Transmission**	1999-05-24	1999-05-24	0w	0w
7.4	Lab / Test Equipment	1999-02-22	1999-11-26	40w	4w
7.5	IF Transmission	1999-01-25	2000-03-24	61w	120w
7.5.5	Preliminary Design	1999-01-25	1999-05-14	16w	20w
7.5.6	**PDR: FO System (IF Transmission)**	1999-05-17	1999-05-17	0d	0w
7.6	LO Transmission	1999-06-01	2000-09-29	69.8w	100w
7.7	Round-trip Phase Transmission	2000-10-02	2001-04-30	30.12w	88w
7.8	M/C Transmission	2001-04-30	2001-10-01	22w	72w
7.9	Bins & Interconnect	2000-03-03	2000-03-30	4w	10w
7.10	**CDR: FO System**	2000-03-31	2000-03-31	0d	0w
7.11	Integration & Test	2000-04-03	2000-06-23	12w	26w
7.12	**Deliver Bench Prototype FO System**	2001-01-31	2001-01-31	0d	0w
7.20	**Deliver FO Field Prototypes to Test Interferom**	2002-03-01	2002-03-01	0w	0w
8	Correlator	1998-06-01	2007-03-30	461w	500.34w
8.1	Specifications	1998-06-01	1998-11-13	24w	18w
8.2	Test Correlator	1998-07-20	2000-03-31	89w	45w
8.3	Preliminary Design	1998-09-15	1999-09-01	50.4w	40.54w
8.4	Sampler	1999-04-12	2001-07-06	117w	13.27w
8.5	Finite Impulse Response Filter	1998-07-03	2000-12-01	126.2w	9.92w
8.6	Custom Boards	1999-06-07	2002-01-11	136w	211.4w
8.7	Correlator Chip	1999-01-04	2002-07-05	183w	43w
8.8	Racks	2000-08-03	2001-07-16	49.6w	39.5w
8.9	Post-Correlation Processor	1999-08-30	2001-03-16	81w	13.72w
8.10	**CDR: Prototype Correlator**	2000-07-31	2000-07-31	0d	0w
8.11	Software	1999-02-01	2003-05-30	226w	66w
8.12	Prototype Correlator Production	2000-01-03	2003-05-30	178w	0w
8.13	Site Correlator Production	2002-11-11	2006-10-06	204w	0w
8.14	Continued Support	2003-06-02	2007-03-30	200w	0w



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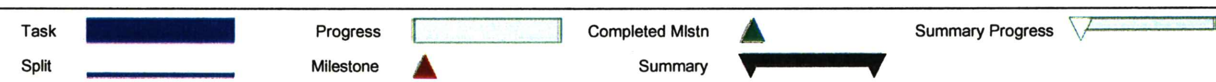
Summary Tasks: underline



ALMA US Task Scheduling

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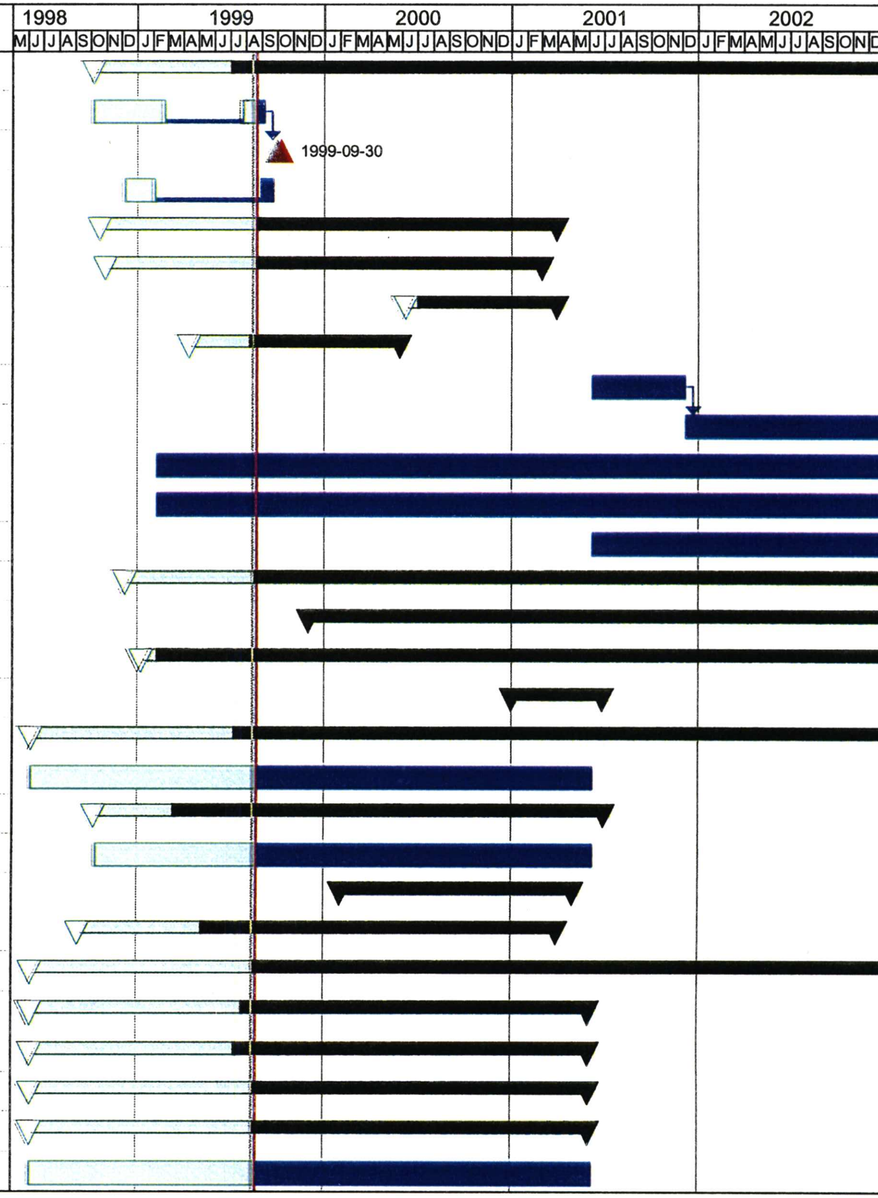
WBS (f)	Task	Start	Finish	Duration	Work
9	**Computing**	1998-10-01	2006-07-18	406.8w	296.5w
9.1	Initial Requirements Specification	1998-10-01	1999-08-30	26w	15w
9.2	**PDR: Comp. Requirements & Control Software**	1999-09-30	1999-09-30	0d	0w
9.3	Software Practices and Standards	1998-12-01	1999-09-15	12w	9w
9.4	Monitor and Control	1998-10-12	2001-03-30	129w	103.5w
9.5	Test Antenna Control Software	1998-10-23	2001-03-01	123w	84w
9.6	Commissioning Software	2000-06-01	2001-03-30	43.4w	33w
9.7	Test Correlator Software	1999-04-05	2000-05-28	60w	40w
9.8	Prototype Antenna Software Integration	2001-06-01	2001-11-29	26w	0w
9.9	Prototype Antenna Software Support	2001-11-30	2004-11-25	156w	0w
9.10	Antenna	1999-02-01	2004-02-27	265w	0w
9.11	Correlator	1999-02-01	2004-02-27	265w	0w
9.12	Data Production	2001-06-01	2003-05-29	104w	0w
9.13	Archiving	1998-12-01	2005-12-26	369w	0w
9.14	Near real-time imaging	1999-12-01	2006-07-18	346w	0w
9.15	Scheduling	1999-01-01	2005-11-25	360.2w	0w
9.16	Off-Line Data Processing	2001-01-01	2001-06-27	25.6w	12w
10	**System Integration**	1998-06-01	2003-03-28	252w	621.9w
10.1	Overall Specifications for all systems	1998-06-01	2001-06-01	157w	31.4w
10.2	Specification of interfaces and standards	1998-10-01	2001-06-29	143.4w	30w
10.3	Monitor and Control Coordination	1998-10-05	2001-06-01	139w	13.9w
10.4	Test Interferometer Site Preparation	2000-02-01	2001-04-30	65w	18w
10.7	Holography System	1998-09-01	2001-03-30	134.8w	42w
10.10	Prototype Antenna Integration and Testing	1998-06-01	2003-03-28	252w	486.6w
11	**Calibration & Imaging**	1998-06-01	2001-06-01	157w	565w
11.1	Site Characterization and Monitoring	1998-06-01	2001-06-01	157w	0w
11.2	Configuration Studies	1998-06-01	2001-06-01	157w	0w
11.3	Calibration	1998-06-01	2001-06-01	157w	0w
11.4	Imaging studies	1998-06-01	2001-06-01	157w	0w



Milestones: **bold type**
Summary Tasks: underline

Task
Split
Progress
Milestone
Completed Mlstn
Summary
Summary Progress

Figure VII.3

ALMA U.S. Design & Development Phase Milestones

WBS Milestone tasks, sorted by WBS and date

WBS (f)	Milestone / Deliverable	Baseline	Current	Actual	Responsibility
1	Administration				Brown
1.1.1.10	Project Book: Version 1	1998-07-20	1998-07-20	1998-07-20	Emerson
1.1.4.10	Deliver WBS for D&D phase	1998-09-30	1998-10-16	1998-10-16	Brown
1.1.1.20	Draft Interface Standards	1998-10-30	1998-11-09	1998-11-09	Emerson
1.1.3.10	Complete Draft of Business Procedures	1998-10-30	1998-11-30	1998-11-30	Porter
1.1.6.10	Deliver Management Plan for D&D	1999-01-29	1998-11-30	1998-11-30	Brown
1.1.1.35	Schedule of Reviews	1999-01-29	1999-02-09	1999-02-09	Brown
1.1.2.15	Schedule of Meetings	1999-01-29	1999-02-09	1999-02-09	Wootten
1.1.4.35	Complete prelim cost estimate	1998-12-31	1999-02-19	1999-02-19	Brown
1.1.5.10	Deliver Personnel, Safety & Health Procedures	1999-01-29	1999-03-01	1999-03-01	Brown
1.1.4.15	Deliver preliminary WBS Entire Project	1999-01-29	1999-03-26	1999-03-26	Brown
1.4.4	Partnership Recommendations to NSF	1999-06-30	1999-03-30	1999-03-30	Brown
1.1.4.40	Deliver Prelim Cost Estimate	1999-04-30	1999-05-03	1999-05-03	Brown
1.1.3.15	Deliver Business Procedures for D&D	1999-04-30	1999-06-01	1999-06-01	Porter
1.1.2.20	ALMA Oct 99 Conference	1999-10-07	1999-10-08	NA	Wootten
1.1.4.17	Deliver WBS for ALMA D&D phase	1999-10-11	1999-10-11	NA	Brown
1.3.3.15	Access to OSF Land	1999-06-30	1999-12-27	NA	Hardy
1.3.2	CONICYT Use Permissions	1999-09-30	1999-12-31	NA	Hardy
1.1.1.25	Interface Standards	2000-01-31	2000-01-31	NA	Emerson
1.1.4.20	Deliver final WBS entire project	2000-01-31	2000-04-30	NA	Brown
1.1.6.15	Deliver Management Plan for Construction	1999-09-30	2000-05-01	NA	Brown
2	Site Development				Gordon
2.1.4	Deliver Development Plan, v. 1	1998-12-15	1999-01-15	1999-01-15	Gordon
2.2.4	Deliver revised development Plan	2000-06-30	2000-06-30	NA	Gordon
2.5	Start Facilities Construction Process in Chile	2001-01-01	2001-01-01	NA	Gordon
2.15.2	Hire Construction Manager for Chile	2001-03-01	2001-03-01	NA	Gordon
2.20.5.3	Bid Civil Works Construction	2001-12-03	2001-12-03	NA	Gordon
2.25.5.3	Bid Civil Works Construction	2001-12-03	2001-12-03	NA	Gordon
2.30.5.3	Bid OSF/Array Link Construction	2001-12-03	2001-12-03	NA	Gordon
2.20.10.3	Award Array Site Contracts	2002-03-01	2002-03-01	NA	Gordon
2.25.10.3	Award Contracts	2002-03-01	2002-03-01	NA	Gordon
2.30.10.3	Award Contracts	2002-03-01	2002-03-01	NA	Gordon
2.30.15.3	Accept OSF/Array Link	2002-12-13	2002-12-13	NA	Gordon
2.20.15.3	Accept Site Facility	2004-03-15	2004-03-15	NA	Gordon
2.25.15.3	Accept OSF Facility	2004-03-15	2004-03-15	NA	Gordon
	Antenna				Napier
3.2.2	PDR: Antenna	1998-07-28	1998-07-28	1998-07-28	Napier
3.3.5	Vendor Information Meeting	1998-09-23	1998-09-22	1998-09-22	Napier
3.2.4	CDR: Antenna RFP	1998-11-30	1999-03-05	1999-03-05	Napier

ALMA U.S. Design & Development Phase Milestones

WBS Milestone tasks, sorted by WBS and date

WBS (f)	Milestone / Deliverable	Baseline	Current	Actual	Responsibility
3.3.15	Issue Prototype Antenna RFP	1999-01-29	1999-03-30	1999-03-30	Napier
3.3.17	Antenna Bidders Meeting	1999-03-05	1999-05-18	1999-05-18	Napier
3.3.20	Receive Prototype Antenna Bid Response	1999-04-30	1999-06-30	1999-06-30	Napier
3.3.30	Sign Contract (#1+Option #2)	1999-06-30	1999-10-01	NA	Napier
3.3.35.05	Prototytpe Antenna PDR	2000-02-15	2000-02-15	NA	Napier
3.6.2	PDR: Antenna Metrology	2000-05-24	2000-03-01	NA	Napier
3.5.30	CDR: Antenna Apex	1999-10-29	2000-03-14	NA	Napier
3.8.2	Deliver Transporter Requirements	2000-03-31	2000-03-16	NA	Napier
3.8.4	Issue Transporter RFP	2000-06-30	2000-06-04	NA	Napier
3.3.35.10	Prototytpe Antenna CDR	2000-07-03	2000-07-03	NA	Napier
3.3.35.15	Prot Antenna Complete Design Doc	2000-10-02	2000-10-02	NA	Napier
3.3.35.20	Prot Antenna Final Design Approval	2000-11-01	2000-11-01	NA	Napier
3.8.10	Sign Transporter Contract	2001-01-26	2000-12-24	NA	Napier
3.6.40	CDR: Antenna Metrology	2001-02-14	2001-01-28	NA	Napier
3.5.40	Deliver Prototype Antenna Apex	2001-01-31	2001-01-31	NA	Napier
3.3.35.25	Prot Antenna Fabrication Complete	2001-04-02	2001-04-02	NA	Napier
3.3.35.30	Prot Antenna Assembly Complete	2001-04-30	2001-04-30	NA	Napier
3.6.12	Deliver Prototype Antenna Metrology	2001-05-17	2001-05-17	NA	Napier
3.3.45	Delivery of Antenna #1	2001-06-01	2001-06-01	NA	Napier
3.8.20	Deliver/Accept Transporter #1	2001-06-01	2001-06-01	NA	Napier
4	**Receivers**				**Emerson**
4.1.12.7	Complete 86 GHz vacuum window prototype	1998-11-20	1998-11-20	1998-11-20	Webber
4.1.6.10	Complete 230 LO Plate, sideband source plates	1999-02-19	1998-12-01	1998-12-01	Webber
4.1.8.1.10	Comp. Eval. 200-300 GHz bal & sb-sep prototypes	1999-01-22	1999-03-08	1999-03-08	Webber
4.1.18.5	Deliver Test Ant mixer: 86 GHz band	1999-06-30	1999-06-21	1999-06-21	Webber
4.2.7	Deliver Test Ant Amplifier: 30 GHz Band	1999-06-29	1999-07-12	1999-07-12	Webber
4.2.9	Deliver Test Ant Amplifier: 90 GHz Band	1999-09-30	1999-07-23	1999-07-23	Webber
4.1.18.3	Deliver Test Ant mixer: 230 GHz band	1999-06-30	1999-09-30	NA	Webber
4.3.5	Complete Eval. Rcvr. Interface agreements	1999-05-31	1999-10-01	NA	Emerson
4.1.1.2	PDR: SIS Mixer	1999-01-29	1999-10-15	NA	Webber
4.1.12.10	Complete 86 GHz Vac. Window Development	1999-04-23	1999-10-15	NA	Webber
4.3.10	CDR: Evaluation Receiver	1999-11-29	1999-11-29	NA	Emerson
4.1.9.10	Complete automated mixer testing	1999-12-03	1999-12-03	NA	Webber
4.1.11.2.1(	First MMIC IF Amplifier Tests	1999-04-09	2000-01-07	NA	Webber
4.1.4.7	Complete Cryogenic IF plates for mixer testing	1999-06-01	2000-01-21	NA	Webber
4.2.8	Deliver Prototype Amplifier: 30 GHz Band	2000-01-31	2000-01-31	NA	Webber
4.4.4	PDR: MMA Receiver	1999-09-24	2000-03-31	NA	Emerson
4.1.6.11	Complete 650 LO plate	1999-10-22	2000-04-28	NA	Webber
4.1.8.3.1.9	Start 650 building block mixer tests	1999-10-22	2000-04-28	NA	Webber

