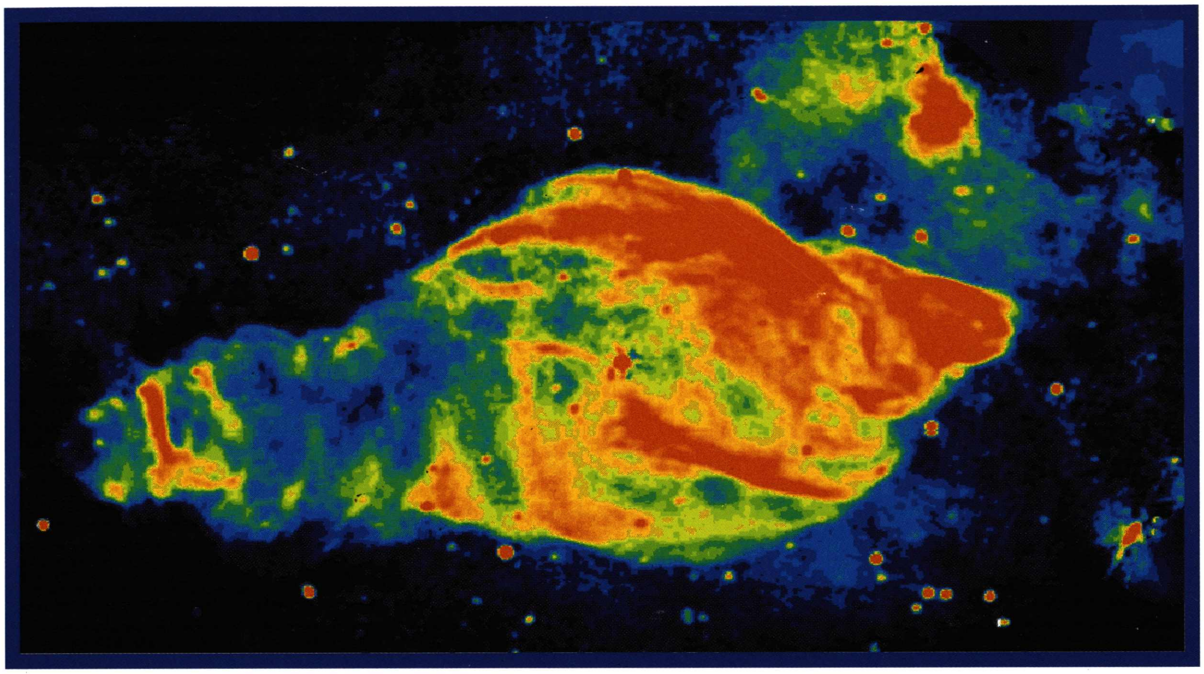

PROGRAM PLAN 1998

NATIONAL RADIO ASTRONOMY OBSERVATORY

Cover: Radio image of the supernova remnant W50. The image was made with the Very Large Array at 1.4 GHz from a mosaic of 58 individual images. The regions of most intense radio emission are shown in red while regions of lower brightness are colored blue. The W50 remnant is powered by the dying star SS433 seen near the center; helical filaments of radio emission can be seen emanating from SS433. Observers: G. Dubner, F. Mirabel, M. Holdaway, M. Goss

NATIONAL RADIO ASTRONOMY OBSERVATORY

CALENDAR YEAR 1998

PROGRAM PLAN

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I. INTRODUCTION

The NRAO and the U.S. astronomical community are very pleased with the FY1998 start of the Millimeter Array (MMA), the final element in the suite of national radio astronomical research facilities appropriate for the needs of students and scholars in the twenty-first century. The Millimeter Array will complete the replacement by NSF of all the original NRAO 1960s-era telescopes. Sometime in the next decade the MMA will join the Very Large Array (VLA), the Very Long Baseline Array (VLBA), and the Green Bank Telescope (GBT) as a complete suite of research instruments that together will enable scientific investigations to be conducted from frequencies of less than 100 MHz to frequencies approaching 1000 GHz. Over this entire span in frequency of a factor of ten-thousand—the full range of radio frequencies for which the Earth's atmosphere and ionosphere are transparent—precision astronomical imaging will be available at a resolution comparable to that of the Hubble Space Telescope. This achievement has been long awaited and is eagerly anticipated. Nineteen hundred and ninety-eight is truly a watershed year for U.S. radio astronomy.

The radio astronomical technique of Very Long Baseline Interferometry (VLBI) will provide still another incremental advance in astronomical imaging resolution by combining the VLBA ground telescopes with the antenna on the Japanese HALCA spacecraft. In FY98 this combination of instruments will lead to resolutions of less than 100 micro-arcseconds at microwave frequencies. As a ground-based complement to this ground-space capability, the NRAO FY98 Instrumentation Plan anticipates a continuation of the program to equip the VLBA with 90 GHz receivers that will also give resolution measured in tens of micro-arcseconds. By nearly a factor of 100, this is the best imaging resolution achievable in astronomy, in any waveband, by any instrument, anywhere.

The Green Bank Telescope will approach completion within the period covered by this Program Plan. Once the Contractor finishes with fabrication of the antenna itself, the NRAO staff will begin to equip it with the NRAO-built receiving systems and with the laser metrology system that will allow the primary surface to maintain its desired parabolic figure even in the presence of the deforming forces of gravity and differential solar heating across the structure.

Finally, in 1998 work will begin to establish a real-time connection between the VLA and the VLBA antenna located nearest the VLA. That VLBA antenna is at Pie Town, New Mexico, 40 km distant from the VLA. An optical fiber connection between the two will improve the VLA resolution by a factor of two at all frequencies and it will permit astronomers to make still more detailed images of those objects of special astrophysical importance.

The emphasis in 1998 for the NRAO includes all the above major instrumental developments that will enhance the scientific opportunities of those using the NRAO in the future. In Section II of the Program Plan we outline the specific scientific plans of those using the Observatory in 1998. The telescopes themselves are described in Section III followed by a description of planned activities in electronics and computing development in Section IV. The section following presents progress on the Green Bank Telescope. Planning for the design and prototyping phase of the Millimeter Array, a major upgrade of the VLA, and work on the

AIPS++ Project are given in Section VI. Section VII describes the scope of research at the NRAO that is done on behalf of, and supported by, agencies other than the NSF. The next section is an overview of educational activities at the Observatory. Finally, the preliminary financial plan for the NRAO in 1998 designed to support all the NSF research activities is given in Section IX.

II. 1998 SCIENTIFIC PROGRAM

1. The Very Large Array

The VLA will continue to serve the whole astronomical community. More than 250 proposals involving more than 600 users were scheduled in 1997 and a similar number is expected for 1998. The VLA will observe a broad variety of astronomical objects ranging from the Sun and other objects in the Solar System to the most distant objects in the Universe, including stars and star forming regions in the Milky Way, nearby and distant galaxies, quasars and the microwave background radiation. The VLA is in high demand, at more than two and one-half times the available observing time.

A sample of the observational programs for 1998 follows.

Surveys

The NRAO VLA Sky Survey (NVSS) will be completed in 1998. The 4-degree by 4-degree NVSS continuum images in all Stokes parameters cover the 82 percent of the sky that lies north of declination -40. The images are available on the World Wide Web (WWW), the observational phase for the FIRST (Faint Images of the Radio Sky at Twenty centimeters) survey was completed in 1997. The FIRST project is designed to produce detailed images of two regions around the North and South Galactic Poles, which will be studied as well by the Sloan Digital Sky Survey at optical wavelengths. Like the NVSS, the FIRST survey has made its images available to the astronomical community through the WWW.

Both surveys have sparked a number of follow-up studies as observers have extracted statistically significant catalogs of a variety of objects, from radio stars to various types of galaxies and quasars. Their spectra and variability will be studied in detail for years to come.

Solar System

The Sun will continue to be studied with the VLA. Observations in collaboration with the orbiting observatories SOHO and Yohkoh will study coronal mass ejections. These are eruptions of the magnetic field and plasma in the solar corona into interplanetary space that can have a profound impact on the interplanetary medium and also on the near-earth environment. The VLA will be used to detect these ejections at centimeter wavelengths.

Other studies of the Sun will focus on coronal loops and their underlying solar storms and flares. Macrospicules and other jet-like events will be studied as well. These are expected to become more frequent as the Sun increases its activity with the beginning of the present solar cycle.

The abundance of iron relative to hydrogen in the solar corona is a fundamental parameter of the corona which is only poorly known. The VLA will be used to measure the thermal bremsstrahlung from suitable features in the solar corona which also will be studied with the EUV imaging spectrograph on board the SOHO satellite in order to determine their differential emission measure. Comparison of the two datasets should yield the desired iron abundance.

The VLA will continue to be a major tool in the study of planets, especially Jupiter and Saturn, with observations of their continuum emission planned at several wavelengths. In addition, new comets also will be observed with the VLA which will study their continuum emission as well as the emission of ions and molecules such as water, formaldehyde and ammonia.

Stars

The VLA will be used to study stars of most types. For example, the highly variable non-thermal radio emission from OB stars has eluded explanation for more than 15 years. Multi-epoch observations with the VLA will test the currently most favored scenario in which the line force instability mechanism gives rise to a distribution of shocks in their stellar winds.

Multi-frequency observations of K5 stars will be used to constrain models of their chromospheric and wind structure.

Other types of stars that will be observed with the VLA include HD 45677, a Herbig AeBe star with peculiar emission lines whose spectrum and degree of polarization will be determined in order to discriminate among several possible emission mechanisms. Observers also will use the VLA to study Sakurai's Object, believed to be a star undergoing its final helium flash, only the second time that such an event has been observed this century.

RS CVn stars will be monitored with the VLA at several frequencies in order to look for evidence of the stellar activity cycle in these stars. A key observation would be that of the reversal in the sense of circular polarization of the quiescent emission of these systems.

Other active binary systems will be observed in order to study stellar flares, as well as the structure and abundances of their stellar coronae. The research will combine observations with the SAX satellite as well as ground-based optical observations with VLA observations of the non-thermal radio emission from these stars.

Observations of the orbital modulation of the radio continuum from the eclipsing binary ζ-Aurigae will provide the first direct (independent of the details of the stellar velocity fields) measure of the mass loss in this system, which consists of a K4Ib and a B5V star. The HII region that surrounds the B star expands and contracts in the wind of the K star as the separation between the stars changes with the phase of their very eccentric orbit ($e \sim 0.4$), which leads to a modulation of the optically thick radio emission.

Multi-epoch observations will monitor several black hole x-ray transient binary systems, complementing x-ray monitoring observations with the RXTE and CGRO satellites. These binary systems also feature evolving jets. The coordinated x-ray and radio observations are essential to discern the relationship between the emission of the accretion disks and that of the radio synchrotron flares associated with the ejection of relativistic plasma. The scheduling flexibility of the VLA allows rapid follow up in the radio of any x-ray transient emission.

In 1994, astronomers used the VLA to discover the first case of (apparent) superluminal motion in our Galaxy. This "microquasar," GRS1915+105, will continue to be studied with the VLA in conjunction with x-ray observations with the RXTE and CGRO satellites in order to elucidate the nature of the oscillations that are seen at timescales of tens of minutes. Future bursts of this system will be monitored in order to learn important information about this system but also will be used to probe the structure of the ISM. Indeed, the observations will take advantage of the changing positions of the rapidly ejected blobs by looking for HI absorption along the line of sight to these moving background sources, thus probing the structure of the ISM on scales between 50 and 200 AU.

Observations of symbiotic novae will attempt to trace their orbital motion using the VLA A-configuration at 22 GHz. The observations should determine fundamental parameters of these systems such as their distance and their binary separation which are critical to the understanding of symbiotic novae.

The VLA also will be used to observe nova remnants such as GK Per 1901 in order to look for changes in their size, total flux density, radio brightness distribution and polarization, and to compare them with corresponding changes seen in various optical emission lines.

The VLA will continue to monitor radio supernovae as well as observe any new supernovae that might be detected optically. The goals of this longstanding project are to: 1) detect at radio frequencies any newly discovered optical supernovae out to the distance of the Virgo cluster, and 2) establish the multi-frequency radio light curves of several known radio supernovae plus any new radio supernovae. This program should yield a better understanding of the mass-loss of the progenitor stars as well as of the nature of those stars.

Timing observations of pulsars with the VLA will continue to study a number of these neutron stars, concentrating on observations of the triple pulsar system PSR B1620-26 and the eclipsing binary system B1744-24. The observations also will probe the apsidal advance, and hence the mass, of binary pulsar systems.

Observers will continue to study the giant pulses of the Crab pulsar. Recent numerical simulations of the plasma in the pulsar polar cap predict that the radio emission should have bandwidths of about ten percent. However, previous observations have suggested much larger bandwidths although low-frequency scattering destroyed all intensity structure shorter than a few microseconds, and prevented detailed wide-band comparisons of the intensity and polarization of the pulses. The new observations will use several pairs of more closely spaced frequencies in the 5, 8, and 15 GHz bands in order to cross-correlate the intensity structure of the various intra-band observations as a test of the numerical models.

Other observations will seek to identify new pulsar wind nebulae. These observations should yield constraints on the pulsars' velocities as well as the energetics of the nebulae and the parameters of pulsar winds.

The Interstellar Medium

Studies of the interstellar medium will probe a variety of objects in the Milky Way, from dense regions of star formation to the diffuse interstellar gas.

Regions of star formation are typically dense, ionized, and clumpy. The versatility of the VLA allows multi-frequency studies with a variety of resolutions which are important in order to disentangle the composition and physics of these regions. A study of ultra-compact HII regions will combine data from the VLA with observations obtained at BIMA in order to model the hot gas through its bremsstrahlung emission and characterize the mass and location of the dust during the evolution of these regions.

The VLA will be used to determine the conditions that precede the ultra-compact phase by studying high-mass protostellar cores using the 22 GHz band to observe several transitions of ammonia. This study will seek to establish the density and temperature structures in these regions, using the ratios of the observed optical depths. The observations also will probe the dynamics of the regions (infall, rotation). Other studies will observe molecular species such as SiO, CH_3OH, H_2O, CS, and H_2CO.

The VLA 43 GHz band will be used to survey proto-stellar disks in the nearby Taurus complex. In these sources, the radio radiation is dominated by optically-thin thermal dust emission. A multi-configuration study will seek to determine the character and distribution of these sources and allow an exploration of the evolution of such disks.

Very young stars are believed to power molecular outflows and Herbig-Haro jets. Some of these young stellar objects (YSOs) are so enshrouded that they are difficult to study even in the far-infrared and most are observed in the millimeter and sub-millimeter bands where their emission is dominated by dust. VLA observations provide the highest resolution information available and, since they are unaffected by dust extinction, can study the immediate surroundings of the exciting sources where the collimation of the outflows takes place. Indeed, VLA observations have provided the most stringent upper limits to these collimation regions. These studies will continue in order to detect more of such collimated, ionized thermal jets.

A number of HII regions will be studied through the observation of a variety of recombination lines to provide a handle on temperatures, structure, and clumpiness. Past studies have uncovered regions of very high apparent helium abundance, as high as 30 percent, showing the importance of ionization corrections when interpreting the observations of such complex regions. Follow-up studies will focus on the HII regions M17, NGC 6334, and W43, which will be studied by observing recombination lines of carbon, hydrogen, and helium. Such studies are needed to interpret a variety of observations ranging from measurements of magnetic fields to the determination of the cosmological abundance of Helium-3.

Supernova remnants develop a variety of fascinating structures. Multi-epoch studies are necessary to measure their velocity fields. In-depth observations of several such remnants will probe the physics of the energy transfer from the bulk flows to cosmic rays. Other studies will continue to probe the interaction of supernova remnants with molecular clouds using the 1720 MHz OH maser emission that is believed to be a consequence of collisional excitation by H_2 in the remnant's shock.

A variety of observations will probe the diffuse interstellar medium using the 21 cm emission line of neutral hydrogen. The observations will probe the spatial power spectrum on parsec scales and constrain the possible sources of energy for the turbulence of the neutral hydrogen. Other studies will probe high velocity gas along several lines of sight.

Observations of absorption due to neutral hydrogen will continue to be an important tool in the determination of distances to a variety of galactic objects, such as the supernova remnant SNR 45.7-0.4 which is believed to be adjacent to the black hole x-ray binary source of superluminal jets (the Milky Way's "micro-quasar") GRS1915+105 discussed above. The determination of the distance to the supernova remnant is necessary to substantiate its association with the micro-quasar which has been postulated to be the remnant of the supernova progenitor that may have been ejected in the explosion with a high proper motion. The same technique will be used to determine the distance to regions of synchrotron emission by searching for absorption of the linear polarization of the emission of the galactic non-thermal background.

A number of observations will continue to probe the magnetic field in the Milky Way through observations of the Zeeman splitting of the emission of neutral hydrogen as well as that of the 1665 MHz and 1667 MHz OH absorption lines against bright (intragalactic) background sources.

The VLA will continue to study the center of our Galaxy with a variety of research programs. The 43 GHz observations will complete a study of the spectral index of the non-thermal filaments in the region of the "galactic center arc." Other studies will address the sources of heating for the giant molecular clouds near the galactic center. Others will probe the HII regions, molecular clouds, and magnetic filaments in this unique part of the Milky Way.

Galaxies

The VLA is an important tool in the study of galaxies of all types. From the largest spiral galaxies through irregulars to dwarfs, observations of neutral hydrogen emission will be used to study their structure and kinematics. HI emission is a tracer of interactions that can be used to explain bursts of star formation that might correspond to the various observed stellar populations. For example, the galaxy VIIZw403, which is the closest example of a blue compact dwarf galaxy, will be observed in HI in order to assess whether it might be in the process of losing its ISM and evolving into a gasless dwarf and examine the relationship between the ISM and current star formation in order to learn about feedback processes.

As irregular galaxies do not have spiral density waves, it is important to understand how these galaxies form stars. Observations of HI in irregular galaxies will probe what determines the level of global activity and its radial distribution in such galaxies in which star-formation rates span four orders of magnitude.

The Tully-Fisher relationship is an important tool to measure the distance to galaxies. The VLA will observe the HI emission from a variety of galaxies recently detected in surveys with several single-dish telescopes in order to better determine their locations and neutral hydrogen distributions. In addition to their distances, the observations will also yield the HI mass function of these samples.

Galaxies show a remarkable variety of structures when viewed in their HI emission. A number of studies will concentrate on galaxies with interesting classes of features such as polar rings, tidal tails, and bridges between interacting or merging galaxies. Starburst galaxies show many kinds of shells in somewhat frothy patterns with trace shocks due to past bursts of star formation that are believed to nucleate current and future star formation sites. The sensitivity and angular scales available with the VLA will support a number of programs that will study these objects in great detail.

Other observations of neutral hydrogen in galaxies will target elliptical galaxies and will address the question of whether the origin, distribution, and kinematics of HI in shell ellipticals are different from those in ellipticals without shells. It might be amusing to remember that not long ago elliptical galaxies were believed to have no gas. The sensitivity of the current 1.4 GHz system at the VLA now allows imaging of such gas-poor systems. Dwarf spheroidals also were long believed to be gasless. In light of observations that show evidence for recent star formation in some of these systems, observers will use the VLA in order to detect and image neutral hydrogen which might trace the gas that has fueled these events.

Observations of low-surface brightness gas-rich galaxies will probe their rotation curves in order to determine their gas content and distribution as well as the distribution of dark matter in these systems. These might turn out to contain a significant fraction of the neutral gas in the Universe.

Studies of HI in clusters of galaxies will continue to probe the fraction of gas-rich galaxies in clusters of various degrees of evolution. These studies have reached sensitivities capable of detecting one-hundred-million solar masses of HI at redshifts of about 0.1. At this sensitivity and with the resolution of the VLA, the images can reveal for the first time the physical mechanisms at work in removing gas from spiral and irregular galaxies as they fall into the dense cluster cores. Previous work that has studied clusters such as Virgo, Hydra, Coma, and Abell 2670 will be extended to study denser and dynamically more relaxed clusters such as Abell 2029.

HI observations will search for high-velocity clouds in other galaxies. This component of the Milky Way has not yet been conclusively observed in other galaxies, but the studies continue.

A variety of galaxies that are seen optically in absorption against distant quasars will be studied with the VLA in the 21 cm line. This will allow a characterization of their kinematics as well as the determination of abundances of the species seen in the optical absorption lines, such as MgII. Other studies will test whether damped Lyman-α absorption systems are indeed associated with ordinary spiral galaxies.

The continuum emission from a variety of radio galaxies will be studied in order to understand the distributions of spectral index that characterize different components. Studies of Faraday rotation and depolarization will seek to determine their dependence on radio luminosity. The environments of high and low luminosity sources will be probed for radio galaxies at redshifts between 1 and 1.5.

Studies of radio galaxies in dense clusters will continue with a variety of systems such as Abell 2163, which contains what appears to be a radio halo extending throughout most of the cluster. The cluster Abell 428 contains a highly unusual spiral galaxy which hosts the kind of powerful FRI radio galaxy previously known only in bright elliptical galaxies. The VLA will be used to obtain multi-frequency images in order to look for evidence of jets and to determine the spectral index distribution over a wide variety of angular scales.

Multi-frequency observations of x-ray emitting elliptical galaxies will test the hypothesis that these galaxies host "dead" quasars, whose total luminosity is low due to an ion-supported, advection dominated, accretion disk. If this model is correct, the radio emission should have an inverted spectrum. Its flux, combined with limits or detections of x-ray point sources, can be used to determine the mass of a central black hole. This would be an important way to explain the fading of radio loud quasars.

Several projects will study jets in active galaxies with the VLA. These will range from statistical studies of jets in FRII radio galaxies to the study of the kiloparsec-scale jets of well-known sources such as 3C273, where the goal is to understand the changes in spectral index along the jet. This requires high dynamic range, multi-frequency observations with the VLA in all its configurations in order to properly sample all of the relevant angular scales. The VLA observations will be added with MERLIN observations for this project. The final images will have a resolution of one-tenth of a second of arc with good fidelity over the extent of the jet (12") at frequencies ranging from 1.4 to 22 GHz and will be compared with observations from ROSAT, the Hubble Space Telescope (HST), as well as with 2-micron images obtained with adaptive optics from the ground. The combined program should allow understanding the jet in 3C273 at a level of detail presently only achieved in the case of the jet in M87.

Other multi-frequency and multi-configuration VLA studies will re-examine the distribution of electron populations and their ages in powerful radio galaxies. Accurate spectra are necessary to properly estimate ages and flow speeds in these sources.

Other observers will search for radio supernovae in representative Seyfert and starburst galaxies by monitoring their continuum emission at various frequencies over several years. This project will seek to establish the existence and determine the contribution of radio supernovae to the overall radio emission. In addition, these data will be used to constrain starburst models and also should constrain the evolution of massive stars in these systems.

Cosmology

The VLA will be used to perform a variety of follow-up studies on several different classes of distant objects, such as quasars, selected in a variety of ways. Some of the studies will target optically-selected samples while others will study the distribution of spectral indices of broad absorption line quasars as well as that of radio-loud, radio-selected, quasars. Still others will address the variability of these powerful objects.

Target-of-opportunity observations are planned to follow-up on upcoming detections of gamma-ray bursters. The flexibility and quick response time of the VLA will allow their study soon after the detection of their gamma-ray bursts with the relevant spacecraft. It is clear that understanding the nature of these objects will require their observation at many different wavelengths. The spatial and time resolution of the VLA observations will contribute to the quick identification of these objects as well as contribute to the understanding of their nature.

In 1997, the VLA made the first detection ever of radio emission from a gamma-ray burster (GRB 970508). This was followed days later by VLBA observations of the same object. Over the course of several months, observers noted scintillation in the radio emission. Measurements of a gradual decrease in the scintillation allowed calculation of the size and expansion rate of the GRB fireball. The VLBA monitoring provided a positional accuracy of less than a milli-arcsecond and showed no measurable proper motion, greatly strengthening the case for a cosmological distance to the object.

Several observing programs will seek to detect highly-redshifted signals from molecular species in distant objects. These range from observations of CO in the highest redshift galaxy (Z=4.92) whose (red-shifted) emission falls within the VLA 7 mm band to observations of several molecular species (CO, H_2CO, HCO^+) in the absorbing systems located along the line of sight to distant quasars.

Gravitational lenses have allowed a high-sensitivity direct determination of Hubble's Constant which is free of many of the sources of systematic errors that have plagued its determination with conventional methods. Indeed, the modeling of the gravitational lens 0957+561 that has followed from optical and radio observations (with the VLA, VLBA, and MERLIN), together with the measurement of the time-delay between changes in the two main components, and a measurement of the velocity dispersion in the lensing cluster, have resulted in a value of H_0 of 67 ± 10 km/s/Mpc. The method is robust enough that it has resulted in a re-evaluation of other determinations. It is important to extend these measurements to other gravitational lenses. The VLA is being used by several different groups to measure the radiostructure and time delays in several gravitational lenses, in addition to continuing the monitoring of changes in 0957+561. Other studies will include the observation of molecular absorption in the lensing systems.

The VLA will study the fine scale structure in the microwave background decrements (Sunyaev-Zel'dovich effect) due to the hot gas in dense distant clusters which distort the spectrum of the background radiation and lead to a spatial anisotropy when the radiation is observed at any given frequency. A measurement of such fine structure would lead to important constraints in models for the evolution of structure in the Universe.

2. The Very Long Baseline Array

With the VLBA, astronomers now are routinely imaging radio sources such as quasars and AGN, molecular masers, stars, and gravitational lenses with milli-arcsecond resolution, or ten to one hundred times better than with the Hubble Space Telescope (HST) or any other telescope. With anticipated improvements in instrumentation and software, the VLBA will approach full-time operation with enhanced sensitivity obtained from increased bandwidth and improved resolution resulting from the start of partial operation at 3 mm wavelength. For many studies, other radio telescopes are used together with the VLBA for enhanced resolution or increased sensitivity.

Within the Galaxy, the VLBA will be used to observe the symbiotic Mira star, R Agr, to determine the rotation rate of the circumstellar envelope; to search for a rotating molecular disk around the massive protostar IRAS 20126+4104; to study the RS CVn binary star AR Lac, and to determine the distance of the bright x-ray source Sco X-1. Other observations will focus on water maser clusters toward the very young *Class O* protostar S106FIR and in the newly formed massive star cluster in W3 IRS5. With the observations of S106FIR, it will be possible to tell whether the masers trace an outflow or are in gravitationally bound gas in a rotating or infalling disk. The fine scale structure of galactic formaldehyde clouds will be investigated by observing their absorption signature against distant radio galaxies. Another program will search for gravitational lensing from a galactic foreground star in front of the radio galaxy 3C435B. High frequency VLBA observations of the magnetic cataclysmic variable AE Aqr, a well-known radio flare star, with 0.3 milli-arcsecond resolution, will resolve the rapidly rotating white dwarf from the K5 dwarf secondary.

Silicon monoxide masers will be observed in the circumstellar envelope of VXSgr, the M supergiant IRC-10414, the Orion-KL nebula, and the Mira variable star TX Cam. Previous VLBA studies of Silicon monoxide masers surrounding Mira variable stars have revealed dramatic structural variations in the maser rings surrounding the star, showing both contractions and expansions. VLBA polarization measurements of the SiO maser emission allow, for the first time, the direct imaging of the magnetic field in the atmosphere of these stars. With the continuing improvements in the reliability and performance of the VLBA, frequent observations of structural changes now are possible. New VLBA observations made every two weeks over a full pulsation period of six months will provide a detailed picture of the changing intensity and polarization structure of the Mira variable TX Cam.

Exploiting the extraordinary angular and spectral resolution of the VLBA, images of water vapor masers orbiting a central mass in the nucleus of NGC 4258, have shown startlingly clear evidence for the presence of a massive black hole in the center of this galaxy. The recent discovery, with the VLBA, of a parsec-scale jet emerging from the nucleus, allows astronomers the opportunity to align the emerging jet with the central energy source with remarkable precision and shows that the jet forms within 100 micro-arcseconds of the central energy source. New VLBA observations will test the Active Galactic Nucleus (AGN)/black hole paradigm in wholly unanticipated new ways and will lead to a new understanding of how energy is focused into narrow jets within a remarkably small region in the nuclei of galaxies. Comparison of the water maser intensities with those of the highly variable continuum jet will determine whether or not the masers amplify the continuum source.

From the absence of Zeeman splitting of the maser lines, VLBA observations show that the magnetic field in the nucleus of NGC 4258 must be less than 200 microgauss, tantalizingly close to providing significant constraints on the magnetic pressure, magnetic confinement, and other important phenomena. More sensitive measurements will offer the very exciting possibility of measuring directly the value of the magnetic field which is thought to confine the broadline emitting region and which is related to the mass accretion rate. In a novel experiment, the VLBA will be used to test the bold suggestion that two QSOs have been ejected from the nucleus of NGC 4258.

Other VLBA observations will include water megamasers in the Seyfert galaxies IC 2560 and NGC 5793 to determine the geometry of the masing disk and the enclosed mass, as well as the weak water vapor masers in NGC 3735 and M51.

With its extraordinary resolution, the VLBA is providing images of quasars and AGN with unprecedented clarity. Narrow jets of relativistic plasma ejected from the central engine flow with apparent superluminal velocity along a curved trajectory characteristic of a rotating nozzle. New observations will concentrate on defining the complex parsec scale structure of quasars and AGN and, by repeated observations, to accurately determine their dynamics to better understand how energy is focused into a narrow beam which may extend hundreds of kpc from the central engine. Particular attention will be given to sources associated with gamma-ray emission, such as 0521+134, which is thought to originate particularly close to the central engine, to frequent observations of rapidly changing BL Lac objects such as OJ287 and BL Lacertae, to radio sources associated with the nuclei of Seyfert galaxies such as Mk 1210, as well as the nearby radio galaxy Centaurus A.