ALMA U.S. Design & Development Phase Milestones

WBS Milestone tasks, sorted by WBS and date

WBS (f)	Milestone / Deliverable	Baseline	Current	Actual	Responsibility
4.1.11.2.14	Complete integrated MMIC IF development	1999-10-01	2000-05-05	NA	Webber
4.1.10.10	Complete Wafer Evaluation circuits	1999-08-13	2000-06-16	NA	Webber
4.1.8.2.3.9	230 balanced mixer tests	1999-11-08	2000-06-20	NA	Webber
4.1.11.4.4	Complete IF development	2000-03-01	2000-06-23	NA	Webber
4.1.13.15	Complete Fourier Transform Spectrometer	2000-03-03	2000-09-01	NA	Webber
4.1.1.5	CDR: SIS Mixer	1999-09-30	2000-11-10	NA	Webber
4.4.35	CDR: MMA Receiver System	2000-07-05	2000-12-29	NA	Emerson
4.10.10	PDR: Cryogenics Development	2000-07-05	2000-12-29	NA	Emerson
4.1.8.2.4.9	230 bal., sideband-sep. mixer tests	2000-05-08	2001-01-23	NA	Webber
4.1.8.3.2.9	Start 650 SSB Mixer tests	2000-04-21	2001-02-02	NA	Webber
4.1.8.3.3.9	Start 650 balanced mixer tests	2000-04-21	2001-02-02	NA	Webber
4.1.8.2.10	Deliver prototype 230 GHz	2000-07-03	2001-03-27	NA	Webber
4.10.15	CDR: Cryogenics Development	2001-03-30	2001-03-30	NA	Emerson
4.3.20	Deliver Antenna Test Eval Receiver	2001-05-01	2001-05-01	NA	Emerson
4.4.30.4	Deliver Prototype Dewar	2001-01-31	2001-07-27	NA	Emerson
4.10.20	Deliver Prototype Cryogenics System	2001-11-30	2001-11-30	NA	Emerson
4.1.8.3.4.9	Start 650 Bal. sb. sep. mixer tests	2001-04-20	2002-02-01	NA	Webber
4.4.50	Complete Prototype MMA Receiver	2002-03-29	2002-05-24	NA	Emerson
4.1.8.3.5	Deliver prototype 650 GHz	2001-11-02	2002-08-16	NA	Webber
4.4.65	Release MMA Receiver for manufacture	2002-10-25	2002-12-20	NA	Emerson
5	**LO System**				**Emerson**
5.3.4	PDR: Multiplier Chain LO	1998-11-16	1999-02-19	1999-02-19	Webber
5.4.2.2	Optical R/T Phase Lab Demo	1999-02-26	1999-03-29	1999-03-29	Emerson
5.4.1.3	Photonic Phase Cal Feasibility Demo	1998-12-31	1999-04-15	1999-04-15	Emerson
5.4.1.5	PDR: Photonic Phase Cal System	1999-05-31	1999-09-28	NA	Emerson
5.4.2.4	PDR: Optical R/T phase meas.	1999-04-30	1999-09-28	NA	Emerson
5.4.5	PDR: Photonic LO	1999-06-30	1999-09-28	NA	Emerson
5.4.6.6	Deliver 100 GHz Velocity Matched photomixer	1999-10-29	1999-10-29	NA	Emerson
5.2.3	PDR: LO Reference	1999-06-30	1999-11-17	NA	Sramek
5.3.3.3.9	Deliver 230 GHz Doubler Power Demo	1998-12-31	1999-12-10	NA	Webber
5.3.5.10	Deliver 230 GHz MC LO for Eval Rcvr	2000-03-01	2000-03-01	NA	Webber
5.4.10	CDR: Photonic LO	2000-03-31	2000-03-20	NA	Emerson
5.4.1.7	CDR: Photonic Phase Cal System	1999-12-31	2000-03-28	NA	Emerson
5.4.2.8	CDR: Optical R/T Phase Measurement	1999-12-31	2000-03-28	NA	Emerson
5.4.2.9	Decision: Opt or Microwave R/T Phase Meas for MMA	2000-01-30	2000-03-28	NA	Sramek
5.3.6.4	Deliver Prototype 230 GHz LO for Prot. Rcvr.	1999-12-27	2000-05-15	NA	Webber
5.5	CDR: LO System	2000-06-30	2000-06-30	NA	Emerson
5.6	Decision: Multiplier Chain or Photonic LO	2000-06-30	2000-06-30	NA	Emerson
5.3.3.8	CDR: Multiplier Chain LO	2000-03-31	2000-12-01	NA	Webber

ALMA U.S. Design & Development Phase Milestones

WBS Milestone tasks, sorted by WBS and date

WBS (f)	Milestone / Deliverable	Baseline	Current	Actual	Responsibility
5.4.1.9	Deliver Photonic Phase Cal prototypes	2000-12-31	2001-01-02	NA	Emerson
5.2.35	Deliver LO Reference bench prototype	2001-01-31	2001-01-31	NA	Sramek
5.2.40	Deliver LO Ref Field Prototypes	2002-03-01	2002-03-01	NA	Sramek
5.4.13	Deliver Prototype Photonic LO	2002-08-23	2002-08-09	NA	Emerson
5.8	Production Review: LO	2003-02-28	2003-02-28	NA	Emerson
5.4.1.11	Production Review: Photonic Phase Cal	2003-05-05	2003-03-03	NA	Emerson
6	**IF System**				**Sramek**
6.3	PDR: IF System	1999-04-30	1999-05-17	1999-05-17	Sramek
6.10	CDR: IF System	2000-03-31	2000-06-30	NA	Sramek
6.15	Deliver (Bench) Prototype IF System	2001-01-31	2001-01-31	NA	Sramek
6.20	Deliver IF Field Prototypes to Test Interfeometer	2002-03-01	2002-03-01	NA	Sramek
7	**FO System**				**Sramek**
7.5.6	PDR: FO System (IF Transmission)	1999-05-14	1999-05-17	1999-05-17	Sramek
7.13	Decision: Analog/Digital Transmission	1999-07-30	1999-05-24	1999-05-24	Sramek
7.6.6	PDR: FO System (LO Transmission)	1999-06-30	1999-09-28	NA	Sramek
7.10	CDR: FO System	2000-03-31	2000-03-31	NA	Sramek
7.12	Deliver Bench Prototype FO System	2001-01-31	2001-01-31	NA	Sramek
7.20	Deliver FO Field Prototypes to Test Interferometer	2002-03-01	2002-03-01	NA	Sramek
8	**Correlator**				**Webber**
8.5.3.3	Decision: FIR Filter or Analog BBC	1998-12-31	1999-02-18	1999-02-18	Webber
8.3.5	PDR: Correlator	1999-08-02	1999-10-01	NA	Webber
8.5.8	CDR: Finite Impulse Response Filter	1999-07-01	2000-02-28	NA	Webber
8.2.6	Deliver Test Correlator to VLA site	2000-03-31	2000-03-31	NA	Webber
8.10	CDR: Prototype Correlator	2000-07-31	2000-07-31	NA	Webber
8.5.16	Deliver FIR Filter for Test Interferometer	2000-12-01	2000-12-01	NA	Webber
8.12.5	Deliver Prototype Correlator to VLA site	2003-05-30	2003-05-30	NA	Webber
8.13.1.5	Deliver 1/4 Correlator to MMA site	2004-06-18	2004-06-18	NA	Webber
8.13.2.4	Deliver 1/4 Correlator to MMA site	2005-03-25	2005-03-25	NA	Webber
8.13.3.4	Deliver 1/4 Correlator to MMA site	2005-12-30	2005-12-30	NA	Webber
8.13.4.4	Deliver 1/4 Correlator to MMA site	2006-10-06	2006-10-06	NA	Webber
9	**Computing**				**Glendenning**
9.4.4	Deliver: M&C Draft Interface specifications	1999-06-01	1999-06-14	1999-06-14	Glendenning
9.2	PDR: Comp. Requirements & Control Software	1999-06-30	1999-09-30	NA	Glendenning
9.7.4	CDR: Test Correlator Software	1999-09-01	1999-11-28	NA	Glendenning
9.4.8	CDR: Monitor & Control System	2000-03-31	2000-01-30	NA	Glendenning
9.5.7	CDR: Single Dish Antenna Test System	2000-03-01	2000-03-01	NA	Glendenning
9.4.10	M&C Board available	2000-03-31	2000-03-31	NA	Emerson
9.7.7	Deliver Test Correlator Software	2000-03-01	2000-05-28	NA	Glendenning
9.13.3	CDR: Archiving	2000-05-29	2000-05-29	NA	Glendenning

ALMA U.S. Design & Development Phase Milestones

WBS Milestone tasks, sorted by WBS and date

WBS (f)	Milestone / Deliverable	Baseline	Current	Actual	Responsibility
9.5.11	Deliver Single Dish Antenna Test System	2001-03-01	2001-03-01	NA	Glendenning
9.4.13	Deliver: M&C System	2001-03-30	2001-03-30	NA	Glendenning
9.6.1.4	Deliver Holography System Software	2001-03-30	2001-03-30	NA	Emerson
9.14.3	CDR: Real-time Imaging	2001-07-24	2001-07-24	NA	Glendenning
9.15.3	CDR: Scheduling	2000-12-28	2003-12-01	NA	Glendenning
10	**System Integration**				**Emerson**
10.7.3	Design Review: Holography System	1999-03-29	1999-04-19	1999-04-19	Emerson
10.1.1	System Block Diagram for Array	1999-09-01	1999-10-01	NA	Emerson
10.10.2	Deliver Prot. Ant. Testing Plan	1999-07-02	1999-09-20	NA	Emerson
10.1.2	Test System Block Diagrams	1999-10-01	1999-10-01	NA	Emerson
10.2.3	Deliver MMA Interfaces and Standards Document	1999-04-30	1999-10-31	NA	Emerson
10.4.2	Design Review: Test Int. Site Preparation	2000-04-03	2000-04-03	NA	Sramek
10.7.6	Deliver Holography System	2000-06-30	2001-03-30	NA	Emerson
10.4.7	Test Interferometer Site Complete	2001-04-30	2001-04-30	NA	Sramek
10.10.4.4	Antenna #1 Outfitting Complete	2001-11-02	2001-09-03	NA	Emerson
10.10.9.4	Antenna #2 Outfitting Complete	2002-05-31	2002-04-01	NA	Emerson
11	**Calibration & Imaging**				**Wootten**
11.1.6.1	Site Char. & Monitoring Review (URSI meeting)	1999-01-11	1999-01-11	1999-01-11	Radford
11.3.3.4	Initial Amplitude Cal Review	1999-05-31	1999-06-07	1999-06-07	Wootten
11.3.2.1	Initial Radiometric Phase Cal Review	1999-05-31	1999-06-08	1999-06-08	Wootten
11.3.2.4	Decision: 183 or 22 GHz Phase monitor	2001-05-31	1999-08-23	1999-08-23	Wootten
11.2.3	Design Review: Array Configuration	2000-01-31	2000-01-31	NA	Wootten
11.1.6.2	Mid-term Site Char. & Monitoring Review	2000-03-31	2000-03-31	NA	Radford
11.3.2.2	Mid-term Radiometric Phase Cal Review	2000-05-31	2000-05-31	NA	Wootten
11.3.3.5	Mid-term Amplitude Cal Review	2000-05-31	2000-05-31	NA	Wootten
11.1.6.3	Final Site Char. & Monitoring Review	2001-03-30	2001-03-30	NA	Radford
11.3.2.3	Final Radiometric Phase Cal Review	2001-05-31	2001-05-31	NA	Wootten
11.3.3.6	Final Amplitude Cal Review	2001-05-31	2001-05-31	NA	Wootten

VIII. NEW INITIATIVES

1. VLA Expansion

Introduction

The Very Large Array (VLA) is 25 years old in the year 2000. Since its commissioning it has been used by thousands of astronomers from every continent for research which spans the entire breadth of modern astronomy, yet the VLA has only fulfilled a fraction of its true potential. The antennas, site, array layout and infrastructure—the most expensive components of any array—are fundamentally sound. The electronics which sit atop this foundation are years behind modern technologies. We have begun work on a two-phase project to implement modern technologies on the VLA, and improve its observational capabilities by more than an order of magnitude.

It has been clear for some time that the VLA's impact on astrophysics could be increased dramatically by (a) adding new frequency bands, (b) by upgrading or replacing current receivers, (c) replacing the data transmission system and correlator, (d) by improving its frequency coverage, (e) by improving its ability to image large regions of low surface brightness and wide fields of view with a super-compact configuration, (f) by increasing its angular resolution by connecting VLBA antennas to the array and, (g) by incorporating new antennas at locations between the VLA and the VLBA.

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. The continuum sensitivity will increase an order of magnitude or more in several bands. New frequency bands and increased bandwidth ratios could permit continuous frequency coverage from 300 MHz to 50 GHz. The bandwidth that can be processed by the spectrometer, and its spectral resolution, will increase by about a factor of eighty. The resolving power will improve tenfold. Finally, the new instrument, when cross-linked with the VLBA and with new antennas located about 50–300 km from the VLA, will result in a VLBI instrument with greatly increased dynamic range, field of view and frequency scalability, as compared to the present VLBA.

A short selection of unique experiments made possible includes:

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

As with the original VLA, the vast area of "discovery space" opened up by the Expanded VLA makes it likely that the most important discoveries to be made will be those which cannot now be anticipated.

The Observatory plans to submit a formal proposal to the Foundation for the VLA Expansion Project in late 1999/early 2000. The description provided here is intended to give only the outlines of the motivation for the Project and its scope. The proposal will contain the work breakdown structure, cost estimate, and schedule.