An important advance in our understanding of quasars and AGN comes from the ability of the VLBA to measure the polarization distribution in stars, quasars, and AGN with milli-arcsecond resolution. This allows astronomers to measure the orientation of magnetic fields, leading to better understanding of the manner in which relativistic electrons are accelerated and focused in quasars and AGN. Images of the circularly polarized radiation in the AGN NGC 1275, the quasar 3C 279, and other sources will give an entirely new method to probe the magnetic field structure and particle composition of parsec scale radio jets.

Following the earlier discovery with the VLBA of a counter feature in the active galaxy NGC 1275 (3C 84), multi-wavelength VLBA observations of the absorption medium surrounding the AGN in NGC 1275 and NGC 1052 give a unique opportunity to study the suspected accretion torus widely supposed to surround the massive central engine. Observations of HI and OH absorption will probe the distribution of neutral hydrogen and of molecular gas in NGC 1052 and 2352+495.

There has been considerable interest, in recent years, in the phenomena of gravitational lensing. Multi-component images with characteristic separations of milli-arcseconds are expected from lenses with masses of the order of 10^6 $M_{\odot}$, so VLBA studies of milli-arcsecond lenses will place limits on the density of 10^6 $M_{\odot}$ objects in the Universe and whether or not they provide sufficient mass to close the Universe. Observations of redshifted formaldehyde in the lensing galaxy forming the Einstein ring B0218+357 will open a new way of studying the dense interstellar medium of distant galaxies.

The supernova 1993J in M 81 is unique among supernovae due to its proximity and level of radio emission. Observations by two international groups using the VLBA and other radio telescopes give a unique picture of the expanding debris of an exploding star which shows that it has expanded uniformly with circular symmetry, in agreement with theoretical models of shock excited emission. New observations will more accurately measure the growth rate and search for departures from circular symmetry due to hydrodynamical instabilities.

The VLBA also can be used to measure relative positions with accuracy of about 100 micro-arcseconds, or an order of magnitude better than achieved by the best optical astrometry. This is being used to measure parallax and proper motions of stars such as U Her and to search for extrasolar planets by measuring the wobble of radio stars caused by orbiting planets.

VLBA observations of quasars and AGN also have many applications to general relativity and cosmology, including new approaches to determine the value of the Hubble Constant, H_o, wholly independent of the usual hierarchal arguments used by conventional approaches to measure extragalactic distances. Observations of two-sided motion in 3C84 and the quasar 1946+218 will give a direct independent measure of the Hubble Constant, while measurements of the angular size-redshift and angular velocity-redshift relation may be used to determine the value of the deceleration parameter, q_o. Observations of the gravitational lens 2045+265 will be used to determine the structure of the lensing mass in order to more accurately measure the value of the Hubble constant from differential timing measurements.

Continuing observations of proper motions in NGC 4258 with an unprecedented precision of 30 micro-arcseconds per year will better define the dynamical properties of the rotating molecular disk and will lead to a distance estimate accurate to five percent or better and a correspondingly accurate measure of the Hubble constant. Accurate measurement of the angular expansion of SN 1993J will lead to a determination of the distance to M81 with an accuracy comparable to that obtained by HST observations of Cepheids in M81.

In addition, the extraordinary positional accuracy of the VLBA will be used to measure the proper motion, acceleration, and parallax of the guide star of the NASA/Stanford Gravity Probe-B mission intended to measure the relativistic "frame-dragging" due to the diurnal rotation of the earth's mass. Because uncertainties in the proper motion of the GP-B guide star map directly into errors in the measured rotation, the precision of this mission will depend on the accuracy of the guide star proper motion measured by the VLBA. Scientists from the Naval Observatory and from NASA will use the VLBA for precise geodetic and astrometric observations to obtain the most accurate measure of Earth rotation ever, and to locate with millimeter precision the relative positions of VLBA and other antennas. These observations give the most accurate absolute measurement of UT1, the basic unit of time used throughout the world, and trace the motions of crustal plates with extraordinary precision.

The Japanese orbiting 8-meter radio telescope satellite, HALCA, in conjunction with the VLBA and other ground-based radio telescopes, gives greatly improved angular resolution at 6 and 18 cm. This new capability for radio astronomy will give images at these wavelengths comparable to what the VLBA achieves alone at shorter wavelengths, making possible for the first time, studies of spectral distributions at constant submilli-arcsecond resolution. The VLBA, supported by the NRAO Orbiting VLBI Earth station in Green Bank, plays a major role in this new era of space VLBI. Up to 30 percent of the scheduled observing time with the ten-element VLBA provides the major ground-based component of the international space VLBI program. To correlate the space data, the VLBA correlator and supporting software has been modified, with NASA support, and is being used to correlate data from the HALCA spacecraft. Subsequent imaging is carried out with the AIPS imaging package using enhancements introduced for this purpose.

3. The 12 Meter Telescope

The 12 Meter Telescope is now equipped with sensitive, dual-channel SIS receivers covering all the primary wavebands of the telescope from 68 to 300 GHz. The sensitivity and flexibility of these systems allow observers to attack the most challenging and topical problems confronting millimeter-wave astronomy today. Astronomers most often use these dual-polarization, single-beam receivers to achieve the utmost sensitivity toward a single point on the sky, or perhaps to map a limited region. Some of the most fundamental discoveries of recent years, such as the detection of molecular gas in high-redshift galaxies and the discovery of new interstellar molecules have been made with these systems. To enhance further our instrumental capabilities for point-source observations, a new 8-receiver, 4-beam, 3 mm receiver is being constructed. This receiver will allow dual-polarization, double-Dicke beam-switched observing for point sources as well as efficient wide-field imaging.

Many astronomical problems require the ability to rapidly image large fields. Such problems concern the structure of external galaxies and the large-scale structure of molecular clouds and star-forming regions in the Milky Way. The imaging capability of the 12 Meter has undergone a revolution in the past few years with the advent of on-the-fly (OTF) observing modes. This is a highly efficient observing technique that can be used in either spectral line or continuum modes. This technique is made possible by a marriage of the powerful and flexible on-line computer systems and the high-sensitivity receivers at the 12 Meter. OTF observing can be used with all of the 12 Meter facility receivers. Further developments in wide-field imaging are planned, including the construction of the 4-beam, dual-polarization receiver mentioned above.

On-the-fly observing is having a substantial impact on the scientific program of the 12 Meter. Approximately 20 percent of all observing programs specifically request the technique. For example, one group is conducting a comparative study of the CO, dust, HI and optical emission from IC342. The aim of this project is to study the spatial and kinematic properties of each of these species to learn more about the small-scale structure and kinematics of this nearby galaxy.

Astrochemistry continues to be a specialty of the 12 Meter and one of the largest components of the 12 Meter research program. Over the years, the facility has accounted for a substantial majority of the detections of interstellar and circumstellar molecular species. This trend continues; in the past two years the 12 Meter produced detections of over six new species. Over 100 species are now known.

Astrochemistry has matured so that directed chemical studies and new species detections can now be used to address some very challenging problems in astrophysics. For example, in the coming year one program will search for KS in the envelope of an evolved star. This study will constrain some specific predictions of theories of nucleosynthesis involving third-row elements. By studying interstellar aluminum isomers, another program will address specific predictions of nucleosynthesis theories. Further programs will study the details of interstellar chemistry such as grain surface reactions and the chemistry of translucent clouds. Translucent clouds are the simplest category of interstellar cloud to support complex chemistry; hence, they are good astrophysical laboratories.

Research on external galaxies continues to be the major component of the 12 Meter research program. In recent years, the 12 Meter has been a leader in studies of molecular line emission from very high redshift galaxies. Many other projects have concentrated on the structure and star formation in more nearby galaxies. One upcoming project will study CO emission in the strongly-barred grand-design spiral galaxy NGC 1097. This program will determine how the distribution and kinematics of molecular gas vary with morphological type. Another group will seek to complete a comprehensive survey of spiral galaxies with the intent of defining the molecular content of normal spirals as has been previously done for HI in these objects. Other upcoming programs focus on the properties of specific prototypes for general classes of galaxies such as early-type galaxies or barred spirals. The power of the on-the-fly imaging technique will be particularly useful for these studies.

The 12 Meter is participating in millimeter-wave VLBI with increasing regularity and is a participant in the Coordinated Millimeter-Wave VLBI association. Kitt Peak 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 time and frequency standard and the VLBA data recorders. With a global network, millimeter-wave VLBI can achieve resolutions of 50 micro-arcseconds. In the coming year the 12 Meter will participate in several VLBI sessions that will 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.

Although most of the observing programs at the 12 Meter fall into one of the categories mentioned above, the flexibility and sensitivity of the telescope allow a number of other important projects. For example, one project will monitor the CO absorption profiles from the atmospheres of Mars and Venus. The 12 Meter planetary studies have provided unique information not available from any other source. This specific project allows, among other things, for the detection of dust storms in the Martian atmosphere. Another project will address poorly understood variations of ozone and water isotopes in the upper atmosphere of the Earth, as well as twilight variations of molecular oxygen and solar cycle variations of NO. The collecting area and precision surface of the 12 Meter are not strictly necessary for this project, but the wide frequency coverage of the receivers and its versatile back-end instrumentation together make the 12 Meter Telescope a unique facility even for terrestrial studies.

4. The 140 Foot Telescope

In 1998 the 140 Foot Telescope will continue its programs of spectroscopic and pulsar studies, as well as spend a significant fraction of its time in support of space VLBI. There will be two deadlines for receipt of proposals for 1998 observations, one in the autumn of 1997 and the other in the spring of 1998. Most of the usual set of 140 Foot receiving and detecting systems is expected to be available during in 1998. Observations are expected to span the frequency range from 300 MHz to 26 GHz.

There are several studies of pulsars that will continue through 1998. Binary pulsars will be monitored to provide refinements to tests of general relativity and measurements of neutron star masses. Regular monitoring of a select group of milli-second pulsars will place limits on the density of gravitational radiation in the solar neighborhood. Individual pulsars will be monitored for evidence of spindown, glitches, and other period anomalies that shed light on the evolution of these objects. Long-term monitoring of certain pulsars can set bounds on the violation of the strong equivalence principle through dipolar gravitational radiation or variations of Newton's constant G with time. There will be demand for regular monitoring of pulsars by different groups using the 140 Foot Telescope until the GBT becomes available, because of the possibility of biases introduced in the values of timing parameters as a result of covariances between those parameters and instrumental offsets.

Milli-second pulsars are known to have strange emission characteristics that do not easily fit into well established classification schemes developed from slower pulsars. A study will be performed to determine the viewing geometry of the magnetospheric structures in these systems using high-quality multi-frequency polarimetry of a selected set of fast pulsars.

A variety of spectroscopic studies are planned for 1998. Studies of the hyperfine transition of $^3He^+$ to determine its abundance in various parts of the galaxy have been extremely successful in past years and have contributed to defining its primordial value and thus constraining conditions of nucleosynthesis in the early universe and the photon-baryon ratio. Further studies of new objects are expected in 1998, especially since it has been discovered that the strength of the $^3He^+$ line is not simply related to the strength of nearby H^+ lines: many low-emission-measure nebulae turn out to have reasonably strong $^3He^+$ lines simply because they have a large mass of ionized gas.

Models of the early stages of star formation will be tested by monitoring H_2O masers in young stellar objects with molecular outflows. Prior results from these surveys suggest that maser activity occupies at least one-third of the "embedded state" of these young stellar objects, and that there is good correlation between the maser strength and the stellar luminosity.

Among other spectroscopic programs to be carried out in 1998 will be studies of newly formed stars with possible proto-planetary disks, and measurement of recombination lines of ionized carbon to probe the structure, kinematics, and physical properties of photodissociation regions in star forming regions. The chemistry and physical properties of hydrocarbon compounds in cold dark clouds and interstellar shells will also be studied.

Evidence of recent star formation in dwarf spheroidal galaxies motivates a search for neutral hydrogen in a sample of these objects, challenging the assumption that such systems are gas-free. Observations will place constraints on theories of the evolution of galaxies and the local group.

The detection of H_2O Megamasers in nearby galaxies has provided a probe of nuclear kinematics on a very fine angular scale, and allowed interesting limits to be derived on the mass of potential nuclear black holes. A search for further nuclear maser systems will be performed on the 140 Foot in 1998.

Galactic HI studies will continue, both of high velocity clouds and of normal disk gas. The 140 Foot is in demand for this work because the best existing all-sky HI surveys have an angular resolution of only 36 arcminutes, and spectra are available only every 30 arcminutes across the sky. Fully-sampled 140 Foot HI maps have more than an order of magnitude more pixels per unit area, and can supply considerably more detail. Large-scale maps will be made of areas where there is interaction of supernova remnants with the interstellar medium producing spectacular shells, bubbles, and superbubbles in the HI. Several objects known to have HI shells from preliminary searches will also be mapped at higher sensitivity and resolution. These shells may contain enough mass to initiate star formation, and there is considerable question as to whether they are capable of breaking out of the galactic disk and into the halo.

Observation of high-velocity clouds will continue, to test hypothesis both that these objects are remnants of formation of the Local Group associated with nearby Galaxies, and that they are true halo objects in pressure equilibrium with a hot gaseous halo.

Most of the VLBI observing in 1998 will be in conjunction with the Japanese radio astronomy satellite HALCA and will be scheduled either in conjunction with the VLBA and recorded on a VLBA-type recording terminal, or scheduled independently and recorded on the S2 system developed by the Canadian Space Agency. Most observing for HALCA is expected to be at L and C bands. The GBT C band receiver has been mounted temporarily at the Cassegrain focus of the telescope to allow it to be switched into the optical path in a few minutes. This gives us the ability to interleave, quite efficiently, short HALCA observations with longer spectroscopic projects. The 140 Foot Telescope can supply critical baselines between North American and European telescopes, and between North America and Arecibo.

III. USER FACILITIES

1. Very Large Array

Present Status

More than 600 scientists used the VLA for their research work in 1997, and a similar or larger number will do so in 1998 as time previously scheduled for the NVSS becomes available for general use. Demand for the VLA arises both from the multi-wavelength nature of contemporary astronomical research and from the flexibility of the telescope. With regard to the former, it is now 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. Radio observations also may be the focus of research with complementary data provided from observations at other wavelengths. For either case, the fact that the angular resolution and field of view of the VLA is nearly identical or better than that achievable with modern detectors at other wavelengths means that all the data can be merged with no ambiguity. This is the capability astronomers need for their research.