Division into Phases

The VLA Expansion Project comprises two major phases:

Phase 1: The Ultrasensitive Array

- New receivers: 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 40–50 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.
- 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.
- A new correlator, able to support 40 or more antennas, to process broadband signals and to provide improved resolution and flexibility for spectral line work.
- Feasibility studies for an improved low frequency (< 1 GHz) capability, using prime focus feeds and new receivers, with a goal of continuous frequency coverage from 300 to 1000 MHz.
- New online computers, operating software and archiving, to enable more powerful and flexible interaction between the telescope and the operators and observers.

Phase 2: The A+ and E Configurations

- Additional new antennas to provide now unavailable baselines between those in the VLA and those in the VLBA, the A+ configuration.
- Fiber optic links between the VLA and the inner VLBA antennas, and between the VLA and the additional new antennas.
- Possible implementation of an improved low frequency capability and a compact E-configuration with baselines less than ~300 meters, following successful completion of the studies included as part of Phase 1.

The combination of these enhancements will yield an instrument with many fundamentally new capabilities. The continuum sensitivity will improve by more than an order of magnitude in some bands. New and powerful spectral line observations will be possible and significantly more frequency choices will be available. The super-compact E configuration will allow fast imaging of large fields and large objects, greatly enhancing the capabilities of surveys. Linkages to the innermost VLBA antennas and to the added new antennas will increase the maximum angular resolution by a factor of at least eight. The sensitivity increases will allow the increase in angular resolution to be exploited fully when observing a wide (and in many cases for the first time, representative) variety of thermal and nonthermal objects, both galactic and extragalactic. Each of these project elements is now discussed in more detail.

Further Description of Project Elements

Antenna and Receiver Improvements

At the antennas, the project involves improving receivers at the existing observing bands, adding receivers to support new observing bands, 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. Both projects will take two more years to complete.

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, would provide an outstanding capability in studies using Faraday rotation, and will allow the VLA to participate in bistatic planetary radar observations with the Arecibo Observatory. The 33 GHz 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 VIII.1 summarizes the proposed new and upgraded VLA Cassegrain observing bands.

Table VIII.1 Proposed VLA Cassegrain Observing Bands

Band	Range (GHz)	BW (GHz)	BW Ratio	
L	1.1-2.0	0.9	1.8	Upgrade
S	2.0-4.0	2.0	2.0	New
C	4.0-8.0	4.0	2.0	Upgrade
X	8.0-12.0	4.0	1.5	Upgrade
Ku	12.0-18.0	6.0	1.5	Upgrade
K	18.0-27.0	9.0	1.5	Upgrade
Ka	27.0-40.0	13.0	1.5	New
Q	40.0-50.0	10.0	1.25	Complete

New Prime Focus Systems

A design has been developed in which a rotating turret will be installed, permitting access to the VLA antenna prime foci. The turret would contain the current subreflector, plus three or four low-frequency feed/receiver packages, and would enable complete frequency coverage from 300 MHz to 1.2 GHz with good sensitivity. Phase 1 of the Expansion proposal includes funds to permit detailed studies of this design.

Sensitivity Goals

Table VIII.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 VIII.2. VLA Sensitivity

Wavelength (cm)	BW (GHz)	Enhanced VLA		Current VLA	
		T_{sys} (K)	δS (μJy)	T_{sys} (K)	δS (μJy)
90	0.05	80-135	20.0	150	170
50	0.1	55-90	12.0		
30	0.25	30-32	5.3		
20	0.5	30	1.6	32	5.7
11	1.5	25	0.9		
6	3.0	30	0.7	42	6.4
3.6	3.0	30	0.7	35	5.3
2	4.0	35	0.7	110	20
1.3	6.0	50-70	1.0	160	37
0.9	8.0	40	0.9		
0.7	5.0	60	2.0	90	60
0.6	3.0	120	6.0		

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 wideband IF signal. 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 some 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 new correlator will most likely be a close relative to the ALMA correlator, currently undergoing detailed design, since the major characteristics of these correlators (e.g., number of antennas, number of spectral channels, total bandwidth, and polarization capability), are the same. Plans in which these two correlators would be designed and built in parallel are being considered.

High Surface-Brightness Sensitivity – The E Configuration

When the VLA was designed, most astronomers were not aware of the necessity to image with high brightness sensitivity, or to image very large fields, or to image with an angular resolution below that provided by the D configuration. Mosaicing techniques did not exist and it was believed that, in any case, these issues were better addressed with large single dish instruments. It is now recognized that compact arrays with total power capabilities fill a gap between the imaging capabilities of conventional interferometer arrays and those of large single dishes. A super-compact E configuration with maximum baseline lengths of a few times 100 meters would fill this gap. Given that the Arecibo 305 meter telescope samples a similar aperture, how, specifically, would the capabilities of an E configuration compare with a large single dish?

A large single dish has superior point-source sensitivity—the Arecibo 305 meter is roughly five times more sensitive than the proposed E configuration due to its larger surface area. The advantages of the E configuration lie in its imaging capabilities, where the E configuration could be more than five times faster than a single-feed receiver system on Arecibo. Hence, the role of the E configuration would be to provide a fast, low-resolution imaging capability over large fields via mosaicing.

Several other considerations make the E configuration attractive. Unlike the Arecibo 305 meter dish, to which roughly 30 percent of the sky is visible, the VLA has access to 85 percent of the sky and also will provide frequency coverage up to 50 GHz. As an interferometric instrument, the VLA also has lower systematic errors than a large single dish, i.e., it is less susceptible to pointing errors, and ground pickup is uncorrelated between antennas, so that the spectral baselines are flat.

High Angular Resolution – The A+ Configuration

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 with up to eight new antennas which would be 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.

2. GBT High Frequency Program

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 256 k spectral channels, multiple IF, bandwidth, and spectral resolution modes, and a pulsar mode), a digital continuum backend, 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 should adequately meet the initial needs of the users. Nevertheless, the scientific potential of the GBT is enormous and instrument technology advances quickly. Consequently, there are a number of major opportunities that require a continuing program of instrument development. In particular, two primary areas exist in which advanced instrument development could have a dramatic payoff: high frequency receivers and imaging systems.

For frequencies above 30 GHz, and particularly for frequencies above 70 GHz, the GBT will be without peer 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.

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.

The working group also recommended that 3 mm imaging systems be developed for the GBT for both spectroscopy and continuum work. Especially exciting is the possibility of placing a large-format bolometer camera (up to several hundred pixels) on the GBT. The sensitivity of the GBT in the 3 mm band will allow continuum emission from a variety of mechanisms including dust, free-free, and synchrotron radiation.

Astronomical imaging in the 3 mm band, and at longer wavelengths, is another area in which the GBT can make major 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 a large-format focal plane array. 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.

In 2000, the NRAO expects to begin construction of the first 3 mm system (68-95 GHz). Planning and design work for the next members of the 3 mm suite, including bolometer arrays and spectroscopic imagers, will also begin. At the 2000 Presidential Request level, it will not be possible, however, to begin work on the high frequency receiver suite. To make significant progress on GBT high frequency observing will require additional staff distributed amongst operations, scientific support and electronics. This is indicated in Table X.1 in the "Miscellaneous Requirements" column.

IX. NON-NSF RESEARCH

1. USNO Earth Orientation Station

The NRAO operates a 20 meter telescope at Green Bank under contract with the U.S. Naval Observatory. The 20 meter participates in an ongoing series of VLBI experiments designed to monitor the Earth's rotation, polar motion, and continental drift. Typically the USNO VLBI network includes stations in Green Bank(WV), Kauai (Hawaii), Fortaleza (Brazil), Wettzell (Germany), and Fairbanks (Alaska).

A typical 24-hour experiment will make repeated observations of 20–50 quasars and other compact extragalactic objects. These experiments are part of a global effort to collect data on earth orientation and continental drift. In the U.S., the experiments are coordinated by the National Earth Orientation Service (NEOS).

Earth orientation data, consisting of UT1 corrections (i.e., UT1-UTC) and polar motion vectors (x,y), are published weekly by the USNO in "IERS Bulletin A," which gives recent measurement results and predictions for three months in the future. These data are needed to produce navigational tables and provide corrections that keep world-wide navigational systems, such as the GPS satellite system, highly accurate. These VLBI results are also used for astronomy, astrometry, geophysics, and oceanic and atmospheric sciences.

2. The Green Bank Interferometer and 85-3 Pulsar Station

The Green Bank Interferometer (GBI) is run as a cooperative project by NRAO, NASA, USNO, and NRL. The program monitors variable radio sources for which continuous monitoring of radio light curves is critical to the understanding of event-driven astrophysical phenomena. In particular, GBI data are used in support of X-ray satellite missions such as RXTE and BATSE. An executive committee coordinates proposals for objects to be monitored, and NRAO staff schedule and operate the facility. Observations are made simultaneously at two frequencies, 2.25 and 8.4 GHz. Sources are typically observed daily but can be observed as often as hourly, if necessary. For 2000, operation of the GBI will be examined in light of new X-ray missions such as Chandra and the continuing needs of other projects. A program to make the data available via the web to the general public, and in particular, to students will be initiated.

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 number of important results have been obtained from this program that could not be detected without close monitoring. The program is evaluated annually and will continue in 2000.

3. NASA - 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. NASA has recently committed to continued HALCA support through 2000, although support beyond that point has not yet been determined. It is anticipated that the NRAO Earth Station will also participate in possible future missions such as RadioAstron and ARISE.

X. ORGANIZATIONAL PLAN

During the year covered by this Program Plan we intend to organize all the activities of the NRAO into a work breakdown structure (WBS). It is not intended that this be implemented in the detail appropriate to a construction project. We consider that commercial software packages are typically designed for schedule-driven projects and are not simply applicable to on-going routine operations. Nevertheless, we think a WBS provides a useful management tool for judging the personnel requirements, costs, and performance of operations activities. The outline which follows is an initial attempt to organize the Observatory on this basis. Significant differences between the Presidential Request level and our mission requirements have been noted to the right of the table, and are explained below.

Table X.1

		Presidential Request Budget			Mission Requirements	
		FTE	Totals (k$)		FTE	Totals (k$)
1	Observatory Wide Functions & Programs					
1.1	Director's Office	8.3	947		8.3	947
1.2	Administration					
1.2.1	Business & MIS	4.7	1,163		4.7	[1] 1,343
1.2.2	Fiscal	11.6	707		12.6	757
1.2.3	Safety & Environment	2.8	231		2.8	261
	Total Administration	19.1	$2,101		20.1	$2,361
1.3	Personnel					
1.3.1	Personnel	6.0	447		6.0	447
	Total Personnel	6.0	$447		6.0	$447
1.4	Research Support					
1.4.1	User Support Programs	2.5	289		2.5	289
1.4.2	Staff Science Support		190			190
	Total Research Support	2.5	$479		2.5	$479
1.5	Education					
1.5.1	REU Program	5.8	176		5.8	176
1.5.2	RARE CATS/CTW	0.7	800		0.7	800
1.5.3	Postdoctoral Program	11.7	599		11.7	599
1.5.4	Student Program	6.0	246		6.0	246
1.5.5	Library	2.7	515		2.7	515
	Total Education	26.9	$2,336		26.9	$2,336
1.6	Public Outreach					
1.6.1	Public Relations	5.0	325		5.0	350
1.6.2	GB Visitors Center & Tour Program	1.7	60		1.7	60
1.6.3	VLA Visitors Center & Tour Program	0.3	23		0.3	43
	Total Public Outreach	7.0	$408		7.0	$453
1.7	Computing					
1.7.1	Computing Council & Obs-wide Computing	2.0	451		2.0	451

1.7.2	Observatory Communications	1.0	255		1.0	255
1.7.3	CV Computing Support	6 0	628		6.0	628
1.7.4	AIPS	1.0	96		1.0	96
	Total Computing	10.0	$1,430		10.0	$1,430
1.8	Technology Development					
1.8.1	Electronics - CDL	18.4	1,650		19.4	1,750
1.8.2	Data Management & Analysis - AIPS++	10.0	814		12.0	[2] 924
1.8.3	ILL-NCSA	1.8	200		1.8	200
1.8.4	NSF/CISE	2.0	183		2.0	183
	Total Technology Development	32.2	$2,847		35.2	$3,057
1.9	Equipment					
1.9.1	Instrumentation		100			[3] 800
1.9.2	Operating Equipment		0			200
	Total Equipment		100			$1,000
	Total NSF Obs-wide Functions & Programs	108.2	$10,712		112.2	$12,127
	Total Non-NSF Obs-wide Functions & Programs	3.8	$383		3.8	$383
	TOTAL OBS- WIDE FUNCTIONS & PROGRAMS	112	$11,095		116.0	$12,510
2	ALMA (USA)	53.0	7,840		57.0	[4] 11,500
	TOTAL MILLIMETER ARRAY (U.S. Partic in ALMA)	53.0	$7,840		57.0	$11,500
3	GB Operations					
3.1	Management & Administration					
3.1.1	Site Director's Office	2.0	346		2.0	346
3.1.2	Business Office	4.5	367		4.5	367
3.1.3	Visitor's Residence & Cafeteria	8.2	233		8.2	233
	Total Management & Administration	14.7	$946		14.7	$946
3.2	Computing	7.1	642		7.1	642
3.3	Electronics	27.8	2,058		29.8	[5] 2,158
3.4	Plant Maintenance	17.0	720		19.0	[5] 870
3.5	Scientific Support	12.3	1,256		13.3	[5] 1,316
3.6	Telescope Operations	19.0	1,221		20.0	[5] 1,381
	Total NSF GBT Operations	98	$6,843		103.9	$7,313
3.7	GB Projects Funded by Other Agencies					
3.7.1	USNO Program	5.1	600		5.1	600
3.7.2	NASA - OVLBI Earth Station	7.7	891		7.7	891
3.7.3	NRL/NASA GBI	0.5	85		0.5	85
	Total Projects Funded by Other Agencies	13.3	$1,576		13.3	$1,576
	TOTAL GB OPERATIONS	111.2	$8,419		117.2	$8,889

4	VLA/VLBA Operations					
4.1	Management & Administration	19.9	2,945		19.9	2,945
4.2	Array Operations	22.0	1,103		24.0	[6] 1,243
4.3	Computing Support	17.7	1,428		19.7	[6] 1,628
4.4	Electronics	63.7	4,486		65.7	[6] 4,686
4.5	Engineering Services	46.7	3,257		47.7	3,457
4.6	Scientific Support	11.8	937		12.8	987
	Total NSF VLA/VLBA Operations	186.8	$14,700		196.8	$15,625
4.7	VLA Expansion Project					
4.7.1	Planning Group	2.0	245		4.0	[5] 380
4.7.2	NSF MRI - Pie Town Link	2.0	99		2.0	99
4.7.3	NSF MRI - VLA Q-Band Receivers-MPI	1.0	200		1.0	200
	Total VLA Expansion Project	5.0	$544		7.0	$679
4.8	Projects Funded by Other Agencies					
4.8.1	NASA - OVLBI Science	10.0	1,226		10.0	1,226
4.8.2	MPIfR - VLBA 3 mm Receivers		283			283
	Total Projects Funded by Other Agencies	10.0	$1,509		10.0	$1,509
	TOTAL VLA/VLBA OPERATIONS	196.8	$16,209		206.8	$17,134
5	12 Meter Telescope Operations					
5.1	Administration	4.2	377		4.2	377
5.2	Computing Support	3.0	264		3.0	264
5.3	Electronics	9.5	824		9.5	824
5.4	Telescope Operations	9.5	564		9.5	564
	TOTAL 12 METER TELESCOPE OPERATIONS	26.2	$2,029		26.2	$2,029
6	Revenue & CCR					
6.1	CDL Revenue		(100)			(100)
6.2	CCR		(1,135)			(1,135)
	TOTAL REVENUE & CCR		($1,235)			($1,235)
7	TOTAL MANAGEMENT FEE		840			840

	SUMMARY:					
1	Observatory-wide Functions & Programs	112.0	11,095		116	12,510
2	ALMA (USA)	53.0	7,840		57	11,500
3	Green Bank & GBT Operations	111.2	8,419		117.2	8,889
4	Socorro & VLA/VLBA Operations	196.8	16,209		206.8	17,134
5	Tucson & 12 Meter Telescope Operations	26.2	2,029		26.2	2,029
6	Revenue & CCR		(1,235)		0	(1,235)
7	Management Fee		840		0	840
	Grand Total	499.2	$45,197		523.2	$51,667
	Income (I) & Carryover (C/O)					
	NSF Ops (I)	409.6	32,454		429.6	35,264
	NSF REU (I)	5.8	176		5.8	176
	NSF-MRI & CISE (C/O)	5.0	482		5.0	482
	NSF-Educ. (I & C/O)	0.7	800		0.7	800
	NSF MMA (I)	53.0	8,000		57	11,660
	Other Projects (Non-NSF) (I)	25.1	3,285		25.1	3,285
	Grand Total	499.2	$45,197		523.2	$51,667

Notes:

[1] Replacement of fiscal MIS system required in FY2000.

[2] Two additional programmers required for AIPS++ operations (Section IV).

[3] New instrumentation and equipment must be developed and procured if NRAO is to remain in the forefront of radio astronomy research. Funds in the Research Equipment (RE) area support computing infrastructure upgrades, items related to observing and telescope design and support, and instrument prototypes for new projects. The 2000 Presidential Request RE level will effectively halt all progress in these areas. A more reasonable level is indicated in the mission requirements column.

[4] Additional $3.66M required to cover costs incurred changing ALMA prototype antenna diameter from 10 to 12 meters; also, four new positions to address increased management overhead stipulated by NSF. (Section VII).

[5] Additional positions required for GBT commissioning and first-year operations (Section III).

[6] Additional positions required to support data product refinement projects and to assist in VLA Expansion studies (Section III).

WBS Dictionary

1 **Observatory-Wide Functions and Programs** — Those functional activities that are centrally managed or coordinated across the Observatory.

1.1 Director's Office — Responsibility for the overall management and direction of the Observatory, long range planning and new initiatives, reporting to AUI and NSF, and the maintenance of close relations with the astronomical community at large.

1.2 Administration — All functions connected with the Observatory budget, contracts, business affairs, accounting, financial reporting, MIS, and safety and environment.

1.2.1 Business & MIS — The business affairs for ALMA, the GBT, and the Charlottesville site; the management information system.

1.2.2 Fiscal — All accounting and financial records functions, financial reporting, compliance with applicable regulations and Observatory policies.

1.2.3 Safety and Environment — Compliance with all applicable regulations and Observatory policy with respect to safety and the environment.

1.3 Personnel — All functions and activities associated with implementation of the Observatory Personnel Policy, Affirmative Action Plan, and those required for compliance with applicable federal and state regulations, and with AUI and Observatory policy.

1.4 Research Support — Program of support for users and staff scientific research.

1.4.1 User Support Programs — Program of NRAO support for page charges, travel for observing and data reduction, travel to observe using unique foreign facilities.

1.4.2 Staff Science Support — Travel, data reduction, and page charges for research of the NRAO scientific staff.

1.5 Education — Observatory-wide education functions and site education programs, from secondary school to postdoctoral programs, coordinated from NRAO headquarters; library.

1.5.1 Research Experience for Undergraduates — Observatory-wide summer program for undergraduate students (supplementary NSF funding) together with rising seniors and graduate students (NRAO operating budget).

1.5.2 RARE CATS & Catching the Wave — Green Bank education programs for secondary education science teachers and their students.

1.5.3 Postdoctoral Program — Jansky postdoctoral program.

1.5.4 Student Program — Program that supports graduate students in residence at the NRAO for research program observing, supervised by NRAO staff.

1.5.5 Library — Observatory library, with four site locations.

1.6 Public Outreach — A centrally coordinated program of public education and outreach.

1.6.1 Public Relations — All aspects of public relations including promotional material, web site, and press releases.

1.6.2 Green Bank Visitors Center & Tour Program — Visitors center and education facility in Green Bank; tour program for tourists.

1.6.3 Very Large Array Visitors Center — Visitors center at the VLA site; program of special tours.

1.7 Computing — All NRAO computing activities centrally managed or coordinated.

1.7.1 Computing Council / Observatory-wide Computing — Responsible for Observatory-wide policy and programs, including security, specifying bulk purchases of hardware and software, emergency readiness (e.g. Y2K), and coordination of site-based computing group activities.

1.7.2 Observatory Communications — Responsible for the voice and data connectivity of the NRAO.

1.7.3 Computing Support — Provide computing support to Charlottesville site.

1.7.4 AIPS — Maintenance of software system currently used to process data from NRAO telescopes and many others world-wide.

1.8 Technology Development

1.8.1 Central Development Laboratory — Research and development of electronics showing promise for use in radio astronomy; development and production of devices required for NRAO telescopes.

1.8.2 AIPS++ — New astronomical data analysis software system developed and maintained by an international consortium.

1.8.3 ILL/NCSA — NCSA PACI Alliance program for adapting AIPS++ to massively parallel computing; NRAO/BIMA partnership funded by NCSA.

1.8.4 NSF/CISE — An AIPS++ program to develop visualization of data in both u-v and image planes simultaneously during image formation and processing; funded by NSF Computer and Information Sciences and Engineering.

1.9 Equipment — Program that reviews proposals for (internal) funds to build new instrumentation for NRAO telescopes; operating equipment program.

2 Millimeter Array (U.S. Participation in ALMA) — Program of design and development for the Atacama Large Millimeter Array with work conducted at the Tucson, Socorro, and Charlottesville sites; central project management in Charlottesville.

3 Green Bank Telescope Operations — All functions associated with the commissioning and operation of the GBT; other programs at the Green Bank site.

3.1 Management & Administration — Green Bank site management functions.

3.1.1 Site Director's Office — Responsibility for site management and direction.

3.1.2 Business Office — Local business functions.

3.1.3 Visitor's Residence and Cafeteria — Operation of visitor's facilities

3.2 Computing — Computing support for telescope operations, staff, and visitors.

3.3 **Electronics** — Instrumentation construction and maintenance.

3.4 **Plant Maintenance** — Responsible for maintenance of the physical plant and grounds.

3.5 **Scientific Support** — Support for telescope operation; visitors support.

3.6 **Telescope Operations** — Responsible for GBT observing and other operations activities; coordination of all telescope operations.

3.7 **Projects Funded by Other Agencies** — Green Bank non-NSF programs.
- 3.7.1 **USNO Program** — Earth rotation measurements.
- 3.7.2 **NASA - OVLBI Earth Station** — Ground station for orbiting VLBI programs.
- 3.7.3 **NRL/NASA GBI** — Source monitoring for transient events.

4 **Very Large Array/Very Long Baseline Array Operations** — VLA and VLBA operations; other Socorro-based programs.

4.1 **Management & Administration** — Socorro management functions.

4.2 **Array Operations** — Responsible for VLA and VLBA observing, VLBA data correlation, and other operations activities.

4.3 **Computing** — Computing support for telescope operations, staff, and visitors.

4.4 **Electronics** — Instrumentation construction and maintenance.

4.5 **Engineering Services** — Responsible for VLA and VLBA antenna maintenance.

4.6 **Scientific Support** — Support for telescope operation; visitor support.

4.7 **Very Large Array Expansion Project**
- 4.7.1 **Planning Group** — Responsible for conceptual design and proposal preparation.
- 4.7.2 **NSF MRI-Pie Town Link** — Project to double angular resolution of the VLA.
- 4.7.3 **NSF MRI-Q-Band Receivers** — Project to equip the VLA for 40–50 GHz.

4.8 **Projects Funded by Other Agencies** — Socorro non-NSF programs.
- 4.8.1 **NASA-OVLBI Science** — Participation in the Japanese orbiting VLBI mission (HALCA).
- 4.8.2 **MPIfR-VLBA 3 mm Receivers** — Project to equip the VLBA for 90 GHz.

5 **12 Meter Telescope Operations** — Operation of the 12 Meter Telescope.

5.1 **Management & Administration** — Tucson management functions.

5.2 **Computing** — Computing support for telescope operation, staff, and visitors.

5.3 **Electronics** — Construction and maintenance of instrumentation.

5.4 **Telescope Operations** — Responsible for 12 Meter Telescope observing and other operations activities.

6. **Revenue and Common Cost Recovery** — Income from sales to outside organizations of Central Development Laboratory devices; common cost recovery accessed on non-NSF programs.

7. **Management Fee** — Management fee charged by Associated Universities, Inc.

XI. 2000 PRELIMINARY FINANCIAL PLAN

1. NSF Funding by Function/Site

($ in 000's)

Operational Functions	FTE	Salaries & Benefits	Materials & Services	Travel	Total Presidential Request Budget
Observatory Wide Activities	108.2	$7,234	$3,229	$432	$10,895
ALMA (U.S. Participation)	53.0	4,355	3,235	250	7,840
GBT Operations	98.0	5,939	806	98	6,843
VLA/VLBA Operations	186.8	11,000	3,537	163	14,700
12 Meter Operations	26.2	1,686	314	29	2,029
Revenue & Common Cost Recovery			(1,235)		(1,235)
Management Fee			840		840
Total NSF	472.2	$30,214	$10,726	$972	$41,912

Source of Funds for Total Presidential Request Budget:

Operations	*$32,530*
REU	*100*
MRI Carryover	*299*
CISE Carryover	*183*
ALMA	*8,000*
NSF Informal Educ.	*800*
TOTAL	*$41,912*

2. Non-NSF Funding

($ in 000's)

Funding Source	FTE	Salaries & Benefits	Materials & Services/ Common Cost Recovery	Travel	Total Budget
USNO	5.1	$308	$287	$5	$600
NASA	17.7	1,066	1,000	51	2,117
NRL/NASA	0.5	60	25		85
ILL/NCSA	1.8	113	87		200
MPIfR	0	0	283		283
Total Non-NSF	25.1	$1,547	$1,682	$56	$3,285

3. NSF Funds by Budget Category

($ in 000's)

	New Funds	Uncommitted Carryover of 1999 Funds	Total Available for Commitment	Commitments Carried Over from 1999 Funds	Available for Expenditure
Personnel Compensation	$19,437		$19,437		$19,437
Personnel Benefits	5,831		5,831		5,831
Travel	698		698		698
Materials & Services	7,119		7,119	650	7,769
Management Fee	680		680		680
Common Cost Recovery	(1,135)		(1,135)		(1,135)
CDL Device Revenue	(100)		(100)		(100)
Res & Oper Equipment	100		100		100
Total NSF Operations	$32,630	$0	$32,630	$650	$33,280
MMA Design & Devel	$8,000	$300	$8,300	$7,500	$15,800
MRI (PT & Q)	0	100	100	199	299
CISE	0	183	183	0	183
Education (RC & CTW)	0	500	500	300	800
Total NSF	$40,630	$1,083	$41,713	$8,649	$50,362

APPENDIX A – NRAO SCIENTIFIC STAFF RESEARCH ACTIVITIES

Each of the approximately 80 individuals with Ph.D. degrees at the NRAO is required to maintain as vigorous a program of research as possible within constraints imposed by functional duties, ranging from antenna and instrumentation design and the development of new techniques for the analysis of radio astronomy data, to a wide range of astronomical research programs. Many of these research programs are at the forefront of contemporary radio astronomy. They are critical in pushing the NRAO instruments to new levels of performance and in maintaining the level of expertise needed by the NRAO staff to lead the development of new instrumentation and in supporting visiting observer programs.

Most NRAO staff observing programs utilize the unique NRAO radio telescopes and all are subject to the same competitive review as standard NRAO observing programs. Often, these research programs are in collaboration with investigators from the university community. Some programs are carried out using other radio telescopes and are often the basis of valuable liaisons between NRAO staff, university-based scientists, as well as foreign colleagues. The planned research program of the scientific staff for 2000 is summarized below.

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

Over the past five years, the Cosmic Lens All-Sky Survey (CLASS) has been carried out by the VLA. CLASS has imaged over 13,000 radio galaxies and quasars in order to discover new gravitational lenses. This has been spectacularly successful, and CLASS has so far yielded 11 new lenses, and is the largest statistically clean sample of gravitational lenses obtained at any wavelength! Follow-up studies of CLASS lenses and candidates will continue, resulting in important measurements of galaxy masses, lensing statistics (which constrain the geometry of the Universe and can discern the effects of a cosmological constant) and in the best "golden lens" cases, measure the time-delay along the different lensing paths from which the Hubble constant can be determined.

The proposed connection between gravitational lens systems and compact groups of galaxies will also be studied. In the local Universe the most common environment for galaxies is in poor groups. The evolution of these groups has been difficult to study due to a paucity of known moderate-to-high redshift groups of galaxies. It is difficult to detect poor groups at redshifts larger than $z \sim 0.5$ because of cosmological dimming and background contamination. However, it appears that typical lensing galaxies reside in compact groups. Because most lensing galaxies are at redshifts between 0.5 and 1.0, they may provide an efficient manner of selecting groups of galaxies at previous unreachable redshifts. The environment of lens galaxies will be studied by imaging and spectroscopy at the Palomar and Keck Observatories.

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

The VLA is being used to monitor the gravitational lens system CLASS B1608+656 in order to measure time delays between the four lensed images of the background source. These time delays will be combined with a model of the gravitational potential of the lensing galaxies in order to provide a one-step direct determination of the Hubble Constant at cosmological distances. Although the time delays in this lens system have been measured with the VLA, the uncertainties on the delays are relatively large because the variations in flux density of the background source were small. Thus, the constraints on the Hubble Constant are not as strong as might be desired. If stronger variations are observed, the uncertainties on the time delays, and thus on the measurement of the Hubble Constant, will be significantly reduced. VLBA observations of several other lens systems provide information on the milliarcsecond structure of the lensed images. Mapping these structures is crucial to constraining models of the gravitational potential of the lensing galaxies in the systems as a good model of the entire gravitational lens system is needed to determine the Hubble Constant.

The gravitational lens candidate J1605+3029 was found in a survey of 161 flat-spectrum objects from the VLA FIRST survey. A multi-frequency VLBA study of his object, containing a double source with two unresolved flat-spectrum components, will be carried out to determine if it is a lens with an image separation near 15 milliarcseconds, corresponding to a lensing mass of 10^8 solar masses. If it is truly a lens and not just a compact symmetric object, its discovery will open up a new regime for studies of gravitational lenses, and will have significant impact on the study of the contribution of relatively low-mass objects to the overall mass density of the Universe.

The Cosmic Background Imager (CBI) is a newly-built compact interferometer dedicated to mapping the anisotropy in the cosmic microwave background radiation (CMB). The CBI, which was designed and constructed at CalTech, has recently been installed in its operational site at the Chajnantor reserve in Chile (the ALMA site). NRAO staff who participated in the design and definition of the CBI will be part of the first science observations in late 1999 and early 2000, as well as the later CBI CMB and Sunyaev-Zeldovich Effect (SZE) programs.