Present Instrumentation

The VLA consists of twenty-seven, 25-meter antennas arranged in a wye configuration, with nine antennas on each 13 mile 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 System

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	Cryogenic HFET
40.0 - 50.0	95[2]	Cryogenic HFET

[1] All antennas will be equipped in early 1998; T_{sys} includes galactic background.
[2] Thirteen antennas equipped.

Future Plans — Electronics

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. Since that time, the VLA has been an extraordinarily productive scientific instrument. 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.

A program to upgrade the VLA is described as a Major New Initiative in Section VI of this Program Plan. It amounts to a major overhaul of the entire VLA electronics system. The upgrade will include a new correlator, a new fiber optic data transmission system, and several new wideband receiver systems. Until major funding for the upgrade is available, improvements to the VLA will be in the form of yearly improvements to smaller parts of the electronics system.

Modifications were made to the local oscillator system of the 21 cm receivers to reduce radio frequency interference produced by intermodulation products. This retrofit involves introducing a 180 degree phase switch at the first local oscillator in this band as is done at the other VLA observing bands. This project was completed December 1996.

Work has begun on the next generation of VLA receivers as proposed for the VLA Upgrade. A prototype receiver covering the full waveguide bandwidth from 18 to 26.5 GHz has been installed on the VLA for evaluation. A second receiver is under construction and should be on the array by the end of 1997. The third and fourth wideband receivers should be installed in 1998.

A plan is being prepared to incorporate the PT VLBA antenna as a real-time active element of the VLA. In this arrangement the PT antenna would provide a long baseline for the VLA A-configuration. This is now feasible since a fiber optic connection has recently been completed by Western New Mexico Telephone

Company between the VLA control building and the PT antenna. An MRI proposal has been submitted to the NSF and if funds are made available construction will begin in late 1997. Limited astronomical testing could start by mid-1999.

A series of tests are planned to assess the impact of the Motorola IRIDIUM communication satellites on radio astronomy observing in the 1610 to 1612 GHz observing band. There is a possibility that out-of-band emissions from this constellation of 66 satellites will exceed the harmful threshold level for OH observations in this protected band. Three modified VLA antennas will be used for drift scan observations while an IRIDIUM satellite is transmitting at full power.

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. Three antennas are being prototyped to test this concept. If no problems are found, the full array will be modified. Going to the full 100 MHz bandwidth would require extensive modifications to the IF system which are not warranted at this time.

VLA — Repair and Maintenance

When the new 7 mm receivers were first installed on the VLA, the aperture efficiency of the antennas was between 10 and 15 percent at that short wavelength. This low efficiency was due to small irregularities in the surface of the primary reflectors. Holographic measurements of the antennas provided the corrections needed to bring the antenna surfaces back to their true figure. In 1996 and 1997 the VLA antenna mechanics adjusted the surfaces of the thirteen antennas with 7 mm receivers and improved the efficiency to about 40 percent. This program will continue in 1998 with the other VLA antennas.

The maintenance of the VLA infrastructure continues as a high priority. As in the past, the major long-term projects are rail maintenance, access port replacement, and antenna painting.

Rail system maintenance has emphasized mainline leveling in 1997 and this will continue in 1998. This involves aligning, gauging, and reballasting the rail track between the antenna stations. Two kilometers of rail line that have been leveled on the east arm have greatly reduced the swaying of the transporter during antenna moves.

The aging of the VLA is seen clearly in the rust and staining on a large number of the VLA antennas. A program for painting the VLA antennas was initiated in 1993 to attack these problems before mechanical deterioration set in. By the end of 1997, fourteen antennas will have been painted. This work is performed by a four-man NRAO summer crew. Since three antennas can be painted each summer, this round of painting will be completed in 2002. After that, antenna painting will become a lower level maintenance item.

In 1991, the azimuth bearing in VLA Antenna 21 failed, putting the antenna out of service for almost a year. Monitoring of the metal content of the bearing grease and the vertical play of the azimuth bearings shows that there are other antennas with worn or damaged bearings. In 1994, the azimuth bearing of Antenna 9 was replaced as part of its regular overhaul. In late August 1996, the bearing of Antenna 23 was replaced, and the bearing in Antenna 1 will be replaced in October 1997. Several other antennas will need bearing replacements in the near future.

There is a program to replace the waveguide access ports at the VLA with steel culverts. The existing concrete access ports are deteriorating and collapsing. By the end of 1995, 45 access ports had been rebuilt out of a total of 122. Due to a lack of funds no progress was made on this project in 1996. This replacement program was restarted in 1997 with six access ports replaced. At least six more years will be needed to complete this project.

Much of the VLA outdoor maintenance is done during the summer months, taking advantage of the longer days and moderate weather. During this period, the regular NRAO staff is augmented by seasonal employees, and the VLA maintenance staff goes to a ten-hour workday. In 1997, fourteen temporary employees were hired for work on the rail and painting crews and for carpentry and vehicle maintenance. In 1998, a similar number of seasonal staff will be hired.

2. Very Long Baseline Array

Status

The VLBA continues to observe roughly 50-60 percent of the available time, with a further 20-25 percent of time used for testing and maintenance. Improvements to the array since last year include implementation of sub-arraying, automatic tape allocation at the antennas (removing the need for detailed user specification of tape motion), an enhancement of the allowable data rate produced by the correlator, installation of the first 90 GHz VLBA system (three more are expected in the next year), and successful processing and support of Space VLBI data from the Japanese HALCA satellite. A rebuild of the operations software system started in 1997, and is expected to be completed in 1998, after which the VLBA should be able to observe approximately 75 percent of the available time.

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 milli-arcseconds at 90 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 low-frequency receiver (330 and 610 MHz) is a room temperature GaAsFET. The cooled receiver for each band is in a separate dewar mounted directly on the feed to minimize noise contributions from waveguides, etc. All receivers cover both right and left circular polarization. There is a dichroic/ellipsoid system that allows simultaneous observations at 4 and 13 cm, primarily for geodesy and astrometry.

Table III.2. VLBA Receiving Systems

Frequency Range (GHz)	Typical Zenith SEFD‡ (Jy)	Typical Zenith Gain (K Jy^{-1})
0.312 - 0.345	2256	0.092
0.600 - 0.630	2261	0.084
1.30 - 1.70	316	0.097
2.13 - 2.35	338	0.092
2.13 - 2.35*	425	0.078
4.50 - 5.14	309	0.131
7.88 - 8.93	323	0.117
7.88 - 8.93*	398	0.113
12.0 - 15.4	562	0.111
21.1 - 24.6	1001	0.103
42.3 43.5	1339	0.084
85.0 - 92.0#	6000	0.02

‡System equivalent flux density.
* With 13/4 cm dichroic.
\# PT 1997, LA 1998

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 Haystack Observatory. The recorder is similar to the one used in the Mark III and Mark IV VLBI systems. There are two drives at each VLBA station to allow more than 20 hours of recording at 128 Mbits/second between required visits by station personnel for tape changes. The tapes are 16 microns thick, with about 3.4 miles of tape on a 14-inch reel.

The VLBA correlator is located at the AOC in Socorro. It is able to correlate as many as eight input data channels from each of 20 antennas simultaneously. For most modes, 1024 spectral channels can be provided for each input channel. The correlator is of a novel design, pioneered by the Nobeyama Radio Observatory in Japan, in which each bit stream is Fourier transformed to a spectrum before cross correlation (the "FX" architecture). Output data is archived on DAT tapes, while the input tapes are recycled for more observing shortly after correlation. Users receive their correlated data in FITS format on any of several media, including DAT and EXABYTE tapes, typically within two or three weeks of observing.

The correlator now is in routine operation. It can handle the full complement of 20 stations for the majority of types of continuum and spectral line observations, including full polarization data. The core of the correlator real-time code was re-written in late 1994/early 1995 in order to improve its reliability. The improved robustness has been evident in the smoothness of correlator operations since the software upgrade. VLBA postprocessing is done in the astronomical image processing system (AIPS). Software development for VLBI in AIPS is essentially complete, apart from support for some advanced capabilities of the array such as phase referencing. Much work has been done to make the AIPS VLBI sub-system more robust and user-friendly. Astrometric/geodetic processing will be 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, IBM RS/6000-580, and SGI Origin 2000 classes.

Future Plans

Major milestones for the VLBA for the next year include:

(a) A ramp-up to full operational support for Space VLBI. At present, software development on the correlator continues to merge the special requirements of Orbiting VLBI data processing with the current VLBA operational system. Further correlator, AIPS, and operational software development will be required.

(b) Pulsar gating by the VLBA correlator (blanking times of low pulse signal in the input data streams of the correlator) is undergoing testing, and will be available in mid-1998. Specification of the pulsar phase will be done using a polynomial series provided by the Princeton TEMPO software.

(c) Three more 90 GHz receivers for the VLBA are expected over the next year. Once four (or more) receivers are in place, important SiO maser and AGN studies can begin at 90 micro-arcsecond resolution.

(d) The software and information-handling methods of the VLBA Operations group are undergoing major revision for the next year. A new database design and suite of user interfaces are under construction. A major limitation to increasing the level of observing on the VLBA is the current information-handling approach, which evolved during the commissioning phase of the VLBA correlator.

(e) AIPS development and support of VLBA data reduction will now continue for another year, at which time a transition to AIPS++ is envisaged.

(f) An intensive program of antenna calibration and measurement is underway, and will continue for two or three years. Holography of the VLBA antennas has indicated some alignment problems and a possible small subreflector astigmatism, both of which are under investigation.

(g) The maximum recording rate of the VLBA will be expanded to 512 Mb/s (currently 256 Mb/s). This provides high-sensitivity recording for approximately six hours (two tape recorders operating simultaneously). This feature is expected to be particularly useful for millimeter observing. This should be available by mid-1998.

3. 12 Meter Telescope

The NRAO 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 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 new 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 future millimeter-array operation.

Present Instrumentation

Telescope

The basic specifications of the 12 Meter Telescope, its site, receivers, and spectrometers are:

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 receivers 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 extremely effective in terms of cost, manpower, and in operational demands.

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
Eight-beam Receiver:		
220 - 250	8-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

The following filter-bank spectrometers are maintained so that the astronomer will have access to the proper frequency resolution for a particular astronomical observation.

Table III.4. 12 Meter Filter Bank List

Resolution (kHz)	Number of Channels	Number of Filter Banks Per Channel
30	128	1
100	256	1
250	256	1
500	256	1
1000	256	2
2000	256	2

Note: All filter banks except the 30 kHz units can be divided into two 128-channel sections to accept two independent IF channels.

To enhance the telescope's spectroscopic capability and to accommodate the 8-beam receiver, a hybrid filter bank/autocorrelator is available. Its instrumental parameters are as follows:

- 8 independent, tunable IF sections;
- 1536 spectral channels (can be split into 8 sections);
- Maximum total bandwidth options:
  1 x 2400 MHz
  2 x 1200 MHz
  4 x 600 MHz
  8 x 300 MHz;
- Frequency resolution (per channel): variable in steps of two continuously between 1.56 MHz and 24 kHz for each of two IF channels.

Note that the current instantaneous bandwidth is limited by the receiver IF bandwidth. The center frequency of the IF for some receivers is being changed from 1.5 GHz to ~3.5 GHz, to increase this instantaneous bandwidth beyond 1 GHz. This is particularly important for extragalactic observations of high redshift galaxies.

Future Instrumentation Plans

Most millimeter-wave spectroscopic studies of star formation, interstellar chemistry, galactic and extragalactic composition, etc., require observations of a number of molecules in a number of transitions, occurring at many different frequencies. These studies can be carried out most expeditiously, and most thoroughly, if high-sensitivity receivers are available for all the atmospheric windows and if a high-speed imaging capability is available at the most important wavelengths. Together, these requirements define the focus of the long-range plans for the 12 Meter.

All the developments described here are of immediate relevance to the 12 Meter Telescope, and most are equally relevant to the MMA.

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 ~8 compared to our current system. The existing hybrid spectrometer supports 8-IF channels. We hope to have this new 8-receiver, 3 mm system on the telescope within about one year.

Future Single-Beam Systems

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

Antenna Improvements

With the improved surface accuracy, operation of the 12 Meter Telescope at the highest frequencies (~300 GHz) is becoming more productive. This puts a more critical demand on the pointing characteristics of the telescope. In order to improve the pointing, we have implemented several upgrades in the past year. We are also installing an improved real-time monitoring system for movements of the prime focus, utilizing a laser and x-y translation detector. We expect to implement additional instrumentation (inclinometers, strain gauges, temperature sensors), replace the feed legs with a carbon-fiber design giving less temperature dependence and less aperture blockage, and install a sun screen to reduce thermal distortions of the telescope during daytime operation. We now routinely use an auxiliary optical pointing system to determine the telescope pointing model and to diagnose pointing anomalies. We intend to explore a higher level of automation, with the possibility of offset guiding on optical stars to give accurate tracking of weak sources.

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 ten percent or more improvement in the duty cycle of most observing modes (note that ten 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 observing mode has now 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 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 worth 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. Substantial sizes of maps, 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 is taking place to support continuum OTF observing as well.

Longer Term Future Plans

In addition to continued improvements in the 12 Meter, the Tucson staff will play a growing role in the development of the Millimeter Array. As the MMA project develops, there will be the necessity for real hardware design, prototyping, and testing, including multi-band, millimeter, and submillimeter-wave receivers, digital spectrometers, and continuum back-ends. Software evaluation in astronomical observations such as described above is another important area where the prototyping done at the 12 Meter will further the development of the MMA. Many of the projects already underway in support of the 12 Meter Telescope will become prototypes for, or otherwise contribute to the eventual MMA project. The Tucson staff are already actively participating in site testing for the MMA, with the construction of a portable centimeter wavelength interferometer to be used to study atmospheric phase instabilities at potential MMA sites. An innovative antenna design for the MMA is being explored, and shows great promise for a robust, high precision antenna. It is anticipated that Tucson participation in MMA development and support activities will continue to increase in the coming years.

4. 140 Foot Telescope

Due to delays in the completion of the Green Bank Telescope (GBT), the 140 Foot Telescope will continue to be operated as a user facility in 1998. There will be two deadlines (Fall 1997 and Spring 1998) for receipt of new proposals for observations during 1998. Although it may be necessary to impose some restrictions on the use of specific receivers and backends, most of the 140 Foot receivers should be available throughout the year.

The GBT C-band (4.0-5.8 GHz) receiver will be installed at the Cassegrain focus of the 140 Foot Telescope to support VLBI observations with the HALCA satellite. The GBT Ku-band (12-15 GHz) receiver was removed from the 140 Foot Cassegrain house to accommodate the C-band receiver. After the installation, the GBT receivers available at Cassegrain will cover C, X, and K-bands, allowing changes between these bands in only a few minutes. This arrangement makes better use of telescope time and simplifies scheduling of the HALCA, VLBI, and other observations. Use of the GBT receivers on the 140 Foot also allows them to be tested and debugged in realistic observing conditions before they are installed on the GBT.