The SZE is a distortion of the CMB induced by scattering of the microwave photons from super-hot ionized gas trapped in the gravitational potential wells of massive clusters of galaxies. By measuring and mapping the SZE with the CBI or other radio telescopes, one can inventory the baryonic content of these clusters (which are dominated by this intra-cluster gas) and thus place constraints on the baryon fraction of the Universe. Previous work has demonstrated that only about 11 percent of the mass-energy of the Universe is in the form of normal baryonic material, and that indeed our cosmology is dominated by "dark matter" of some form. This dark matter almost certainly cannot be normal (non black-hole) matter. Also, by combining SZE data with X-ray observations of the hot cluster gas, the distance to the cluster can be measured, providing a measurement of the Hubble Constant independent of the standard distance ladder. In the next year, new SZE results from the CBI will cement the previously reported determination of the baryon fraction of the nearest massive clusters, and point the way toward using the ALMA for similar studies.

Observations of the light element ^{3}He in several diffuse, low emission measure Galactic HII regions were the last scheduled observations on the 140 Foot Telescope before it closed as a user facility in July 1999. The ^{3}He experiment using the 140 Foot spanned about 15 years. These observations serve both as a probe of cosmology and stellar and galactic evolution. The goal has been to measure ^{3}He in enough objects located throughout the Galaxy to disentangle the cosmological and stellar components. The advantage of diffuse HII regions is that they tend to be *simple*, i.e., they have a relatively simple structure which allows the ^{3}He$^+$ spectral line parameters to be converted into a ^{3}He/H abundance. Eight new, distant, diffuse

HII regions have been detected in $^3He^+$ to make a total of about 30 objects. Models will be developed to convert the observational data into a $^3He/H$ abundance ratio. Preliminary results indicate that there is no detectable ^3He gradient in the Galactic disk, which may imply that these measurements are primordial.

Data from the VLA, in conjunction with the data from the millimeter/submillimeter, X-ray and optical/IR telescopes, is being used for the investigation of the gaseous environment and starburst phenomenon as well as their cosmic evolution. Deep VLA radio continuum studies of Canada-France Redshift Survey fields, the ISO Deep Survey fields, the Ultradeep Chandra field, along with other deep HST and ground-based optical and IR fields are currently underway. The evolution of massive starburst systems which contribute to the cosmic star formation history is being analyzed in parallel with the ongoing studies of faint submillimeter sources discovered by SCUBA. Projects to measure the submillimeter dust emission from high and low redshift starburst systems at CSO and JCMT will be used to derive their dust content and dust properties. This work may eventually reveal if any evolution is present in the gas-to-dust ratio among such active star-forming galaxies. Searches for CO emission in promising candidates with good redshifts will be conducted at the VLA and with the CalTech millimeter array in order to derive their molecular gas content. The novel use of radio-to-submillimeter spectral index as a redshift indicator will also be further developed and refined as this may be the only feasible way of determining the redshift distribution of these extremely important but optically-faint galaxies.

A continued effort is aimed toward understanding how more normal systems appear when viewed at cosmological distances. Not that there actually are any Milky Way doppelgangers at $z = 5$, but instruments like ALMA are frequently benchmarked on their ability to detect them anyway. The question then becomes, "What would the Milky Way look like if it existed where the temperature of the cosmic background is much above that found locally?" and it is not an entirely trivial one.

The new 90 cm system on the VLA will provide an exciting new opportunity to study the faint radio populations in the directions of distant rich clusters such as A370. These long wavelength observations will complement other high resolution observations at 20 cm. The radio observations will be supported by spectroscopy of optical counterparts using data from the WIYN 3.5 m and the Steward 2.3 m. These observations are revealing that dust-obscured, star-forming radio galaxies associated with rich clusters are much more numerous at $z = 0.4$ than in the local universe. Multiband widefield optical/IR imaging is also planned for these fields in order to obtain photometric redshifts for the large number of radio sources found in the VLA surveys.

There is particular interest in the hunt for forming galaxies in the distant Universe. Theoretical studies suggest that millimeter-wave and submillimeter surveys could find these elusive objects if they contained significant amounts of dust. Indeed, such galaxies were found recently with the SCUBA bolometer array on the JCMT by several groups, and follow-up observations with the OVRO millimeter-array are planned in collaboration with the SCUBA groups. Furthermore, as the detection and imaging of these faint distant galaxies is one of the prime scientific drivers of ALMA, predictive theoretical models are being developed that can quantify the results of submillimeter galaxy surveys. It is clear that the ALMA observations will be crucial to unraveling the mystery of galaxy formation, and steps need to be taken during the design stage to ensure that this instrument is ready and capable of carrying out these tasks.

There has been considerable recent interest in observing highly redshifted HI emission from cosmological HI before the epoch of reionization by the first generation of quasars and the possibility of making this important observation is being investigated.

2. Radio Galaxies, Quasars, Active Galaxies, and Gamma-Ray Bursts

Although designed for targeted observations, the VLA has proven to be a remarkably powerful and flexible survey instrument, both for all-sky surveys (down to moderate sensitivities) as well as for deep integrations on selected fields. The NVSS is now is available on the web and has enjoyed great use by the astronomical community.

Observations will begin for a planned 4 m continuum survey covering the 10.3 sr of sky north of -40 deg declination using the VLA BnA and B configurations. The principal data products will be a set of images with 80 arcsec FWHM resolution and a catalog of more than 100,000 sources brighter than 0.4 Jy/beam. The primary beam at 4 m is so large (10 deg FWHM) that making a gridded all-sky survey actually uses the VLA more efficiently than directed observations of many individual targets. The main scientific goals are: (1) To construct the first really large flux-limited sample of sources at a very low frequency. Samples selected at 4 m are completely dominated by isotropic radio emission, unlike those found at higher frequencies. They will give the only unbiased view of the parent populations used in "unification" models. (2) To find extremely steep-spectrum sources, including millisecond pulsars, relic radio sources, and high-redshift radio galaxies. (3) To extend the radio spectra of known source populations to 4 m, where free-free absorption and synchrotron self-absorption become increasingly important. (4) To image very extended (up to 30 arcmin) steep-spectrum sources such as galactic SNRs and halos and tails of nearby galaxies. (5) To disentangle the superposition of sources along complex lines-of-sight in our Galaxy via the contrast between bright nonthermal emitters and free-free absorbing HII regions. Like the NVSS, this survey will be made as a service to the entire astronomical community, and the results will be made available promptly on the web.

Detailed comparisons will soon begin between Chandra X-ray images and VLA intensity and rotation measure distributions for several radio galaxies embedded in cooling flow clusters. The X-ray measurements probe the density of the hot gas while the rotation measure distribution is sensitive to both the density and magnetic field strength. Several other radio cluster halo candidate sources which have been identified earlier in the D-array VLA observations at 20 cm will be studied with better angular resolution.

A systematic search is planned with the VLA to determine the frequency of giant (Mpc scale) radio sources associated with sources with known radio structure on kpc scales. This is a follow up to the discovery of some extreme examples of weak, FRI radio galaxies with such structures found in the NVSS.

Massive starburst and AGN activities may be closely linked through the fueling processes such as a galaxy merger. The quasar-starburst link will continue to be explored using the VLA and the millimeter/submillimeter telescopes to study the non thermal radio continuum as well as dust and molecular gas emission. Ongoing study of tidal dynamics and response of the cold gas in major galaxy mergers will be pursued with VLA HI data and CO data from the Caltech millimeter array.

A series of VLBA observations of Seyfert galaxies has taken place over the last several years, emphasizing the spectral characteristics of the radio components (free-free emission and absorption, and synchrotron self-absorption), as well as jet speeds, to study the gas distribution in and near the circumnuclear tori in Seyfert galaxies. Analysis of the multi-frequency observations of a number of galaxies, to study the absorption, will continue in the next year. Two-epoch observations of two Seyferts have revealed apparent speeds of only 0.1 c within a parsec of the nucleus, indicating that the intrinsic jet speeds are much slower than in strong AGN and quasars. A third epoch will be obtained on each of these two galaxies, in order to confirm the previous speed measurements.

The unified scheme for Seyfert galaxies is that Seyfert 1 and Seyfert 2 galaxies are the same objects seen from different directions. However, radio-observed samples of Seyferts have been subject to a number of selection biases that have led to conflicting results for different samples. A VLA program will be carried out to observe the Palomar Seyfert galaxies, identified by a spectroscopic survey of all galaxies brighter than 12th magnitude, to a uniform emission-line equivalent width. The VLA program will assess the importance of compact and extended Seyfert type radio sources, as well as their relation to data from other wavebands, and will be followed up in the longer term by VLBA observations of the most compact nuclei. This should provide a stringent test for the "unified scheme" which is the basis for the currently accepted models of active galactic nuclei.

The merger galaxy NGC 4038/9 ("The Antennae") is undergoing an extreme starburst. A series of sensitive VLA observations have revealed a number of complexes of radio emission on size scales of 100 parsecs and smaller; the detection threshold of 40 microJy is just a few times the strength of the galactic supernova remnant Cassiopeia A at the Antennae distance of 20 Megaparsecs. Analysis of the populations of O stars and supernova remnants required to energize the radio emission, and comparison to the starburst properties derived from observations in other wavebands, will be completed in the next year.

The Very Long Baseline Array is being used in a flux limited survey of Seyfert galaxies to look for evidence of free-free absorption, as was proposed to explain the results of the neutral hydrogen absorption experiment, and to locate true flat-spectrum radio cores that might best mark the location of the active nucleus. Eight out of the twelve surveyed galaxies were detected, and, in a few Seyfert galaxies, there is evidence of a low frequency turnover suggesting free-free absorption. These findings argue in favor of a small scale obscuring medium that might act as a fuel reservoir for the central black hole. There is also evidence in one Seyfert galaxy for a thermal free-free emission source that is resolved out by this VLBA experiment. This thermal source may trace emission from the ionized surface of the nuclear obscuring medium. Follow-up experiments will test this scenario.

The interstellar medium within the inner few parsecs of AGNs is also a topic of intense study. The goals of this research are (1) to find evidence of a parsec-scale medium that may obscure the central engine in narrow-line active galaxies (e.g., Seyferts type 2), and (2) to study the kinematics of the near-nuclear gas and look for evidence of infall that might ultimately fuel a central, supermassive black hole. Completed this year was a survey of neutral hydrogen absorption observed using the VLA. Neutral hydrogen absorption, viewed in the 21 cm ground-state spectral line, was detected in most of the radio-bright Seyfert galaxies surveyed. The surprising result was an absence of absorption towards what appear to be the radio nuclei, even in those cases known from X-ray studies to be obscured by a large quantity of cold, neutral material. Three explanations are considered: (1) a foreground, ionized medium completely absorbs radio continuum from the true radio nucleus; (2) the excitation temperature of neutral hydrogen is enhanced by radiative processes, in which case absorption would be suppressed; (3) the neutral hydrogen is in rapid motion, broadening the absorption line below detectability. In any case, the implication is that the obscuring medium must be very compact, no larger than a few tens of parsecs.

In contrast, the hydrogen absorption detected in Seyfert galaxies appears to trace rotating disks with sizes on the order of a few hundred parsecs. These central disks align and co-rotate with the outer galaxy disks. What is unusual is that these central disks appear to be rich in neutral hydrogen, although non-active galaxies tend to show a deficiency of neutral hydrogen in the inner kiloparsec. Active galaxies may be fueled by this excess reservoir of neutral hydrogen that non-active galaxies lack.

Several tens of high-redshift ($z > 4$) quasars found in the Sloan Deep Sky Survey will be observed at radio and submillimeter wavelengths using the VLA, IRAM, and JCMT. The goal is to determine the radio/millimeter spectra of a large sample of these sources, and from these to test preliminary indications that the host galaxies are undergoing extreme starbursts. The unusual polarization properties of Sgr A* suggest that there may be a separate class of radio object from the radio-loud quasars. VLA observations of the linear and circular polarizations of nearby, weak radio sources will test this proposition.

A sample of 52 Compact Symmetric Objects (CSO) in the northern sky has been recently identified. These are valuable objects for testing unified schemes since a large fraction of CSOs are thought to lie close to the plane of the sky. Follow-up observations of neutral hydrogen (HI) in absorption are in progress in order to detect the obscuring torus and place constraints on the mass contained within the central parsecs of AGN.

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 motions in the FR I radio galaxy, M84.

Since beginning operation nearly five years ago, the VLBA has been used in repeated observations to characterize the relativistic outflow in a sample of the strongest 150 quasars and AGN. Apparent transverse ejection velocities up to 15 times the speed of light are observed, consistent with unified models which consider the flow to be oriented close to the line of sight. Perhaps surprisingly, there is no significant difference between the motions seen in quasars, AGN, or BL Lac objects which are thought to have systematically different orientation to the line-of-sight and thus should be subject to different projection effects which describe the motions. Powerful gamma-ray sources appear to have faster motions consistent with the idea that gamma-ray sources are oriented particularly close to the line of sight. Further observations, planned over the next few years will increase the sources sample and extend the time span in order to more accurately determine the velocity of motion and to detect any possible accelerations and decelerations. Particular emphasis will be given to high redshift quasars with the goal in mind of exploring the use of the angular velocity-redshift relation to distinguish among world models.

The early polarization VLBI results for active galactic nuclei indicated a striking difference in the magnetic field structure of sources identified optically as BL Lacs or quasars. BL Lacs appeared to have jet components with inferred magnetic fields perpendicular to the predominant structural axis of their jets while quasar jet magnetic fields appeared to be parallel to the predominant structural axis, and where measurable, weaker fraction polarization at jet components than in between them. These observations are consistent with models which posit that jet components are the result of longitudinal compressions of the jet fluid (i.e., shocks) and call for the existence of a dominant longitudinal component of magnetic field in quasars alone, perhaps due to the jet interacting with the surrounding material which generates their emission lines, and which distinguish them optically. From this work, it appeared that the magnetic field orientation may be an effective tracer of the jet flow direction (projected onto the plane of the sky). However, with the advent of the VLBA—with its higher sensitivity, better image fidelity, and wider frequency coverage—the picture is considerably more complicated as more of the jet material is detected and resolved. Members of both classes of sources exhibit magnetic field structures previously thought to belong only to the other. Aberration and projection effects are also likely to be important in these sources (the basic phenomena is thought to arise from a relativistic jet oriented nearly along our line of sight) since the jets of the presumed (non-aligned) parent populations of quasars and BL Lacs are commonly observed to bend. It is therefore appropriate to examine in detail the magnetic field structure of a sample of sources thought to be among those with jets likely to be most closely aligned with our line of sight—the EGRET "blazars." The goal is to determine at what level the geometrical effects (as well as radiative transfer and Faraday effects) may be distinguished from the intrinsic structure.

Therefore, a program of observations is currently underway to map and trace the evolution of the magnetic field structure of a small sample of EGRET blazars at a wide range of frequencies with multi-epoch VLBA observations, both alone at higher frequencies (8, 15, 22, 43 GHz) and with the Japanese orbiting VLBI antenna, HALCA, as an array element at lower frequencies (1.6, 5 GHz). Initial results indicate complex longitudinal and transverse structure in both the polarized and total intensity emission. Analysis of additional epochs is underway and is expected to yield effective measurements of the relationships among polarization fraction, inferred magnetic field position angle, spectral index, Faraday depth, and total intensity morphology and evolution. Plans to observe these sources on larger scales (e.g., with the VLA and/or MERLIN) are being developed—it is desirable to trace these properties over the largest range of scale that source spectra and sensitivity allow. Additionally, comparison with observations in other parts of the spectrum (e.g., optical polarization) will be fruitful. Collectively, this research program has implications for studies of physical jet models, line-of-sight and Doppler factor constraints for jet sources, gamma-ray emission mechanisms and their geometrical requirements, the determination of the fundamental intrinsic differences between quasars and BL Lacs, and the place of such sources in the unified classification schemes for active galactic nuclei.

The new 3 mm receivers on the VLBA will be used to study compact emission from gamma-ray emitting blazars. Preliminary results from a survey of all northern hemisphere EGRET sources has shown that peak gamma-ray luminosity is a strong indicator of millimeter-wave brightness temperature. The gamma-ray blazar 2255-282 is being observed by the VLBA at high frequencies at three epochs in order to search for new radio components generated at the time of a millimeter-wave and gamma-ray flare that took place in late 1997. Component evolution in total intensity and polarization will be studied to see if components can be traced back to the outburst, and if the initial speeds following flares are higher than those typically observed a few milliarcseconds from the cores. Such observations can be used to constrain the details of the jet generation by the supermassive black hole powering blazars and other strong radio sources.

VLBA observations of the rotation measure structure of both typical quasars and known high rotation measure sources are continuing in order to understand the nature of the Faraday screen on the parsec scale.

So far the major contributor to the high Faraday rotation measures appears to come from the optical narrow-line region close to the nucleus.

The VSOP Continuum (AGN) Survey is an ongoing 5 GHz VLBI survey of nearly 300 bright and compact extragalactic radio sources using up to three-Earth-diameter baselines using the HALCA satellite in conjunction with large ground-based radio telescopes. Since sensitivity to high brightness temperature improves only with increases in baseline length, this survey will yield a sample of such measurements less constrained by the limit imposed by the size of the Earth and allow an effective study of the role of the inverse Compton limit in the AGN phenomenon. Comparison with ground based VLBA 2 cm images, which have comparable resolution, will better characterize the spectra of relativistic jets leading to an improved understanding of their evolution. Additionally, the future space VLBI missions, such as the Japanese VSOP2 and NASA's ARISE will benefit from these studies.

Near-simultaneous, multi-frequency VLBA observations of the AGN in NGC 1275 (3C 84) and continued observations at 2 cm show a central core which feeds plasma southward to an expanding bubble. Free-free absorption of the counter-feature, which is being imaged with sub-parsec resolution, is evidence of the accretion disk surrounding the central engine. This is the most direct observation so far of the putative accretion disks supposed to power the massive black hole in quasars and AGN. New VLBA observations made with even better angular resolution will better define the nature of the accretion disk on parsec scales and how it may have changed over the past few years. Initial analysis of 22 GHz recombination line observations suggest that the stimulated emission recombination lines from the absorbing gas are not detected. This places interesting constraints on the physical parameters of the absorbing system. VLBA images of the NGC 1275 nucleus core at 7 mm have 150 micro arcsec resolution, and show knots of emission moving at 0.05c, 0.08c, and 0.2c (±0.03c), at increasing distances along the jet, indicative of acceleration within the first parsec. Moreover, progressive flux changes in these slow-moving knots indicate a wave of brightening, moving out at a phase velocity of 0.9 ±0.1c.

Long term VLBI monitoring observations of 3C120, incorporating data over a nearly 20 year span show the ejection of new superluminal somewhat more often than once a year. At least one of these components has been followed, first at 5 GHz, then at 1.7 GHz, from when first seen resolved from the core with 1 mas resolution, to near its current position over 50 mas from the core. There are indications that moving components pass through stationary features—positions of increased or decreased brightness. These observations, like those of 3C 84 and other sources will constrain aspects of the geometry and dynamics of the source with the aim of better understanding the acceleration and collimation of relativistic plasma ejected from the central engine.

In-depth millimeter wavelength VLBA studies of the compact and variable sources NRAO 530 and III Zw 2 show that these observations are probing the region of jet formation. Accelerating features are apparent. Models for the young/confined radio source PKS1413+135 are being developed and will be compared with observations being made with the VLBA and HALCA. VLBA observations of the nearby AGN in the radio galaxy M87 will be used to better define the apparent helical structure of the sub-parsec scale jet and to trace the outflow from sub-parsec scales where the jet moves with a velocity of only 10 percent the speed of light to kiloparsec scales where it becomes close to the speed of light. The VLA will continue to be used at 20 cm to image the M87 halo source. By comparison with existing 4 m images, these observations will allow us to study the radio spectral properties and thus model the age and particle acceleration necessary for this AGN which dominates the energetics of the center of the Virgo cluster.

Radio afterglow studies of gamma-ray bursts have proven important in determining the physical parameters of the explosion (energy, density, etc). Furthermore, because of the long-live nature of the radio afterglow they are a powerful probe of the external environment into which the explosion occurs (constant density vs. circumstellar wind) and are very sensitive to the geometry (jet-like vs. sphere) of the explosion. Since radio photons propagate unaffected by dust absorption, they have also allowed for the detection of radio afterglows in dusty, gas-rich environments where the optical afterglows are dim or absent entirely. Taken together, the observations at the VLA are providing a strong link between gamma-ray bursts and high redshift supernovae.

The VLA and VLBA will continue to be used to study GRB afterglows. In particular, the launching of SWIFT and other missions will soon significantly boost the rate of radio afterglow detections. The event rate, currently at one per month, is expected to rise at one per week. VLBA observations of a nearby GRB afterglow could yield a direct measurement of the rate of expansion of the fireball and tell us much about the energetics and environment of these explosive events. The VLA, the premier radio facility engaged in this work, will continue its successful program of searching for the radio counterparts of gamma-ray bursts.

3. Normal Galaxies

Now that the optical positions of all UGC galaxies have been measured with better than 2 arcsec accuracy, the UGC catalog is being cross-identified with far-infrared sources in the IRAS catalogs and with radio sources in the NVSS catalog. About one-quarter of the UGC galaxies were detected at both far-infrared and radio wavelengths. Since the IRAS and NVSS catalogs are comparably sensitive to "normal' galaxies obeying the far-infrared/radio correlation, they can be used to distinguish radio sources powered by stars and stellar remnants from genuine active galactic nuclei. The fainter far-infrared and radio sources will provide the first large sample of low-luminosity galaxies for which the far-infrared/radio correlation slope changes. This may be used to determine whether the breakdown of the correlation at low luminosities indicates cosmic-ray escape or dust heating by older low-mass stars. Samples of low-luminosity AGN will be selected for high-resolution observations with the VLBA. The local radio luminosity function will be extended to very low luminosities. The VLA will be used to look for radio continuum emission from a sample of field E+A galaxies to see if these apparently post-starburst galaxies actually have dust-obscured, ongoing star-formation as is found in $z = 0.4$ clusters.

The structure, kinematics, and evolution of normal galaxies as probed by their gas content remains an important research topic. The VLA will be used to map the HI content of spiral galaxies in the context of cluster formation and evolution. It is anticipated that this study will be extended to $z = 0.2$ using the VLA. The 12 Meter millimeter telescope will be used to investigate the CO Tully-Fisher relation with a sample of galaxies in the Perseus-Pisces ridge. This will serve as a $z = 0$ calibration for future ALMA CO Tully Fisher-studies at high redshifts. On-The-Fly mapping technique at the 12 Meter will be employed to map the CO distribution in Ursa Major spirals. HI column density maps and CO distributions and kinematics will then be compared in detail as a function of the interstellar radiation field. Other VLA observations will be used to measure neutral hydrogen absorption against radio galaxies.

To promote a better understanding of star formation and galaxy evolution from the perspective of nearby galaxies HI data for a major subset of BIMA observations will be compiled, both from the VLA archive as well as from new observations, in order to pursue a comparison of CO and HI distributions in nearby galaxies. The observations will include an examination of the radial distribution of molecular gas in nearby galaxies and an analysis of variations in the conversion factor between CO emission and molecular hydrogen column density.

An HI 21-cm line survey of 475 'flat' spiral galaxies was completed using the Nancay Radio Telescope and the 140 Foot Telescope. The targets were late-type, edge-on spiral galaxies with large disk axial ratios (a/b>7), moderate-to-low optical surface brightness, and no published redshifts. A detection rate of over 50 percent was obtained within the search range of 9500 km/s, demonstrating that gas-rich, 'pure disk' galaxies are among the most common star-forming galaxies in the nearby universe. A new program for measuring redshifts and HI line widths has been initiated at Arecibo and will be continued on the GBT when it becomes operational.

Follow-up optical imaging of a large subsample of the HI-detected flat galaxies was obtained using the WIYN telescope at Kitt Peak National Observatory. Spiral galaxies with the dynamically coldest disks are predominantly low-mass galaxies with rotational velocities of 200-250 km/s, low optical surface brightness and high neutral gas fractions, indicating they are a population of "under-evolved" galaxies. Vertical structural analysis of several of the galaxies also reveal examples of the smallest vertical disk scale heights ever measured (140-200 pc). It appears that massive dark matter halos are required for stabilization of these systems over a Hubble time.

VLA observations of the neutral hydrogen in face-on spiral galaxies will be used to measure the velocity dispersion and detailed line profile shapes over their entire optical disks, and beyond. Preliminary results for one galaxy are rather puzzling; the gas appears to be less turbulent in regions of current star formation (e.g. spiral arms) away from the Galaxy Center, while the line shape can be modeled as the sum of two Gaussians with constant width/intensity ratios, despite a wide range in total linewidths.

Previous VLA HI observations of Blue Compact Dwarf galaxies (BCDs) have shown that the gas is rotationally dominated, suggesting that there is no evolutionary link between BCDs and dwarf ellipticals, which have very little rotation. New VLA work on low-luminosity BCDs shows that the gas kinematics of a few is not characterized by rotation. The gas in these systems is being severely affected by strong bursts of star formation, and it may eventually be expelled from the system. This suggests that some BCDs may indeed evolve into dwarf ellipticals.

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 study of kinematics in flocculent galaxies will be pursued in HI and CO, and will also utilize optical and near-infrared data from the Ohio State Galaxy Survey. An analysis of the properties of star-forming regions using ISO Short Wavelength Spectrometer data will continue. Observations of various tracers of the interstellar medium—far infrared emission from dust, neutral hydrogen and molecular (CO) line studies—will be used to investigate the origin and role of the ISM in elliptical and S0 galaxies, and particularly to test models of dust distribution and heating.

An analysis of the low-luminosity compact star cluster nuclei of four nearby, low surface brightness Sd-Sdm spirals (NGC 4395, M33, NGC 4242, ESO 359-029) was undertaken using data from HST. The circumnuclear environments in all cases are quite diffuse and devoid of significant dust, and none of the galaxies possess a significant bulge component. All four nuclei were partially resolved and found to be extremely compact, and more structurally complex than normal star clusters. NGC 4395 is the lowest luminosity Seyfert 1 galaxy known, yet its nucleus shows a distinct bipolar pattern and ionization cones analogous to those of other Seyferts. The M33 nucleus exhibits complex structure, including elongated isophotes and an optical jet-like component. The NGC 4242 nucleus shows evidence of a bar-shaped feature at its center, while the ESO359-029 nucleus is relatively featureless at the resolution limit of the data. The origin of compact nuclei in galaxies with shallow central gravitational potentials remains enigmatic

Optical spectra are being used to separate ages and metallicity effects in ellipticals, bulges, and Baade's window. The stellar component of spiral disks and the dynamical effects of bars will be studied along modeling the radial distribution of Fe and alpha elements in disks and bars using narrow-band images. The dynamics of the Large Magellanic Cloud is being studied using its carbon stars with emphasis on a dynamical study based on observations of ~600 carbon stars over the central 3 kpc of the LMC.

The 12 Meter Radio Telescope is being used to detect CO 1-0 emission from a sample of 13 edge-on, low surface brightness (LSB) Sd spirals from at least one-third of the galaxies, representing the first successful detections of CO emission from LSB spirals. The molecular gas contents of LSB spirals appear to be typically ten times smaller than those of normal spirals with comparable HI contents.

Although much of the observational work on the interaction between galaxies has focused on the violent merger of galaxies of comparable mass, it is likely that most interactions will occur when a dominant galaxy captures one of its dwarf companions. Such interactions have been analyzed in n-body simulations but because the rate of induced star formation is low these objects are not generally notable in the infrared or in H-α, and have therefore not been systematically observed. However, by selecting from a sample of HI profiles observed for isolated spiral galaxies those objects having asymmetries typical of binary systems it is possible to construct a candidate list of galaxy/dwarf interactions seen at different stages of the process. Objects from this list will be mapped in HI and in the radio continuum in order to follow the development of the merger as traced by the gas in the system.

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

The observed properties of the diffuse ionized gas (DIG) in our Galaxy and other galaxies are not easily reconcilable with simple photo-ionization models, which are very successful in HII regions. It appears that an additional heating source is required which depends either linearly on the density or is a constant. The role of turbulence in the DIG will be explored by using a numerical program to study the physical conditions in this important component of the Galaxy. In particular the properties of the DIG will be modeled perpendicular to the plane (z-direction) where interesting results are found for our Galaxy.

Work will continue on trying to understand the source of ionization of the diffuse interstellar medium. By examining diffuse HII regions, whose radio continuum luminosity gives a lower limit to the total ionizing flux from the stellar cluster, and looking for Helium radio recombination lines, which give a limit on the hardness of the radiation, it should be possible to determine whether an HII region is ionization bound, or rather has substantial leakage of ionizing photons into the general interstellar medium. The data have been taken on the 140 Foot and analysis is underway. The 140 Foot has also been used to map over 2400 square degrees of the Galactic Plane in the HI line. The analysis, which involves considerable attention to proper calibration and an extensive correction for stray radiation, should reveal many examples of HI supershells which delineate areas of extensive supernova activity.

VLA L-band observations of more than 300 sources with strong linear polarization in longitude range 355 degree< l< 15 degrees have been made and are being analyzed to better define the the magnetic structure of our Galaxy.

The spatial power spectrum of interstellar HI has been studied by using the VLA to measure the visibility function of emission in the Galactic plane. Substantial modeling of the data is necessary to interpret the observations unambiguously, and this is now underway. The results should extend our knowledge of the spatial power spectrum to significantly smaller scales that previously studied in HI emission.

Centimeter- and millimeter-wavelength interferometers as well as single dishes will be used to study the kinetic temperature and spatial density structure within young stellar and protostellar environments with emphasis on the molecular and dust emission properties within these regions.

HI Absorption towards GRS 1915 was detected to vary over ~5days, as the background ejecta moved at ~24 mas (~250 AU) per day. Observations during future flares will enable such tomography to repeatedly probe the HI structure along varying lines of sight, as Galactic rotation moves the background source by ~5.8 mas/yr.

The study of physical and chemical conditions in small translucent molecular clouds will continue. These involve self-consistent models in which the physical conditions (radial dependence of density, temperature, ionization; external radiation field) have all been derived in terms of hydrostatic equilibrium polytropic models. An extensive study of ion-molecule chemistry in these objects has been completed. The study includes detailed modeling of some 38 species, including a recent study of 13 hydrocarbon species, which constitute the backbone of gas-phase chemistry. Excellent agreement between chemical models and observed abundances has been obtained.