A number of other GBT systems will be tested or used at the 140 Foot in 1998. The GBT metrology group has recently mounted three retroreflectors on the 140 Foot Telescope backup structure which will be used to test the laser ranging system software on a moving structure in the field. Other planned tests include the monitor and control software, AIPS++ single-dish software, spectral processor, and optical fibers for IF distribution. Also planned are holography measurements using GBT software in preparation for similar observations on the GBT. The 140 Foot operators are receiving a new workstation to allow them to assist in the development of the GBT operations interface.

In 1997 the VLBI recording terminal at the 140 Foot has become fully compatible with those at VLBA stations. The "D-rack,", tape recorder, and station computer are identical to standard VLBA equipment. VLBI observations are coordinated through Socorro, usually as part of experiments involving the VLBA. When the GBT becomes operational, the VLBA recording terminal will move from the 140 Foot to the GBT.

An S2 VLBI recording terminal has been loaned to NRAO by the Canadian Space Agency for use on the 140 Foot, primarily for VLBI experiments involving the Japanese radio astronomy satellite HALCA. The S2 system is in use for HALCA-related observing around the world, including sites in Australia and Canada.

Equipment to support the SETI Institute's Project Phoenix has been installed at the 140 Foot. The SETI Institute has proposed to use the telescope as a dedicated instrument for their program, with all costs being paid by the SETI Institute, upon completion of its operation as a user facility.

Spectrum Management and RFI Control

The 140 Foot Telescope will be used for test observations of the IRIDIUM satellites to measure the spectral power flux density of the emissions from the satellites in the 1610 - 1614 MHz band that is allocated to radio astronomy. The telescope's L-band receiver will be temporarily modified for the test observations.

The Interference Office in Green Bank continues to administer the National Radio Quiet Zone (NRQZ). The Interference Officer processes approximately one application per day for fixed transmitters located within the NRQZ. Additionally, the Officer assists applicants with the design and location of transmitters and verifies that the transmitters are installed in accordance with FCC licenses.

An Interference Protection Group was established this year to address the technical issues of the radio frequency interference that may be generated at the Green Bank site itself. The group has focused its efforts on measuring and reducing the interference produced by equipment that is to be installed at the GBT. Next year the group will broaden its scope to work on the detection, prevention, and excision of interfering emissions from any source. The goal is to reduce the general level of interference at Green Bank and to be able to identify and respond to any interfering signals detected during observations at the GBT.

IV. TECHNOLOGY DEVELOPMENT

1. Electronics Development Equipment

Cooled HFET Development

NRAO has worked on the development of HFET (heterostructure field-effect transistor) amplifiers for many years and is the recognized leader of cooled HFET amplifiers for radio astronomy use. State-of-the-art Indium Phosphide HFETs were made for NRAO by Hughes Research Laboratories and successfully incorporated into amplifiers starting in 1995. The highest frequency amplifiers cover the bands 65-90 GHz and 75-110 GHz with noise performance comparable to SIS mixers and much wider instantaneous bandwidth. This has the potential to provide superior performance in continuum receivers and increased operating ease for spectral line work in the frequency range below 115 GHz.

NRAO has produced many HFET amplifiers for use on NRAO telescopes (VLA, VLBA, 12 Meter, 140 Foot, and GBT) and for others in the radio astronomy community and other research areas. These range from low-frequency amplifiers (< 1 GHz) used in fundamental particle physics and magnetic resonance imaging development to the highest attainable frequencies for cosmic microwave background experiments. At the lowest frequencies, special balanced amplifiers have been developed which largely eliminate the need for bulky isolators and have better immunity to the effects of interference.

In 1998, a major goal is to begin work on an integrated IF amplifier for SIS mixers covering a 4-12 GHz IF band. This large instantaneous bandwidth will be needed for maximum continuum sensitivity by the MMA.

Major effort will continue to be expended on the development and production of amplifiers which will be used in the Microwave Anisotropy Probe (MAP) project, a joint effort with Princeton and NASA Goddard Space Flight Center. The receivers at 22, 30, 40, 60, and 90 GHz will be used in a new satellite to be launched in the year 2000 which will provide unprecedented accuracy in measurements of the cosmic microwave background radiation at angular scales down to 0.2 degrees and whole-sky connectivity. The amplifiers (except 60 GHz) will be directly usable on NRAO telescopes. In 1997, new amplifiers covering 26 to 110 GHz were developed and produced for use in test radiometer apparatus by Princeton. The objective is to complete construction of all MAP amplifiers and spares by mid-1998.

Millimeter-Wave Receiver Development

The design and fabrication of SIS (Superconductor-Insulator-Superconductor) mixers covering the frequency range 68-300 GHz are done by the CDL primarily in collaboration with the Semiconductor Device Laboratory at the University of Virginia, whose ability to provide rapid turnaround of new designs is crucial to the development effort. Mixers have been produced not only for the 12 Meter, but for other radio astronomy organizations as well. The noise temperatures now being attained in laboratory receivers are only three to six times the photon temperature hf/k, so in many cases the dominant noise sources are external to the mixers.

A new 200-300 GHz tunerless mixer has been fabricated and tested with good results; it is a forerunner of the future development of a mixer with an integrated IF amplifier. A 260-370 GHz mixer of modern design is under development to replace the existing mixers on the 12 Meter Telescope and achieve lower noise. Initial results have been disappointing, possibly due to a problem with resonant wire lengths during assembly; experiments are continuing.

Spectral line observations require only a single sideband response, whereas mixers typically provide a double sideband response. At the 12 Meter, receiver temperature is typically 60 K at 230 GHz, of which about 30 percent is due to unwanted image noise. In 1997, initial tests were made on a 200-300 GHz image separating mixer, which uses two properly-phased mixer elements to achieve sideband separation. A single mixer block contains a quadrature hybrid, LO power splitter, two mixers, and a cold internal image termination; it provides both upper and lower sideband outputs simultaneously. This device has been manufactured by JPL's Center for Space Microelectronics Technology in a new collaboration.

Results from early tests of the image separating mixer are shown for both upper and lower sidebands in Figure IV.1. The receiver single sideband noise temperature, referred to the vacuum window, is 50-80 K from 205-240 GHz and rises slowly at higher frequencies; most of this rise is believed to be due to other receiver components rather than the mixers. The sideband rejection is ~10 dB or better up to 290 GHz, which is sufficient to reduce the atmospheric contribution from the unwanted sideband by a factor of ten, which is the initial design goal.

Development and testing will continue through 1998. Different mounting structures will be tested which may improve the sideband separation.

A prototype planar SIS mixer has been designed for 590 GHz, and awaits SIS junction fabrication so its performance can be evaluated.

A development effort in collaboration with the University of Virginia (UVA) and the Smithsonian Astrophysical Observatory has produced an experimental traveling-wave SIS mixer for the 260-370 GHz range. The first device produced had good noise temperature but less than expected tuning range. Such mixers have been shown to work well at frequencies above 300 GHz and their development may allow mixers that work up to 700 GHz to be made by the UVA; this is important for development of receivers for the MMA. This work has been delayed by the departure of a UVA graduate student but will resume in 1998.

Present single-ended mixers are susceptible to LO sideband noise, which often has severe effects, increasing receiver noise temperature by as much as a factor of two. They also require high LO power because the LO is injected by means of a directional coupler. Both of these problems could be significantly helped by development of a balanced SIS mixer. A balanced mixer for 200-300 GHz will be developed which incorporates a quadrature hybrid, two mixers, and a 180-degree IF hybrid. These will incorporate the same design principles and structures already proven in the image separating mixer. It is expected that initial tests will occur before the end of 1997, and that the work will continue in 1998.

Noise Temperature of the Complete SSB Receiver

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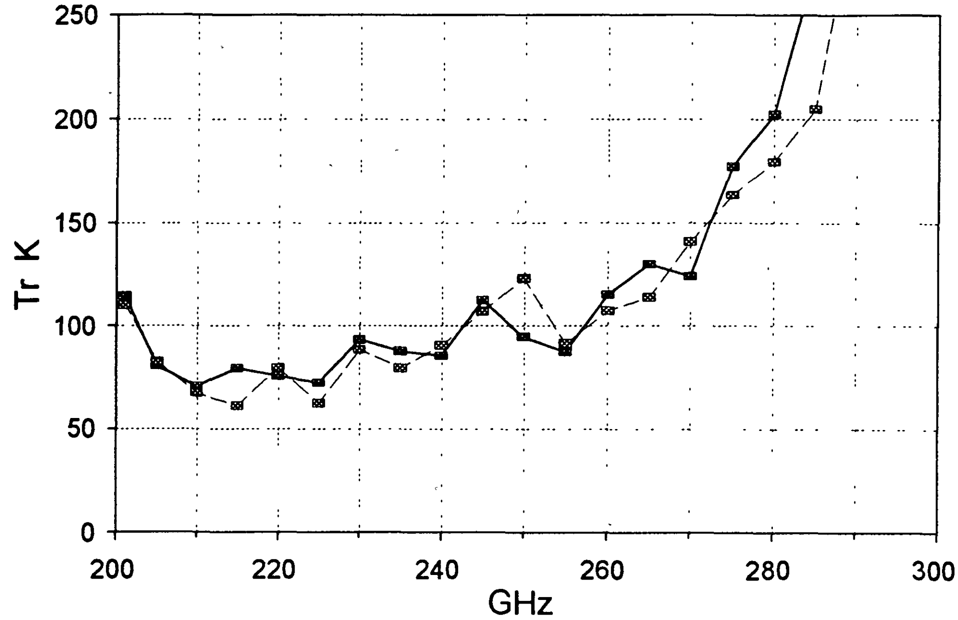


Image Rejection

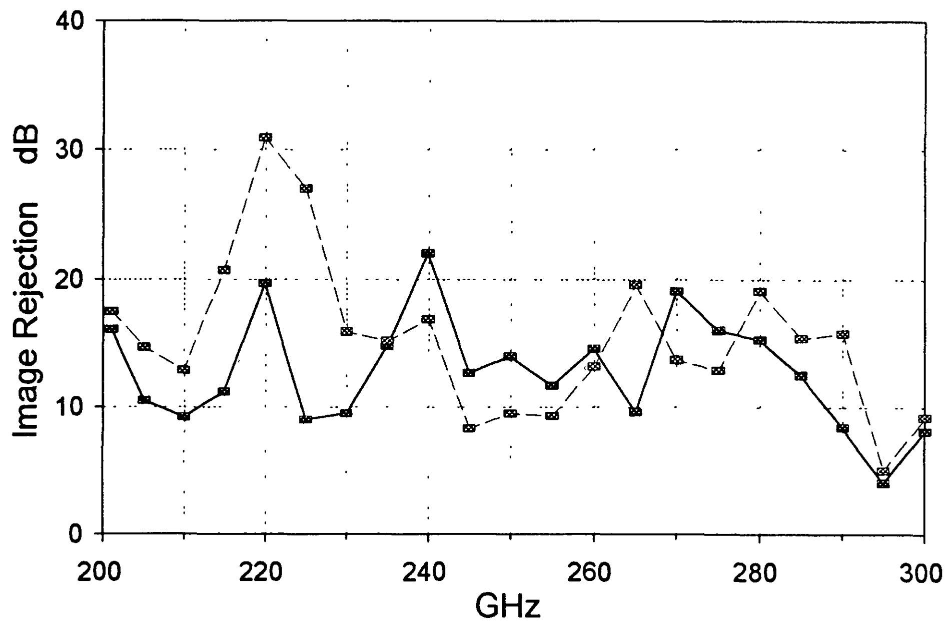


Figure IV.1

The instantaneous bandwidth of present mixers is limited because of the need for an isolator between the mixer and IF amplifier. Results obtained at Owens Valley Radio Observatory show that it is practical to produce a mixer with an integrated IF amplifier and achieve a bandwidth of 4 GHz. A development of this type is planned to achieve an IF bandwidth of 8 GHz for use by the MMA. Initial planning has begun with discussions within the CDL and with other researchers interested in this area, particularly H. Zirath (Chalmers University) and S. Weinreb (University of Massachusetts); either a discrete InP transistor or MMIC device may be used.

From the above discussion, it may be deduced that the ultimate goal of the mixer development effort is to produce an image-separating balanced mixer with integrated IF amplifiers, which will provide both upper and lower sidebands with the lowest possible noise, low LO power requirements, and wide IF bandwidth.

Electromagnetics

Wider band amplifiers and mixers require wider band supporting elements. The CDL has designed and tested several new components with the goal of having receiver performance limited only by waveguide band response. A new orthomode transducer (OMT) has been designed and fabricated for the 18 to 26 GHz band as the first of a new generation of such components. It provides excellent, resonance-free polarization separation over a frequency ratio of 1.4:1, thus covering the entire waveguide band. In 1998, a new lower loss version of the OMT will be fabricated in copper in a collaborative arrangement with the Max Planck Institute for Radio Astronomy (MPIfR) in Germany. Also, a new phase shifter to be used in conjunction with the OMT to convert between dual linear and dual circular polarization has been designed and built. It provides a 90 degree phase shift with an axial ratio less than 1 dB over the entire waveguide band, but it has proven difficult to fabricate with sufficient accuracy; a new electroformed version is now under test. Further work will be done to make similar devices more compact at lower frequencies and easier to fabricate at higher frequencies.

The combined goal of amplifier and passive polarization components is to enable full waveguide band frequency coverage, without mechanical tuning, for continuum and spectral line measurements. At lower frequencies, where severe interference may cause amplifier saturation problems when full waveguide coverage is implemented, other solutions to wideband frequency coverage must be sought.

New feed developments have also been pursued. A new family of feeds for the VLA Upgrade project will be designed in conjunction with an investigation of how best to optimize performance in the VLA asymmetrical subreflector system.

86 GHz VLBA Receivers

One prototype receiver employing InP HFET amplifiers was successfully completed and tested on the VLBA Pie Town antenna. Three additional receivers will be completed, installed, and undergo initial tests before the end of 1997, and used extensively for observations in 1998. Full upgrade of the VLBA to 86 GHz will require additional funds.

Green Bank Spectrometer

System testing continued in 1997 for the 262,144-channel GBT spectrometer, which will be able to analyze instantaneous bandwidths up to 800 MHz. This extended testing has now successfully produced a spectrum of an 800 MHz-wide signal and control software to operate different spectrometer modes was written in 1997. Testing of the basic functioning of the entire spectrometer will be completed in 1998, and the equipment will be moved to Green Bank for integrated testing in the control mock-up facility.

A duplicate of the Green Bank spectrometer with slight modifications is under construction at the MPIfR. Another duplicate is under construction at the CDL for use with the 12 Meter antenna; the IF electronics are being built in Tucson. A third, smaller copy is under construction for use by the University of Massachusetts.

Other Hardware Developments

Spillover shields for the GBT have been designed and are under construction to reduce scattering by the feed arm structure in the vicinity of the subreflector. These shields redirect the energy outside the subreflector onto the main reflector and onto the sky. They will reduce the system noise temperature accordingly.