The Heinrich Hertz Telescope will be used to observe CI in translucent clouds. Because the models being used for translucent clouds depend on generalized CO chemistry models, CI provides a crucial test of these models. Dedicated searches with the 12 Meter will be made for two new molecular species, CO^+ in translucent clouds, and SiO^+ in Galactic sources in general. The former is key to understanding the "early" (pre-CO) chemistry. SiO^+ is important in understanding the origin of SiO, which forms by one route if

$[Si^+] > [Si]$ as in diffuse and translucent clouds, and in shocks; and by another route in dark clouds where $[Si] > [Si^+]$.

Analysis is underway of the large spectral band scan at 2 mm (130 to 170 GHz) of eight sources, with unprecedented sensitivity and is available on the web. New catalogs will be key to the identification of the 12700 lines detected in the spectral survey. After all possible identifications have been made, the task will begin to analyze abundances of the many molecular species detected. This will include a merging of the 2 mm survey with the earlier NRAO 3 mm survey. A spectral survey of IRC+10216 from 200–230 GHz is nearing completion.

Using a novel new approach to the observation of the Zeeman effect, a strong upper limit of 20 uG has been obtained in TMC-1 from observations of the C_4H molecule, which occurs in regions of much higher density than any other species. If the field were frozen-in the TMC-1 region where density is $\sim 3\times10^4$ cm^{-3}, the strength would be ~320 uG. The observed upper limit for the first time shows that the field has essentially completely leaked out of the region, and can play little or no role in any future star formation there. Zeeman observations of the CN molecule will be made at 113 GHz with the12 Meter Telescope in bona fide star-forming regions, using the same new technique.

Very sensitive HCO^+ absorption spectra have broad components from the undifferentiated diffuse gas parcels along long, low-latitude lines of sight; we see HCO^+ just as broad as HI! The origin of HCO^+ will be traced at 235 GHz. The HCO^+ is also of interest because it explains the observations of CO in diffuse clouds over more than four orders of magnitude in N(CO), just by "being there."

Water masers trace out very dense gas regions. Toward these low-luminosity sources, they almost always occur in sources with high-velocity molecular outflows. In some scenarios, the masers arise as a flow that impacts quasi-stationary objects, such as planets. Current research has concentrated on proper motion studies of the water masers in a few such objects using the VLBA. In addition, the VLBA will be used to try to determine the strength of the line-of-sight magnetic fields in the immediate stellar/accretion disk vicinity using the by measuring the Zeeman splitting of individual water maser "spots."

The OH and water masers provide the only possible way to obtain kinematic information at high angular resolution. A multi-wavelength program has been begun, using the VLA to image the OH and water masers, and using the HST to image the optical emission. This program has already demonstrated, for two bipolar proto-planetary nebulae, that the spatio-kinematic distribution of OH masers relative to the HST optical structure is consistent with the hypothesis that the optical lobes result from a fast outflow interacting with a slower, denser wind originating from when the star was on the asymptotic giant branch. In the next year, a larger number of sources will be observed, both at the VLA and using the HST, to provide better statistics and to help refine hydrodynamic models of the interaction of the two outflows.

A long-term polarization monitoring project of SiO masers toward evolved stars continues using the 12 Meter Telescope.

Wolf-Rayet stars are occasionally associated with ring nebulosities, some of which are bright enough to appear in catalogues of HII regions. It appears that the ring nebulae result from three different epochs of mass loss—an O-star phase, a luminous supergiant phase, and the W-R phase. The interaction of the wind and the surrounding interstellar medium occurs primarily in the first (O-star) phase. Several attempts have been made to measure the neutral material associated with these outer rings, since knowledge of the mass and dynamics of this material would provide information about the duration and extent of the mass-losing phase of the progenitor O-star. The angular extent of the rings has made molecular line studies difficult, but it is hoped that new observations with an improved on-the-fly mapping system will be able to map the molecular cloud into which the wind is expanding, for two or three of the most favorable cases. The study will begin with the CO (1-0) transition, but if the initial study is successful some observations of a transition characteristic of shocked gas, such as SO or SiO, will be undertaken. The optical observations of the W-R galaxies imply that star formation in these galaxies occurs in brief bursts with an unusually flat initial mass function. The VLA scaled array will be used to test if this is supported by radio spectrum information.

Other studies will concentrate on the earliest and latest stages of stellar evolution including how some dense cores of molecules and dust form multiple stars, and how they are transformed by the stars within them. At the end of their lives, moderately massive stars return material to the interstellar medium. The dissipating cloud of material has, to some approximation, a well understood geometry, making it a good physical and chemical laboratory for understanding interstellar cloud processes.

The coldest cores have been shown to be propitious locales in which to seek the youngest stars. These objects, with spectral energy distributions of 'Class 0', have been targeted in an ammonia survey, which has now obtained VLA maps of ten or so of the dozen known objects. Curiously, these objects tend to occur gregariously, with several cases of multiple objects within a single core known. In these maps, differences among the objects become quite apparent. In objects so young that no bipolar flow has commenced, such as IRAS16293B or NGC1333IRAS4C, ammonia structures are readily discerned. In another group of objects, including L483, IRAS16293A, NGC1333IRAS4B and VLA1623-2418, very cold ammonia exists, but shows only subtle correlation with cold dust structures enveloping the star. Work is finishing on a high resolution ammonia study of HH212, a source in which has mapped water maser proper motions over two week time scales in the inner few AU of the system. VLA ammonia maps revealed a rotating disk whose surfaces are concave upward, suggesting its role in directing the bipolar flow. In turn, the flow apparently excavates the surface of the disk, resulting in its concave appearance. A study of the Ophiuchus 'A' molecular core, shows four dense clumps which have formed a single star, but other clumps may be in the earliest formative stages of star production. The protostar VLA1623 will be shown to be an example of star formation induced in the core by expansion centered on HD147889, a nearby O star. In other objects warm ammonia correlates well with the dust emission, and may show up in outflowing gas as well. It appears that ammonia becomes severely depleted, perhaps through freezing onto grains, in the final stages before stellar ignition.

Water maser monitoring in low mass stars, a continuing project on the 43 m telescope and the VLA, has revealed some interesting parameterizations of low mass stellar masers. Even on several AU scales, the velocity shifts associated with the bipolar flows are evident. How, then, does the maser emission arise? One possibility is that it arises at the working surface of the bipolar jet on the ambient molecular cloud; another holds that it occurs where material entrained in or along the jet interacts with the surface of a protoplanetary disk. VLBA observations with a fine timescale map the proper motions of the masers, and therefore explore the kinematics of outflow gas. These studies are being expanded to include the masers near SVS13 and near IRAS4 in the NGC 1333 complex. Early results suggest a ring-like structure, possible associated with a disk, in the former object. VLA and VLBA observations are determining the proper motion of masers near the massive young stars S106FIR and IRAS20050 and an interesting microjet feature, with a dynamic age of only two years, associated with a bow shock measuring only 3 AU in extent. A search for a CO counterpart of this flow in high-J lines at the CSO suggests that the flow is too young to be measured in the CO lines

1.3 mm BIMA observations of the innermost region of S68N, are being used to follow up an earlier SCUBA study of this extremely young protostar. Interestingly, a density profile derived from the SCUBA maps succeeds very well in reproducing the H_2CO spectrum observed toward the envelope of this protostar; the BIMA maps extend the investigation into the inner region where the star is actually formed. In a similar investigation the L483 protostar, again, the collapse model deduced from the ammonia observations predicted the azimuthally averaged run of flux density very well. These observations probe the ionization fraction in the dense cores of the S68N, L483, and other clouds. Previous studies have determined that the low ionization fraction in their envelopes does not impede collapse. Emphasis is on higher excitation transitions observed at the CSO to investigate the ionization fraction within the denser portions of the cores. The BIMA images refer to lower-lying transitions at good resolution for comparison to the higher resolution CSO observations.

Infall appears to be a characteristic phenomenon among the youngest 'Class 0' objects. The parameters of infalling gas have been studied in HCO^+ lines in an assortment of lines. A comprehensive set of formaldehyde data is being assembled to test whether these models of infall are sensitive to the choice of molecular data used to derive them, as may be the case if complex chemistries operate in near-protostellar regions. Many objects have been modeled successfully, revealing the detailed structure of young stellar envelopes. Millimeter wave interferometry has, as yet, no temperature/density diagnostics similar to the ammonia lines available to the centimeter interferometry. Partly, this is because sources tend to be more highly resolved at the higher frequencies. A new program will try to develop H_2CO as a tool for diagnosing temperature and density in the millimeter region, by including zero spacing data with interferometer maps.

5. The Galactic Center, Pulsars, Novae, Supernovae, X-ray Binaries, and other Radio Stars

Investigations of the compact, non-thermal radio source in the Galactic Center Sagittarius A* will be made in a variety of modes and with a variety of instruments. The recent discovery of circular polarization coupled with low levels of linear polarization presents a significant new parameter space. The VLA will be used to study the high frequency spectrum of circular polarization. The ATCA will be used to continue study of the cm wavelength variability and spectrum of Sgr A*. Knowledge of the spectrum and the degree of variability will determine whether the origin of the circular polarization is intrinsic or extrinsic to the source. BIMA array polarization observations at 86 GHz and 230 GHz will also be made to test the proposition that the linear polarization from Sgr A* is destroyed by an intervening thermal plasma. These observations will also be coupled with monitoring of the variability of Sgr A* from centimeter to submillimeter wavelengths. The highest frequency observations will be made with the JCMT SCUBA instrument. 3 mm VLBI observations of Sgr A* will show convincingly whether or not Sgr A* is fully obscured by interstellar scattering.

VLBA observations of background sources used in an earlier VLA proper motion study will probe the scattering region and test for small positional offsets in frequency in the position of Sgr A*. VLBA observations of interstellar hydroxyl and methanol masers in the Galactic Center region will be studied for the effects of scattering. These observations of co-spatial emission will test the expected wavelength-squared dependence of scattering and the spatial range of scattering in the Galactic Center.

VLBI observations of SN 1993J in M81 will continue to trace the morphological evolution and deceleration of the radio remnant, with emphasis on confronting models for the radio/X-ray light curves with the observed source structure. The long-term program of monitoring Cas A flux density between 30 and 120 MHz with the small interferometer at Green Bank will continue.

VLBA and VLA observations are planned for a number of the radio sources associated with X-ray transients, including monitoring of approximately ten of the known sources and target-of-opportunity VLBA observations of several Galactic jet sources. Combined with X-ray data these observations directly measure the relation between mass accretion and relativistic jet ejection. Radio images, in addition, directly determine the speed and morphology of the ejecta, and indicate the direction and rough strength of the associated magnetic fields.

VLA, MERLIN, and VLBA observations of SS433 will be combined to yield the first images sensitive to the full range of structures in this source; preliminary reductions show a low surface brightness 'halo' of emission around the core, and indicate that we should be able to measure velocities on scales from a few to some hundreds of milliarcseconds.

CI Cam, the only X-ray transient known to have ejected a sub-relativistic synchrotron shell, continues to surprise, with an apparent deceleration of the ejecta a year after the event; further MERLIN and VLBA observations are planned.

Polarization observations of the individual pulses from pulsars often indicate that their radio emission preferentially occurs at two polarization position angles separated by 90 degrees. The emission at each position angle also seems to prefer a particular sense of circular polarization, indicating that the emission modes are orthogonally and elliptically polarized. A statistical model for the orthogonal modes of pulsar polarization is based on the simple assumptions that the individual modes are superposed and completely polarized. The model adequately describes the observed fluctuations in the polarization properties of the radio emission. To justify the validity of the model's underlying assumptions, polarization data recorded with the Arecibo radio telescope will be used to rigorously test the model for statistical consistency. Additionally, the temporal and spatial scales over which the modes are superposed can be measured with an autocorrelation analysis of the polarization data and may indicate how the modes are actually generated. The fractional linear polarization of pulsar radio emission decreases with increasing radio frequency. Although a number of depolarization mechanisms have been proposed, it is generally believed that the emission depolarizes via the increased occurrence of orthogonal modes at high radio frequency. However, no quantitative evidence has been published to support this belief. High-quality data will be used to quantitatively show that pulsar rates of depolarization are anticorrelated with the relative frequency of occurrence of the orthogonal modes, thereby demonstrating that pulsars depolarize via the orthogonal modes.

Combined VLA, UKIRT, and RXTE observations of the AU-sized jet in the micro-quasar GRS1915+105. show: (a) the disappearance of thermal X-rays from the accretion disk, due to a disk instability, and/or the advection of the disk onto the black hole; and (b) the simultaneous ejection of relativistic electrons, as traced by the hardening of the X-ray spectrum, and synchrotron emission in the radio and IR bands. VLBA images during such activity revealed a synchrotron jet of size 1-10 AU, pulsing with

~30 min period, in response to the injection of plasma from the disk instability. VLBA astrometry shows a motion of about 5.8 mas/yr, primarily in the galactic plane due to secular parallax, in agreement with the HI distance of 11 kpc. Target-of-Opportunity observations will continue, to refine the astrometry, and clarify the co-evolution of the accretion disk and the AU-scale jet. A multi-wavelength search for new micro-quasars has been initiated on the VLA, RXTE, & UKIRT, with VLBA follow-up. VLBA monitoring of WR140 as the binary approaches periastron will determine the morphology of the wind-shock emission region between the stars. Follow-up observations using IR speckle-masking at Keck are planned.

Multiwavelength observations and modeling of events in X-ray and transients will be a main focus of research in the upcoming year. On the observational side this involves weekly monitoring of recurring transients using the VLA, searching for radio counterparts of new X-ray transients with the VLA, follow-up imaging of transient events with the VLA and the VLBA, and continued participation in observations with the Green Bank Interferometer of X-ray binaries to understand the dynamics of mass exchange and accretion. A major part of this effort will be using models of conical jets and expanding tori of relativistic plasma to predict and fit light curves and images from transient events. Studies of the appearance of relativistically moving source models will have applications to extra-galactic as well as galactic sources. The analysis and modeling of radio and other data from nova shell ejecta will be continued and there will be a new effort to make detailed HST, VLA, and possibly VLBA images of nova shells as part of an international effort to study the nova phenomena.

A representative sample of the 58 brightest (S > 2.5 mJy at 1.4 GHz) radio stars north of -40 deg declinations was extracted from the NVSS catalog. Follow-up 1.4 and 8.4 GHz VLA observations measured their instantaneous radio spectral indices, and optical spectroscopic observations using the 2.16 m optical telescope of Beijing Astronomical Observatory are being used to classify the new radio stars. These data will be analyzed to yield an unbiased picture of radio emission from stars in our Galaxy. The OVLBI 45 foot telescope will continue to monitor the galactic plane at 8.35 and 14.35 GHz, searching for transient radio sources

6. The Solar System and other Planetary Systems

The VLA remains an important instrument for solar radio observations with high spatial and time resolution. Solar research on the VLA is directed primarily toward understanding flares on the Sun and stars, and scattering of radio waves in the solar wind. The new 74 MHz receivers on the VLA will be exploited to search for coronal mass ejections from the Sun. Given the geomagnetic impact of this energetic phenomenon, interest in coronal mass ejections and related phenomena is keen in the solar and "space weather" communities. In collaboration with other solar astronomers, concepts are being developed for the construction of a Frequency Agile Solar Radiotelescope (FASR) to study transient solar phenomena with high spectral resolution and broad frequency coverage.

With the recent visit of comets Hyakutake and Hale-Bopp, interest in the molecular spectral line emission from comets has increased dramatically. A number of studies of Comet Hale-Bopp utilized the efficient 12 Meter system. The analysis of images of the HCN, CO, H_2CO, HCO^+, and CH_3OH emission obtained in these investigations will continue and will lead to a better understanding of the kinetic temperature evolution of this remarkable visitor.

7. Geophysics

NRAO scientists participate in regularly scheduled geodetic/astrometric VLBI observations including a series of global observations, involving up to 20 antennas total, that occur six times per year. These observations are used to explore improvements in geodetic VLBI technique, to place the VLBA antennas in the International Terrestrial Reference Frame, to maintain and extend the International Celestial Reference Frame (ICRF), to provide the highest accuracy Earth Orientation Parameters (EOP) available, and to provide calibrator positions for VLBA phase referencing observations. The geodetic results of these observations are of interest to geophysicists studying motions of the Earth's crust, including, but not limited to, those due to the motions of the techtonic plates. The EOP results provide information on the structure of the interior of the Earth and on the distribution of the global momentum budget. This is the only technique for measuring Earth Orientation Parameters which refers, to a reasonable approximation, to an inertial reference frame - the distant quasars. The International Celestial Reference Frame is the fundamental reference frame used in astronomy because VLBI provides the most accurate absolute positions available, with errors of well under a milliarcsecond for most sources.

Phase referencing allows the VLBA to observe sub-milliJansky sources and is being used in nearly half of all VLBA projects. It depends on good interferometer models, accurate station and calibrator positions, and good EOP. These all are all obtained from the geodetic VLBI observations.

8. Instrumentation

In preparation for future observing programs and to help define the parameters of planned new radio telescopes members of the NRAO scientific staff are actively investigating the appearance of the deep centimeter/millimeter/submillimeter sky as will be viewed by the Atacama Large Millimeter Array, by the Green Bank Telescope, the expanded VLA, and the Square Kilometer Array. These simulations predict the appearance of the high-redshift sky in deep surveys, akin to the Hubble Deep Field. The ALMA simulation demonstrates the power of submillimeter wave continuum observations towards locating high-redshift ($z > 4$) galaxies, with, at least, several thousand galaxies detected in reasonable integration times. The VLA simulations demonstrate how the expanded VLA will be able to image large volumes of the nearby universe, providing a statistical view of nearby galaxies not biased, for example, by active star-formation. The proposed survey also holds the promise of discovering new, optically faint galaxies. An adopted luminosity function is used to describe the galaxy population, including an evolution term to account for brightening of galaxies during the past. The projected density of submillimeter (350 GHz) galaxies approximates that seen by the HST, even with relatively short (two hour) ALMA integrations. Since ALMA and the expanded VLA will always operate in a spectral line mode, they will be sensitive line as well as to continuum emission. Estimates suggest that at least one spectral line will fall within a 16 GHz ALMA bandpass at a detectable flux for roughly one third of the galaxies measured in the continuum. In this way, the ALMA field provides redshifts, hence the third dimension of distance, a dimension lacking in the HST survey. Although the collecting area of the Green Bank Telescope is huge, fluxes fall rapidly toward millimeter wavelengths. Nonetheless, we calculate that the GBT equipped with a 3 mm bolometer camera such as BOLOCAM should be equivalent in distant galaxy detection rate to the SCUBA/JCMT combination. These studies will continue during the coming year.

NRAO staff are also active in other aspects of the planning for a next generation radio telescope, known as the Square Kilometer Array and in discussions for LOFAR, a major new low frequency array to be built jointly, probably in New Mexico, by the Naval Research Laboratory and the Netherlands Foundation for Research In Astronomy. SKA activities at NRAO include interference suppression, the design of large correlators, configuration studies, and in formulating the scientific rationale.

Considerable effort is directed at preparing the GBT software for commissioning and initial observations. A program to set up a pointing reference system has been started and will be continued to construct complete calibrator lists at different wavelengths for the GBT starting with the NVSS and GB 6 cm survey. Submillimeter observations with the SCUBA array of an interesting evolved star with a fossil circumstellar envelope are planned to gain experience with the goal of exploring the potential for installing a bolometric imaging instrument on the GBT. Research continues on developing an efficient practical array feed which will greatly enhance the power of the GBT. The full-sampling focal plane array prototype receiver will be tested and investigation of amplifier cooling and economic beam-forming networks will begin.

Research on RFI canceling techniques will continue. Sources of man-made interference continues to proliferate—especially in space—and threatens the long term health of radio astronomy. While NRAO staff continue to be active in national and international forums to control the spread of interfering transmitters, an active program to excise interfering signals from our radio telescope is equally important. A variety of RFI and DSP techniques are being explored with promising early results.

The ALMA configuration work will reach an important point in its development when it undergoes the preliminary design review next spring. The important tasks to be conducted in the immediate future include the optimization of the preliminary designs for minimizing construction and operation costs, a site survey for pad positions, and soil analysis. The adoption of 183 GHz water line radiometer for the project is already made, but continued evaluation and testing of the existing radiometer systems need to be followed closely. The phase correction software development at CalTech also requires a close attention and active involvement in testing. An important, yet under-addressed, issue in the ALMA project is the mosaic imaging capability and its possible limitations, such as the total power requirement. Related imaging and calibration issues will receive significant attention in the coming year with the support of AIPS++ group.

The engineering staff continues work on the development of ALMA cryogenics, local oscillators, and signal processing. Work will continue on the development of a broadband fully-integrated (MMIC) SIS mixer for the 600-720 GHz band. This design will use the superconducting capacitively-loaded coplanar waveguide (CLCPW) as the transmission line medium and the Twin-Junction tuning circuit to tune out the junction capacitance. 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 If successful, this design will be used later as a building block in the more complicated balanced, sideband-separating submillimeter SIS mixer for ALMA.

At the VLA, the effort to improve the pointing performance and the overall sensitivity for the high frequency bands will continue. The testing and the verification of the performance of the upgraded encoder system is an important step in reaching the stated goal of 6 arcsec pointing accuracy for all VLA antennas. The Jodrell Bank-VLA Astrometric Survey will be extended to negative declinations and to low Galactic latitudes.

The 3 mm receivers currently placed on four VLBA antennas will be rebuilt by the end of 1999. Construction of five more complete receivers, with funding from MPIfR, will occur over the next two years. Significant effort will be devoted to user support, and the development and testing of improvements in antenna metrology, aperture efficiency, data recording rate, pointing, and calibration.

An automated system for monitoring the hardware of the VLA phase monitor and more secure methods of graphical data examination are being implemented. Data quality checks for the VLBA and AIPS development are ongoing. A simplified set of data reduction procedures for VLBI users is under construction. An AIPS-based pipeline, VLBACAL has been prepared to aid in the reduction of VLBA radio continuum data. The goal is to make VLBACAL easy-to-use in order to encourage astronomers who are new to VLBI techniques. To this end, there are only a limited number of adjustable parameters in the pipeline, but there remains enough flexibility to account for special cases. The only interactivity with the pipeline, once it is running, is during an optional data editing phase. The end-product of the pipeline are frequency-averaged, time-averaged, and gain-calibrated data sets. Since one of the main advantages of the VLBA is its ability to phase-reference and therefore observe fainter sources, VLBACAL was written especially to accommodate phase-referenced observations. Specifically for phase-referenced observations, VLBACAL also produces a multi-source database comprising the reduced phase calibrator and target source data; this database is suited for further self-calibration of the phase-reference and target sources. VLBACAL is distributed over the Internet.

The reliable reconstruction of low surface brightness structure requires accurate deconvolution of the typically more compact bright structure. 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. An adaptive uv data weighting scheme (and its impact on self-calibration) is under study.

The HALCA Continuum Survey suffers from fringe detection difficulties owing to HALCA's low sensitivity and the large uncertainties in reconstructing the interferometric geometry of the orbiter. This forces fringe searches over a large range of plausible orbiter geometries with an attending higher probability of false detections. Existing astronomical fringe searching software (e.g. in AIPS), being optimized for imaging work, is not well-matched to this detection problem. Thus, more effective fringe searching algorithms, including incoherent averaging, are under study as a means of deepening the survey.

Other software developments include an innovative port of a MS-DOS(c) sky-viewing and ephemeris program which has been prepared for the Palm Pilot where it will be known as Astrid. The parallelization of wide field imaging routines, and the development of algorithms to correct for positional dependent phase and gain errors, including the effect of non isoplanatism and effect of strong sources in sidelobes continues to receive attention.

APPENDIX B - SCIENTIFIC STAFF

Research Interests and Current Functional Activities

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

T. S. Bastian - Solar/stellar radio physics, interferometry, image deconvolution and reconstruction; on leave to the Observatoire de Meudon.

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 - Polarization of extragalactic radio sources, planetary nebulae, supernova remnants; Head of GB Telescope Services.

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

A. H. Bridle - Extragalactic radio sources; Chair - Observatory Computing Council.

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

B. J. Butler - Planetary astronomy at radio wavelengths; MMA Project scientific support.

C. Carilli - Radio galaxies, QSO absorption lines, magnetic fields in galaxies, and tropospheric phase effects; VLA scientific support.

C. Chandler - Star formation, protostars, and circumstellar matter; VLA scientific support.

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

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

M. J. Claussen - Masers, HII regions, molecular spectroscopy, spectropolarimetry, and radio recombination lines; scientific support for NASA space VLBI.

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; Assistant Director - AIPS++.

W. D. Cotton - Extragalactic radio sources, interferometry, computational techniques for data analysis; on leave to Leiden Observatory.

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

K. M. Desai - Space VLBI and development of VLBI imaging algorithms; AIPS Group.

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; Assistant Director - Tucson Operations.

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

C. Flatters - VLBI polarization studies of extragalactic radio sources; AIPS++ Group.

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; 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 - Interacting galaxies, extragalactic radio sources, and interferometry; USNO scientific support.

B. E. Glendenning - Starburst galaxies and scientific visualization; Head - MMA Computing.

M. A. Gordon - CO, galactic structure, gas-rich galaxies, and interstellar medium; Site Development - MMA Project.

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.

R. M. Hjellming - Radio stars, radio and X-ray observations of X-ray binaries, and interstellar medium; GBI and AIPS++ scientific support.

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

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 AD - AIPS++ Group.

A. R. Kerr - Millimeter-wave instrument development; SIS design - MMA 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; NASA 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 HII 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; Deputy AD - Tucson Operations (12 Meter).

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

M. M. McKinnon - Pulsar astrophysics, polarimetry, and stochastic processes; Deputy AD for Green Bank Operations.

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

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

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

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

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

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 - MMA Project.

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

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

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

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

D. S. Shepherd - Star formation, molecular clouds, and outflow sources; VLA scientific support.

R. S. Simon - Theory of interferometry, computational imaging, and VLBI; Scheduling - MMA Project.

R. A. Sramek - Normal galaxies, quasars, supernovae, and aperture synthesis techniques; Deputy AD for Socorro Operations.

G. A. Taylor - Active galactic nuclei, Faraday rotation measures, HI absorption, and gamma-ray bursters; VLBA scientific support.

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

J. Ulvestad - Seyfert and starburst galaxies, blazars, and space VLBI; Head - Socorro Scientific Services.

J. M. Uson - Clusters of galaxies and cosmology; on leave to U. Zaragoza.

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, and 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; MMA Project Scientist.

J. M. Wrobel - Normal galaxies, active galaxies, and polarimetry; Head - Socorro Array Operations.

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

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

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

APPENDIX C - NRAO COMMITTEES

1. AUI Visiting Committee

The Visiting Committee is appointed by the AUI Board of Trustees and formally reports to the AUI Board on an annual basis. Its function is to review the performance of the Observatory and to advise the Trustees on how well it is carrying out its function as a national center, the quality of the scientific work, and the adequacy of its instrumentation and facilities. Current membership is:

Thomas Bania	Boston University	Term Expires 2000
Donald B. Campbell	Cornell University	Term Expires 1999
Robert J. Hanisch	Space Telescope Science Institute	Term Expires 1999
Karl M. Menten	Max-Planck Institut fur Radioastronomie	Term Expires 2002
Joseph S. Miller	University of California, Lick Observatory	Term Expires 2002
R. Bruce Partridge	Haverford College	Term Expires 2001
Jean F. Turner	University of California	Term Expires 2001
Stuart N. Vogel	University of Maryland	Term Expires 2002

2. NRAO Program Advisory Committee

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. Membership is currently being organized.

3. NRAO Users Committee

The Users Committee is made up of uses 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 (development of radiometers and auxiliary instrumentation; operation of the telescopes; the computer and other support facilities; and major new instruments). This committee, appointed by the Director, meets annually in May or June. Current membership is:

Z. Arzoumanian	Cornell University
S. B. Charnley	NASA/Ames Research Center
R. T. Clancy	University of Colorado
I. de Pater	University of California, Berkeley
C. G. De Pree	Agnes Scott College
M. Elvis	Center for Astrophysics
A. L. Fey	U.S. Naval Observatory
J. Glenn	California Institute of Technology
L. J. Greenhill	Center for Astrophysics
C. E. Heiles	University of California, Berkeley

P. T. P. Ho	Smithsonian Astrophysical Observatory
J. D. Kenney	Yale University
E. A. Lada	University of Florida
S. T. Myers	University of Pennsylvania
D. J. Nice	Princeton University
C. P. O'Dea	Space Telescope Science Institute
P. Palmer	University of Chicago
R. T. Rood	University of Virginia
E. Skillman	University of Minnesota
T. H. Troland	University Kentucky
S. M. White	University of Maryland
C. Wilson	McMaster University

4. Millimeter Array Advisory Committee

The NRAO Director is aided in the planning process for the Millimeter Array (MMA) by the MMA Advisory Committee. Members of the Committee are experienced in the design of millimeter instruments and facilities. At the annual meeting held in the fall of the year, the Committee is asked to review and comment on the technical direction of the MMA project. Current membership is:

J. H. Bieging	Steward Observatory
G. Blake	California Institute of Technology
J. Carlstrom	University of Chicago
E. B. Churchwell	University of Wisconsin
N. Erickson	University of Massachusetts
N. J. Evans	University of Texas
M. Gurwell	Center for Astrophysics
R. Hills	Cavendish Laboratory
G. Knapp	Princeton University
S. Myers	University of Pennsylvania
L. Rodriguez	Institute de Astronomia UNAM
L. Rudnick	University of Minnesota
P. Schloerb	University of Massachusetts
J. Turner	University of California
E. van Dishoeck	University of Leiden
E. Wilcots	University of Wisconsin

5. AIPS++ Scientific Advisory Committee

The committee advises the AIPS++ Project Manager regarding scientific applications and functionality of the AIPS++ software system. The committee is appointed by the Project Manager with the concurrence of the AIPS++ Consortium Executive Committee. Current membership is:

R. Braun	Netherlands Foundation for Research in Astronomy
J. Chengalur	National Center for Radio Astronomy, India
D. Gannon	Indiana University
W. Jaffe	University of Leiden, the Netherlands
L. Mundy	University of Maryland
R. Sault	Australia Telescope National Facility
L. Stavely-Smith	Australia Telescope National Facility
D. Shone	Nuffield Radio Astronomy Laboratory
D. Tody	National Optical Astronomy Observatory
H. van Langevelde	Joint Institute for VLBI in Europe, The Netherlands
A. Willis	Dominion Radio Astrophysical Observatory
A. Wootten	National Radio Astronomy Observatory