The search for the ultimate vacuum window, required for cryogenic receivers, inevitably results in a compromise between leak rate and electrical loss. The CDL millimeter-wave group has developed new broadband, low-loss vacuum windows for the 90-115 GHz, 8-beam and 200-300 GHz receivers using plastic film vacuum materials. Although these perform well, they are probably too leaky for use with the MMA for extended periods. In 1998, we expect to complete and test broadband vacuum windows using crystalline quartz.

We are developing a new sideband generator for SIS mixer measurement using an 8-18 GHz YIG oscillator, X3 multiplier, 26-40 GHz MMIC power amplifier, and X8 or X9 multiplier to generate signals in the 200-360 GHz range.

A new harmonic comb generator for injection of phase calibration signals into receiver front-ends is under development. The present comb generator works well up to a frequency of about 25 GHz. With the use of RF components capable of working to higher frequencies, it is planned to extend this coverage to at least 50 GHz.

An experimental frequency tripler for use as an LO source with possible MMA application is being developed for use at 93 GHz. It consists of a novel balanced diode arrangement implemented using monolithic techniques. Balanced frequency doublers for use at 80 and 160 GHz for possible MMA application are being developed and will be evaluated in 1997. Use of planar Schottky diode mixers at frequencies of 585 and 690 GHz is being investigated. These designs are similar to SIS mixer designs for 590 GHz and are fixedtuned and broadband. Prototypes have been fabricated and tested at room and cryogenic temperatures with encouraging results.

As part of the effort to develop conventional LO sources for the MMA, the development of a tipping radiometer for use at 690 GHz has been undertaken. This system will employ the technique of starting with a low-frequency oscillator followed by stages of amplification and multiplication to generate the LO signal. It will ultimately be installed at the MMA site in Chile and used for atmospheric opacity measurements.

The CDL, in collaboration with NRAO Tucson personnel and UCLA, is undertaking the development of an LO system for possible MMA use which will employ two phase-locked lasers whose difference frequency is the desired LO signal. The fundamental problem is to develop an efficient photomixer and to couple sufficient energy out of the structure to drive an SIS mixer. In 1998, primary design studies will take place to determine how the optical energy can be coupled to the detector diodes and how the RF energy can be coupled to an output waveguide. This will provide a prediction of the output power and usable bandwidth. Experiments to fabricate and test such a device will probably occur in late 1998 or 1999.

In the present SIS mixer testing system, a mechanical IF switch within the dewar is needed in order to switch in various loads and signals. With currently available commercial switches, good performance is available but static discharge associated with motion of the contacts generates pulses which damage SIS mixers. We currently use specially modified switches which work well up to a frequency of 2 GHz, which is adequate for our present IF band. However, for the 4-12 GHz band envisaged for the MMA, we need new switches. We are cooperating with Novak Corporation (which has built switches used in many VLA receivers) in the design of a new switch which should be usable to > 12 GHz.

Advanced Concept Development

In collaboration with other NRAO personnel and UVA, an adaptive interference canceling receiver has been developed for the 90-100 MHz region in which FM transmitter interference is omnipresent. It employs a digital filtering technique in which supplemental antennas are used to receive interference only and a standard feed is used to receive the sky plus whatever interference enters. An adaptive algorithm is used to subtract the interference from the sky+interference signal. This system was successfully tested on the 140 Foot antenna in June 1997. Some problems with shielding from control room interference sources were encountered. In the second half of 1997 and through 1998, these problems will be addressed by better shielding and by converting the receiver passband to a higher frequency for better match to the characteristics of the spectral processor used in testing. In addition, the use of multiple receivers for the interfering signals will be investigated.

Multiple-feed arrays are currently limited in spatial coverage because the feeds cannot be spaced closely or they will interact and distort the beams. Current multiple feed systems thus cannot provide truly overlapping beams on the sky. A phased-array feed receiver system has been built to test an alternate approach to multiple beam formation. An array of 19 sinuous feeds is equipped with MMIC amplifiers to cover the 1.16 to 1.62 GHz band. The proof-of-concept system is uncooled and has a noise temperature of about 400 K on the sky.

The signals are digitized and combined, four beams at a time, using the spectral line processor. Tests to determine the soundness of the system concept on the sky were conducted in 1997 with good results. Figure IV.2a shows the complex feed response to a point source and Figure IV.2b shows the overlapping beams synthesized in post-processing. It is apparent that the goal of going directly from the raw receiver outputs to a sky map can be achieved in practice. During 1998, the receivers will be improved by installing uncooled balanced amplifiers to achieve a noise temperature on the sky as low as 100 K. Studies of the required dedicated correlator will be performed in collaboration with personnel of the Australia Telescope.

Protection from Radio Frequency Interference

The CDL will continue contributing to the general radio astronomy effort of working for protection from interference through frequency coordination. Two meetings of Working Party 7D of the ITU Radiocummunication Sector are expected to take place during 1998, and A. R. Thompson will attend these as chairman of the U.S. membership of WP7D. Much of the effort at these meetings will be concerned with preparation for the 1999 World Radio Communication Conference at which radio astronomy allocations at frequencies above 70 GHz will be on the agenda for review and possible action. Current concerns include downlink and spurious emissions from the large number of low-earth-orbit satellites planned for implementation during the next few years. Also of concern are various uplink and downlink transmissions of mobile satellite services in the bands between 1 GHz and 2 GHz. The IRIDIUM system of 66 satellites is planned to come into operation during 1998, and Dr. Thompson is assisting in coordination of tests of spurious emission levels in the 1610.6-1613.8 MHz radio astronomy band, in which NRAO will participate in late 1997. Dr. Thompson will also participate in the annual meeting of the Committee on Radio Frequencies of the NAS, and report on activity in the ITU area. Bimonthly meetings of frequency coordinators at the NRAO facilities and other U.S. radio astronomy observatories, coordinated through the CDL, are expected to continue.

2. Computing

Computing facilities at the NRAO provide vital functions for both 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 NRAO made considerable progress in addressing many of the problems of its aging computing infrastructure. First, the Observatory was able to complete implementation of an "Intranet" which has dramatically improved networking between NRAO sites, enabled greatly improved Internet service to

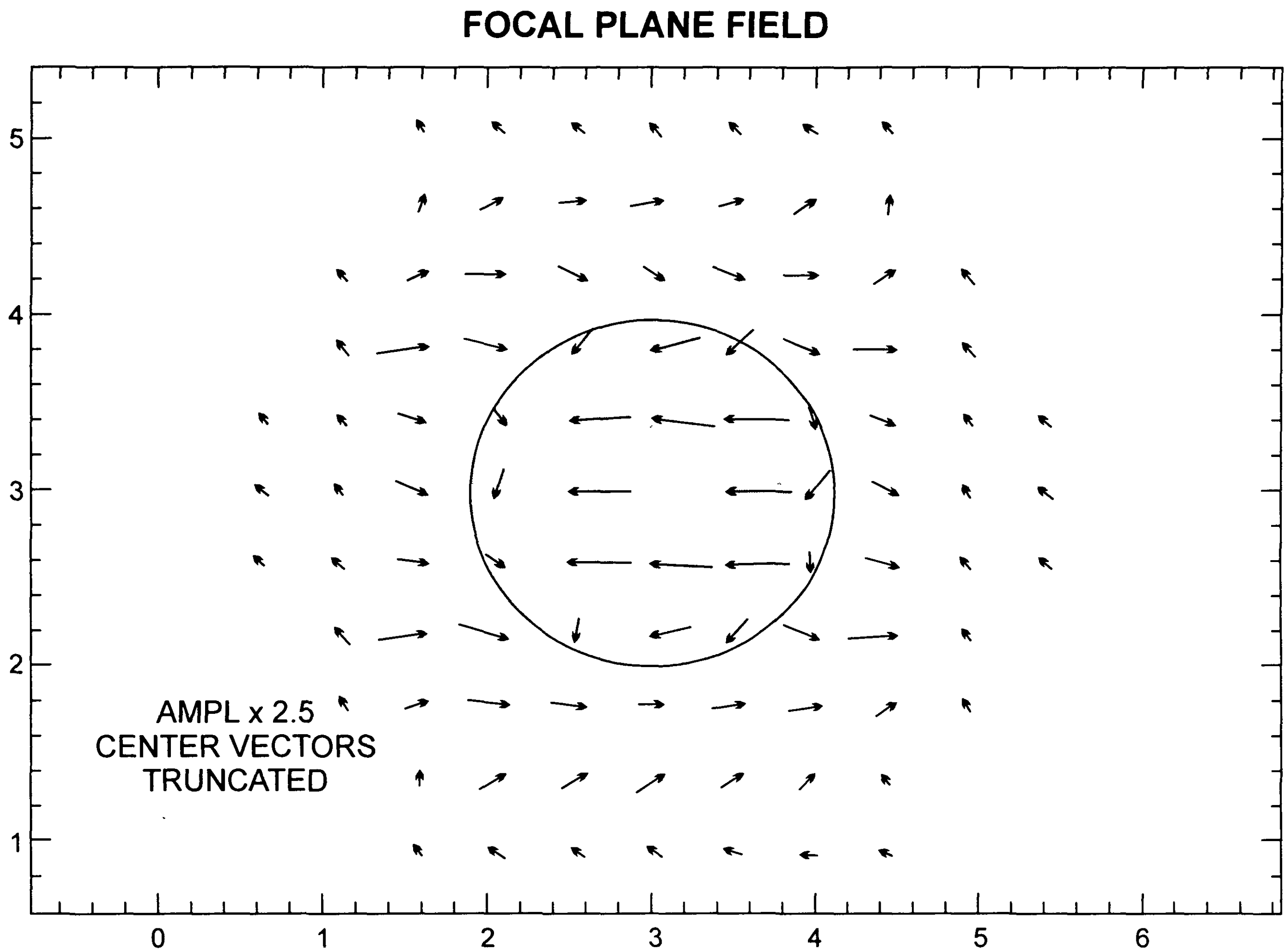


Figure IV.2a. Focal plane fields. Vector plot showing relative electric field amplitude and phase resulting from the array scanned through a point source. For this plot, the amplitude of the center vectors has been truncated by a factor of 2.5. The circle indicates the approximate location of the first null in the Airy pattern.

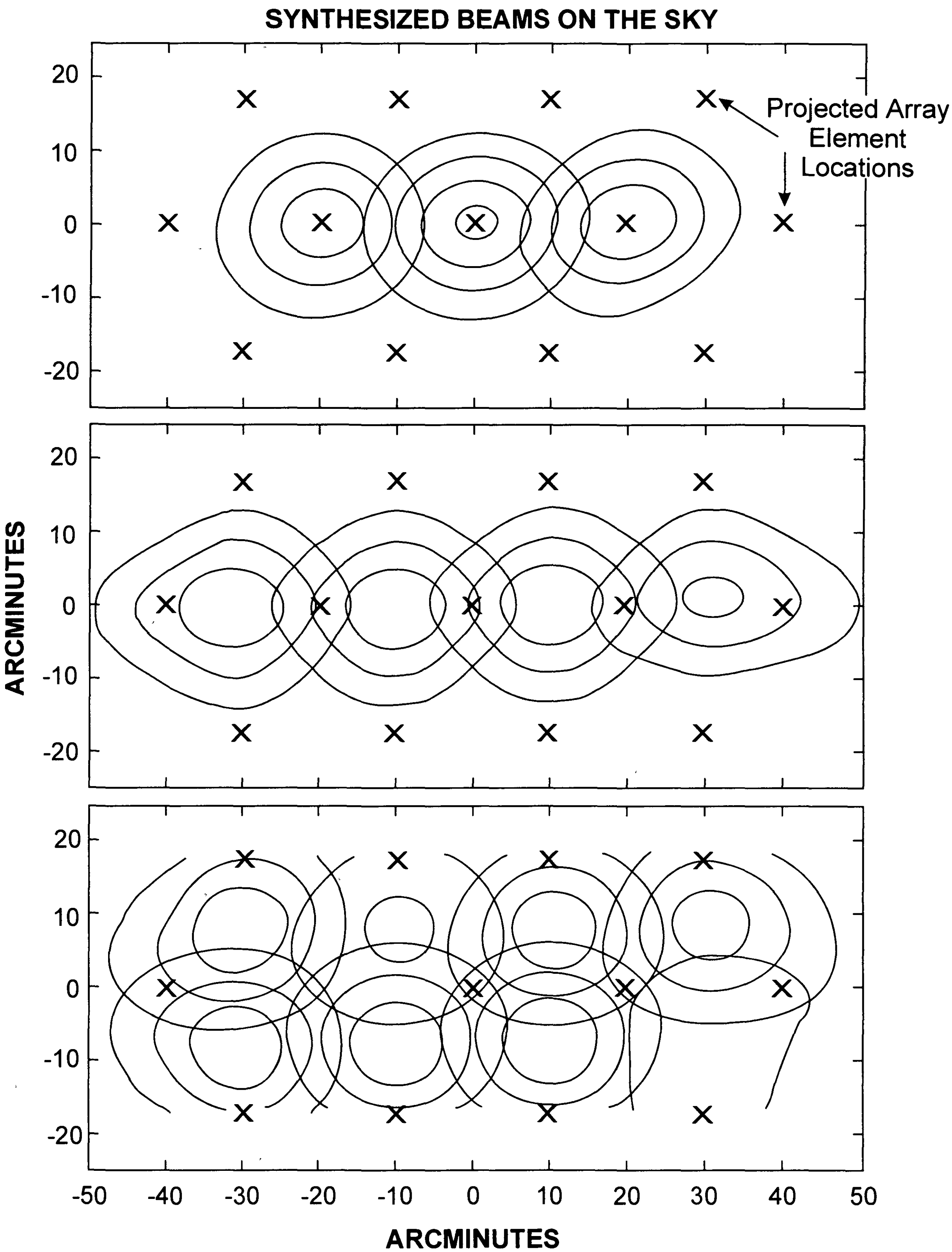


Figure IV.2b. Synthesized telescope beams. Upper plot shows three beams on the projected element locations along the array east-west center line, middle plots shows four beams located between the element locations along the east-west center line, and the lower plot shows beams between the element locations north and south of the center line.

Green Bank, and enhanced security for sensitive communications between NRAO sites, at modest cost. Second, using a combination of savings in computer maintenance, the 1996 RE budget for computing, and funds shifted from smaller expenditure categories, the Observatory was able to replace its old IBM workstations with modern workstations from Sun and Digital in early 1997. Significant investments in local networking infrastructure have been possible in Green Bank and Socorro. Finally, the combination of a more reasonable level of funds for Research Equipment in 1997 and steadily improving capability for modestly priced workstations allowed vitally needed upgrades for approximately 25 percent of the workstations on the desks of NRAO's scientific and engineering staff.

Comparatively small investments in new hardware will continue to significantly improve 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 will also create opportunities for wholly new scientific observations, loosening the computing restrictions currently faced by some advanced research efforts. Finally, continuing modest investment in NRAO's computing infrastructure will 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.

The Japanese VLBI satellite mission, HALCA, will enter full operations in late 1997. Launched in February 1997, HALCA is completely dependent upon NRAO software for key steps in data reduction, especially for fringe finding and calibration. The NRAO software AIPS has fully supported the data reduction for HALCA, and will continue to do so. HALCA is a perfect example of the vital nature of software for radio astronomy, and of the importance to the international radio astronomy community of NRAO's software efforts.

During 1997, NRAO has established a partnership with the National Computational Science Alliance (NCSA - formerly the National Center for Supercomputing Applications). This partnership will help NRAO and 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 or pulsar searching, can require computing resources beyond what NRAO can provide. Establishing an appropriate connection will allow these kinds of research projects to proceed, and lower the barriers between the radio astronomy community and the supercomputing community. The partnership formally begins 1 October 1997, and will be making rapid progress during 1998.

One of the most vital efforts which began in 1997, with potentially the largest impact on NRAO's future, is also the most mundane: assessing, testing, and correcting software and hardware bugs related to the change of century on January 1, 2000. Depending on the results of assessing systems at NRAO and the necessary adjustments required, this effort could have an impact on NRAO ranging from straightforward problem solving handled in the normal course of business to large efforts focused on the problems in some vital systems.

For 1998, 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 in approximately two years and three months, 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.

During 1997 we have begun the assessment and testing phase of preparing for the year 2000 at NRAO. These activities involve both scientific and administrative computing. A triage process is required to prioritize Y2K activities at NRAO: Selected operational and administrative functions must continue for NRAO to continue to function; some activities and functions will be tested and upgraded as time and available personnel allow; some activities and functions will not have specific Y2K efforts directed at them because of either obviously simple solutions or obsolescence.

During late 1997 and continuing into 1998, critical systems at NRAO will be tested in an operational mode, to verify their performance after the millennium change. Until this assessment is completed, the full impact of Y2K problems at NRAO cannot be accurately assessed; the good news is that there are no obvious areas of disastrous vulnerability for NRAO known at the present time. NRAO does not face the problems which the banking industry faces, with hundreds of millions of lines of customized software which is heavily date dependent. Instead, we face the challenges of finding and resolving many small potential Y2K problems, which will require detailed testing of critical systems.

Y2K vulnerabilities at NRAO break down into the following areas:

- Fiscal, Payroll, and Personnel: These are critical to NRAO's continued operation. Most major pieces are believed to be Y2K compliant, but detailed testing and verification are required.
- Telescope Operations: Most of our on-line systems should be Y2K compliant, but only detailed testing can find the many likely small errors. Detailed tests at NRAO will require considerable planning to insure that we can back out such tests and return to normal operations.
- Embedded PC's: Many of our most complex electronics systems use embedded PC's and chips which may not be Y2K compliant. Detailed testing is required to see which systems are affected, and where updates or replacement might be needed.
- Communications: Our phone systems and PBX's, the Intranet, the Internet, and long distance telephone services are all vulnerable. We need to review the weaknesses or potential problems in the hardware we own, and develop contingency plans if important communications services are unavailable or crippled in the first part of 2000.
- Utilities and Other Key Outside Requirements: Our planning will need to include the possible disruptions in power delivery to NRAO sites. Other services to be concerned about are being identified.

Completion of detailed assessment and testing in late 1997 and early 1998 will reveal the size of NRAO's Y2K vulnerabilities. Under worst-case scenarios, Y2K fixes at NRAO may require substantial resources from NRAO's Research Equipment budget in 1998 and 1999. More likely, there will be a modest impact on RE budgets and personnel, with the full impact becoming clear only after the assessment and testing phase is completed. 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 1998, approximately one-quarter of the workstations at NRAO should be upgraded to more capable systems. This level of machine replacement will allow NRAO to continue to retire obsolete workstations purchased in 1991 and earlier. These older machines have reached the end of their operational lifetimes, and are expected to no longer be supported by the manufacturer starting in 1998. Their upgrading or replacement is also required by the increasing demands on computational capability at NRAO from both increased demands from NRAO users and increased observational capabilities brought about by technological advances and improved observational techniques. These upgrades will allow most workstations at NRAO to be replaced or upgraded by the end of their useful lives (typically three to four years for scientific workstations). Without this level of effort, 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. The cost of this effort will be ~$250,000 for hardware acquisition during 1998. This level of investment will accomplish three goals:

- Reduce the difficulties faced by users getting time on higher end workstations at NRAO for 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, as expected, resources are constrained during 1998, the 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.

Networking and Networking Upgrades

At each of its major sites NRAO operates a complex networked computing environment. This offers numerous advantages for efficiency and flexibility in meeting the needs of computer users at NRAO, and allows a small support staff to support a large number of workstations. The tightly networked computing systems at NRAO also allow the Observatory to provide significant support to its users, especially outside users. For example, NRAO is able to provide support and documentation to its users through the facilities of the World Wide Web on the Internet (NRAO's home page on the WWW is 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 ongoing VLA sky survey projects, the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty-centimeters survey (FIRST).

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.

During 1996 and 1997 we were able to begin the process of modernizing NRAO's network infrastructure. This process needs to continue during 1998, and will include upgrading the networks at the sites to provide improved bandwidth to critical workstations and groups of workstations. This process should be accomplished in time for major new observational capabilities and opportunities at NRAO associated with the GBT and OVLBI, as well as the VLBA and the 12 Meter. 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.

The estimated cost for improving the performance of the internal computer networks at NRAO will be $250,000, spread over 1998 to 1999. Deferring this work will reduce the overall engineering and scientific productivity of NRAO staff and visitors.

Engineering Computing

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, the proposed Millimeter Array, and the proposed VLA upgrade. These projects are heavily dependent on the use of advanced engineering workstations to carry out various aspects of their design and fabrication, even at an early stage. If engineers at NRAO are faced with carrying out design efforts using obsolete or inadequate workstations and PC's, their productivity will suffer. Efforts in this area have been started in 1997 and should continue into 1998 and beyond. Estimated cost of this effort during 1998 will be approximately $80,000. This will allow both the acquisition of appropriate workstations and required software.

Addressing this need will increase the productivity of NRAO's engineers, and the effectiveness of NRAO's operations over the long term. Deferring this expenditure during 1998 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 nearing the end of its useful lifetime. The computers and disks used in the system are nearly 11 years old, and represent an expensive maintenance problem. Some of the disk systems are completely obsolete, and can be maintained only by having a large number of such ancient disks for spares (support and repair from the manufacturer is no longer available). This situation can be rectified before any disastrous failures occur by a gradual process of upgrading and replacing the aging systems with modern systems. The effort will yield several benefits, including a large reduction in risk of major system failures, a modest reduction in downtime for the VLA, a reduction in the cost of annual service contracts, and lay the preliminary ground work for any upgrades to the VLA related to the VLA upgrade effort. The effort will cost up to $150,000 during 1998. Deferring this effort increases the operational risks faced by the VLA and the risk of significant downtime for the array.

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. During 1997 we have begun the process of selecting and testing a new generation of mass storage devices, particularly new, more capable tape systems. In 1998 we plan to begin limited deployment of these new systems. This initial deployment 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 expected demand.

A desirable level for data storage and handling facilities at NRAO during 1998 would be $120,000. This would allow significant enhancement of current facilities and add new capabilities for especially large scientific problems. Individual tape systems are not that costly, but adding enough drives to create a useful capability here at NRAO does require 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.

Computing Personnel

The current level of personnel for computing support at the Observatory is only adequate to meet critical needs, and is not adequate to pursue the 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 in computing support and software development. As a result, NRAO is barely able to provide adequate 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 for enhancing computing support.

During 1998 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. Significant software challenges face our plans to get the VLBA and the GBT fully operational. Increased personnel for software development for the VLBA would dramatically enhance the observational capabilities of the VLBA, while additional personnel for the GBT will reduce the time required to bring the GBT laser ranging system into full operation. No new positions are currently budgeted for FY98.

V. GREEN BANK TELESCOPE

Antenna Construction

The accompanying photographs of the Green Bank Telescope (GBT), taken in late September 1997, shows that major portions of the tipping structure are in place atop the alidade. These include the elevation shaft, box structure, horizontal section of the feed arm, and the elevation wheel. Primary elements of the servo and electrical systems have been installed on the alidade and the antenna is rotated frequently to aid in the erection process.

The reflector backup structure (BUS) has been completed on the 175-foot square concrete slab at the telescope site and lifting of its 22 modules onto the box girder has begun. The entire BUS was constructed on the ground and consists of 7,652 different members and joints weighing approximately 2.1 million pounds. During construction all joints in the BUS were aligned with a positional accuracy of ± 0.25 inches. When finished, the jacks at the top of the 110 scaffolding towers were backed-off, leaving the BUS supported only by the 17 reinforced concrete piers on which it was built. The deflected shape of the BUS under gravity load was measured to verify the predicted values of the finite element analysis.

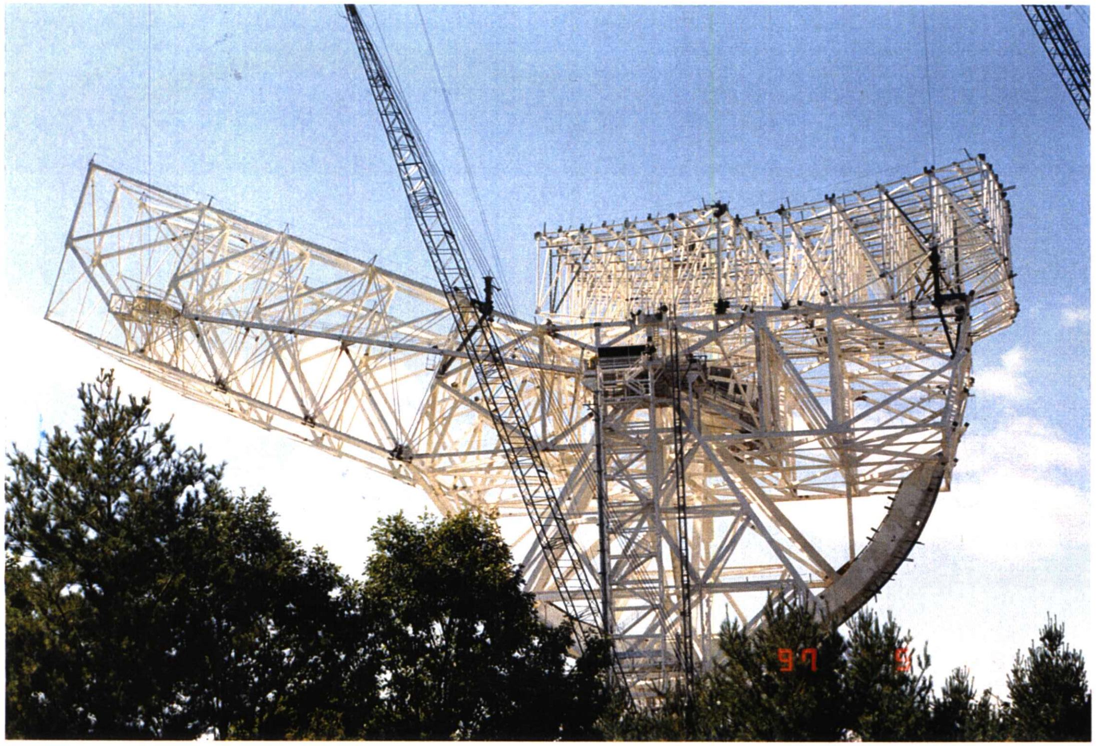
The Contractor has brought in additional heavy lifting equipment to reposition the 11 modules on the left side of the BUS because they are out of range of the main tower derrick. Individual modules will be sequentially placed at the base of the main derrick, the surface panel support actuators will be installed, and the module will then be lifted and placed on the box structure. Modules vary in weight between 25 tons and 74 tons, the rigging used for lifting weighs an additional 40 tons, making the heaviest lift 114 tons. As the modules are placed on the structure, the 1,072 interconnecting beams between the modules will be reinstalled for both stability and accurate positioning of neighboring units. Completion of the reflector BUS is scheduled for mid-1998.

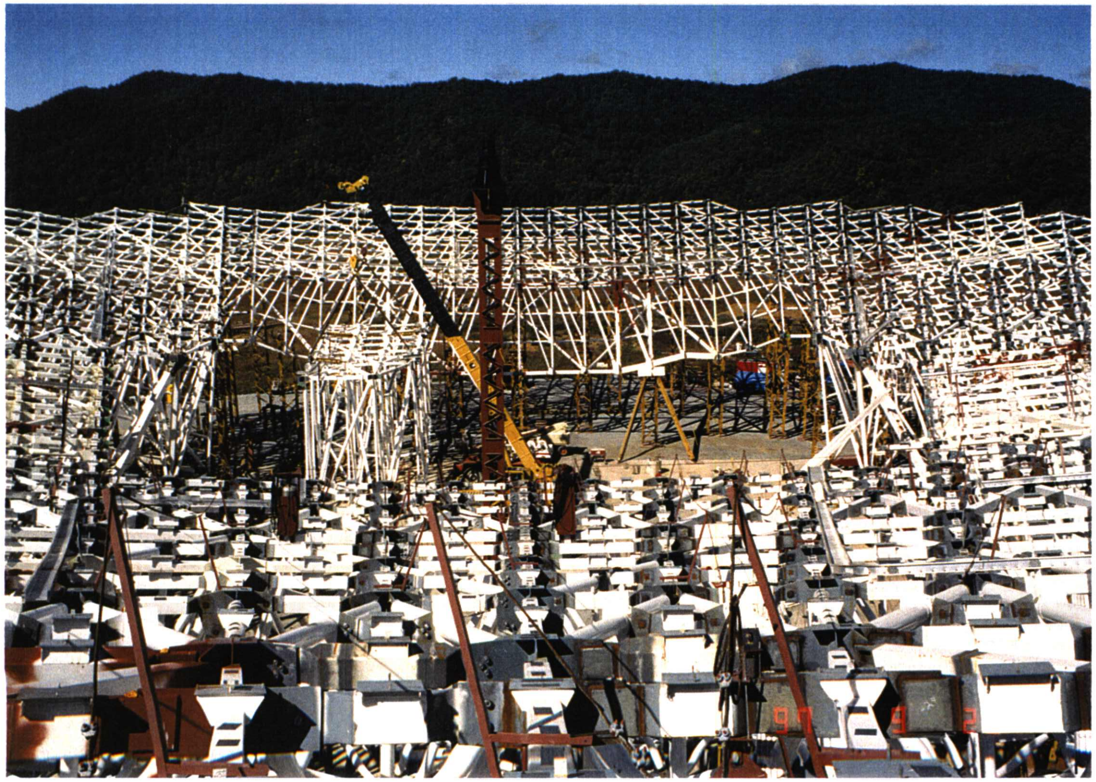
The upper most 60-foot portion of the feed arm was trial-erected at the site including the deployable prime focus boom, the prime focus rotation mount, the subreflector, and the subreflector adjustment mechanism. The feed/receiver room has been located nearby with the secondary focus feed turret in its roof. The feed arm servo, which controls all of the above equipment, has been installed and tested along with some of the NRAO monitor and control hardware. Photogrammetric setting of the subreflector surface and calibration of the six subreflector "Stewart platform" actuators remains to be done. These calibrations will be made in the fall of 1997.

The 200-foot dual tower section of the vertical feed arm was trial erected at the Contractor's fabrication plant in Mexia, Texas. It has been disassembled and shipped to the Green Bank site where final assembly will begin mid October, 1997. It is scheduled for erection after the BUS is in place. At that time it will be installed on the structure along with the upper 60-foot tip of the feed arm.

The 2,004 main reflector panels are now in production at the Contractor's plant. Installation and alignment of the surface is scheduled for late summer of 1998.

Photo taken in late September 1997 showing construction progress of the Green Bank Telescope (GBT).





ABOVE: UPPER FEED ARM
UPPER LEFT: INSTALLATION OF BACKUP STRUCTURE
LOWER LEFT: BACKUP STRUCTURE MODULES

Servo

NRAO's initial responsibility with respect to the GBT servo involves monitoring the progress of the servo contractor. This entails reviewing schedules, test procedures, and other documents. It also involves witnessing tests of various subsystems and evaluating the results. Finally, it requires the clarification of requirements and specifications as the design process evolves. The Contractor is providing two servo systems for the GBT, one to control the AZ/EL motion (AZ/EL servo) and a second to control motion of various components near the tip of the feed arm (feed arm servo). The Contractor will deliver a servo system which enables the telescope to operate at 15 GHz; NRAO assumes the responsibility of assuring that the servo will be suitable for frequencies higher than this.

The main thrust of this year's effort was the testing of the feed arm servo, in Green Bank, on the tip of the feed arm. Initially this consisted of refining the test plan prepared by the Contractor. This was followed by the installation and testing of all components of the servo. In general, the provided system has been proven capable of meeting its specifications. However, during the course of the testing, several problems were identified. Some of these problems have been fixed, some are being studied by the Contractor, and some have been addressed and will require continued testing of the system to verify the fix. In several instances, "problem areas" were related to damage by moisture within components and enclosures. Vents were added to many components to prevent future damage; these components will be monitored until the telescope is formally handed over to NRAO.

The availability of the feed arm servo during 1998 will present NRAO with several significant opportunities. First it will allow continued testing of the feed arm mechanisms when operated under various weather conditions, to ascertain that specifications are met under all environmental conditions. Second, it will provide a real platform on which to test the monitor and control interface with the servo system. Third, it will allow NRAO to gain familiarity with the control system provided by the Contractor. Finally, it will provide an opportunity to judge the acceptability of the Contractor's remedies to identified problems.

System Integration

In the first quarter of 1997, an integrated testbed, or Mock-up, of the GBT Electronics and Monitor and Control systems was assembled in the Jansky laboratory. It consists of all the completed IF, LO, and computer hardware. When needed, a cryogenic front-end is included. This Mock-up is available full-time for use by the GBT project. It has been vital in integrated tests of software and hardware. Use of the Mock-up will continue until the GBT antenna is delivered and outfitting begins.

During 1997, the laser rangefinders were used in precision pointing measurement tests at the 140 Foot Telescope, and measurements of the as-built GBT structure. These efforts have been useful integrations of hardware and software systems for the GBT's advanced measurement systems.

Fabrication of most GBT hardware components is nearing completion. Software components are growing more mature. The new GBT spectrometer correlator will move to Green Bank in early 1998 for integrated testing with the other electronics systems. Development of user interface software for all systems remains a major effort. Staff additions have been made in Green Bank and GBT Telescope Operations to work on the development of detailed operations and maintenance plans. The sections below provide more details on progress in systems built for the GBT by NRAO.

Electronics

At the beginning of 1997 we began setting up the GBT Mock-up Area in the Jansky laboratory basement. Included in this Mock-up is a significant portion of the GBT electronics which will be housed in the Receiver room, Alidade Servo room, Equipment room, and the Control room. This system is connected to the Green Bank Timing Center for LO reference, time, and weather information. It is also connected to the Spectral Processor, via fiber optic cabling, at the 140 Foot Telescope. Much hardware and software testing has been and will be completed with the help of this Mock-up.

During the next 12 months we expect to complete the following work:

- The testing of seventeen 100 MHz Converter Filter modules for the GBT Analog filter rack.
- The testing of the GBT LO Reference system.
- Construction of one fiber optic IF transmitter module and receiver module: fully temperature-controlled and with a digital AGC feedback loop.
- The testing of the GBT C-Band and L-Band receivers.
- The testing of the GBT Five-Band Prime Focus receiver, OMTs, and feeds.
- Fabrication of a receiver room wide-band filter bank prototype, testing and production of the remaining system.
- Design and construction of Q-Band receiver.
- Design, construction, and testing of low band digital filters for the GBT Spectrometer.
- RFI testing on receiver room electronics and necessary modifications to equipment.
- Construction of the 86 GHz Water Vapor Radiometer.

Monitor and Control

In 1997 major effort went into making the Mock-up a working system. Software was implemented for specific devices, notably the IF system, and by the end of 1997 the spectral processor, DCR, and holography back-ends will be supported. In the coming year, front-ends at L-, S-, and Q-band will be supported as they become available. Programming for the GBT spectrometer should be complete in early 1998 when the hardware moves to the Mock-up in Green Bank.

Hardware and software for the single-board computer remote access and reset system were completed. A system is in place to monitor all telescope processes running on the Sun workstations and to issue warning messages and mail whenever these processes fail. Such a system is yet to be developed for the single-board computers. A message system is in place, although many enhancements are planned for it. When complete, this code should be able to detect and broadcast notice of failure in any task in the system.

Antenna software is in good shape as code for both the main and secondary axes is running and has passed its unit tests. As reported before, software for the main axes is used regularly at the 140 Foot Telescope by SETI. Still remaining is an agreement for the interfaces to the metrology system and weather stations, and to precision pointing. The trajectory pre-processor, needed to forestall ringing of the structure while position-switching, also remains to be implemented.

A prototype of the observing interface to the GBT has been completed. This will serve as a working design specification for further efforts by the Monitor and Control group. The operator's interface has been prototyped at the highest level, by design of the many screens which will convey information from the GBT to anyone interested in monitoring its fully-detailed operational status.

A data storage and archival system will be purchased for the GBT one year before completion; as presently envisioned, this will be a RAID system which provides high throughput and failsafe duplication of data across disks. Other important matters to be addressed during 1998 include support for VLB and development of a scan simulator which will serve as a check on the validity of proposed observing program.

Open Loop Active Surface

Open loop surface construction and development continued in 1997. Work on hardware was low-key since most of the system was constructed and tested in previous years. During 1997, eight bulkhead panels were completed; these panels will accommodate the 2209 actuator cables entering the room. Wirelists for interconnection of various components in the Actuator room were developed. Software development concentrated on several key elements: first, software that monitors many system components and takes appropriate action in various failure modes was designed and partially implemented; second, software interface to the "outside world" was completed and tested; third, system initialization software was completed. Additionally, cross listings of actuators were generated to ease development, installation, and testing.

The software effort should end in 1998 with the completion of several minor tasks and a fairly large effort in system-level testing. Minor tasks remain in the hardware area as well, dealing with components having limited shelf life, and these tasks will commence approximately six months before system installation.

Closed Loop Active Surface and Laser Pointing

By the beginning of 1998, the laser metrology system will have completed the following steps:

- With the delivery of the instrument base castings scheduled for September 1997, the final instrument hardware component will be machined and 20 instruments will be fully assembled and tested.
- The Laser Metrology Interface Configuration Diagram (drawing D35420K014) will have names assigned to each block.

- Weld plates at cardinal points on the box, feed arm, BUS, and elevation weldments will be mounted in order to insure permanent, reproducible measurement points for the GBT Performance Measurements Program.
- Ten spherical retroreflectors will be mounted, calibrated, and ready for use with the GBT Performance Measurements Program, and 140 Foot Telescope experiments.
- The prototype panel setting tool will be released to the Contractor for evaluation.
- The Laser Metrology and Precision Pointing groups will have demonstrated software interfaces at the 140 Foot Telescope experiments.

With the completion of the instrument hardware, attention will turn to absolute calibration procedures for the instruments, ground monuments, and group index of refraction. The hydrostatic level will be used to set the ground monument. An atmospheric model will be developed to yield the group index of refraction as a function of elevation. Experimental work will begin on the construction phase of the GBT Performance Measurements Program. A comprehensive plan will be developed to measure and confirm calculated structural parameters. The remaining three monuments (ZY107-ZY109) will be poured as soon as the BUS is out of the way. Instrument shelters will be designed and built. Tipping structure mounts, cable runs, and access will be designed. Additional panel setting tools will be built. Retroreflector mounts will be built and calibrated for the rim of the dish. Data on retroreflectors and as-built panel geometry will be incorporated into the software. The finite element model of the telescope will be incorporated into the software in order to point the lasers. Contractor procedures on metrology-related topics will be reviewed. Special attention will be given to any opportunities to expedite delivery of the telescope and accelerate Phase III operation.

GBT Data Analysis

Standard GBT data analysis will be based on AIPS++. During 1997, a single-dish analysis package was developed using AIPS++ tools. The first release of this package, with limited capabilities, is expected at the end of 1997. A single-dish analysis package capable of replacing the existing NRAO single-dish package, UniPOPS, is expected in 1998. The AIPS++ single-dish group will begin developing multi-dimensional imaging tools for single-dish data in 1998. AIPS++ will continue to provide limited support for the display and analysis of engineering log data from the GBT.

Tools which will help observers interact with the on-line and archival GBT data will be developed in late 1997 and early 1998. This will include some simple automatic analysis of the data in real time to help assess the quality of the observations.

The use of FITS binary tables for all data ensures compatibility with an astronomical data standard. Having data in a standard format makes it possible to process GBT data using several data analysis systems in addition to the AIPS++ system.

Pointing

In 1998 the Precision Pointing Group will be continuing work on the several systems which will be used to improve the pointing and surface accuracies of the GBT.

As delivered, the GBT will have a total, non-repeatable pointing accuracy of 14 arcseconds, including wind and thermal effects. If the wind is light and the thermal distortions are small, the pointing error will be reduced to near 7 arcseconds. In this phase the repeatable pointing errors will be estimated using a traditional model; an algorithm of this form has already been integrated into the Monitor and Control system. A data analysis program which will produce estimates of the appropriate coefficients will be completed during the year.

It is useful here to note the complicated nature of the general pointing problem that the offset geometry introduces. The dividing line between pointing effects and focus-tracking effects has been defined such that changes in the prime focal point are called pointing corrections, while changes in the feed arm location are called focus-tracking corrections. The Metrology group is developing systems which will provide the additional information necessary to measure the non-repeatable pointing and the displacement of the optics. The Precision Pointing Group is completing the algorithms which will control the focus-tracking, and are beginning development of the analysis system for precision pointing.

The adjustments needed to correct the prime-focus boxes for sag of the feed arm are relatively simple to calculate and an algorithm for making these corrections has been installed in the Monitor and Control system. The proper adjustment of the Gregorian mirror is a more complicated issue that requires extensive ray-tracing, as well as calibration of the subreflector actuators. The Focus-Tracking Module for the Gregorian mirror is comprised of three functions. The first function will compute the target coordinates of the nominal first and second foci of the ellipsoid; this computation will depend only on the structural model and the best-fitting-paraboloid. The second function will accept these target coordinates, plus offsets, and will compute the subreflector coordinates which will image the first focal point onto the second. The third function will convert the subreflector coordinates into actuator lengths and will have provision to include actuator calibration.

A critical milestone in the development of the focus-tracking system will occur in the fall of 1997, when the module which commands the location of the prime focus feed and the Gregorian subreflector is integrated into the Monitor and Control, and the total system is then used to control the optics during and after the feed arm servo acceptance tests. The initial effort will be to test the "static" behavior of the focus-tracking algorithm. With the Monitor and Control code operating and connected to the subreflector rack, various elevations will be commanded (in Glish or by the Operator Interface) and the subreflector will be observed to verify that it moves in the correct direction and by about the correct amount. In the next phase, a test of the "dynamic" behavior of the subreflector servo system will be made. All six actuators will be commanded to move one by one, and the period and amplitude of the sinusoid will be varied to study the dynamical response of the total system (Monitor and Control command system, focus-tracking algorithm, PCD electronics and subreflector mechanism).

Once the basic parameters of the focus-tracking hardware are known, an effort will be made to model the effects of observational errors on the calibration of the position of the subreflector, in order to better understand the precision with which in-situ calibration can be performed, and to explore which observational techniques will be most useful. The study will be based on Monte Carlo simulations. Possible ways of using laser ranging measurements to improve knowledge of the calibration of the actuators and to give more accurate estimates of the mirror position will be studied during 1998.

It is anticipated that the program of pointing measurements on the 140 Foot Telescope will be completed by the end of 1997. In this program, four rangefinders and three spheres, the latter mounted on the backup structure of the 140 Foot, are used to monitor the orientation of a plane defined by the retrospheres. By doing so, we learn how frequently ranges must be sampled in order to provide a robust estimate of position, and we explore the limitations to the accuracy that might be imposed by the environment and by the instruments themselves.

When rangefinders and reflectors are available on the GBT in the winter 1997/98, the effort will switch to monitoring locations on the antenna during construction. This should help in the understanding of the wind driven oscillations in the structure, and will in addition, provide invaluable data on the principal modes of the structure.

Concurrently with these developments, details of the production analysis system will be worked out. These include scheduling of rangefinder measurements, fitting of structural models to the measured ranges, filtering and predicting pointing and surface corrections, and interaction with the Monitor and Control system. It is anticipated that the work in these areas will continue throughout 1998.

To maximize performance, the figure of the primary mirror surface will be determined by the positioning of the actuators. In the initial stages the commanded position will be deduced from the structural model of the telescope. Since the optimal position for the telescope optics requires knowledge of the figure of the primary mirror, this effort has been closely integrated with the work on focus-tracking. A prototype program has been developed to command the actuators to drive the requisite distance to attain the desired surface figure. During the next year the program will be refined and integrated into the Monitor and Control system.

The Quadrant Detector development has been promising. This device will provide information about the position of the feed arm relative to the primary mirror at rapid intervals. The information will be used in the Metrology system to update the positions of the feed-arm lasers, and in the Focus-Tracking Module to improve the estimate of the motion of the subreflector needed to maintain focus. It is planned to make a first integration of a prototype of this device into the Focus-Tracking Module in 1998.

VI. MAJOR INITIATIVES

1. The Millimeter Array

In 1998 we look forward to beginning the next major initiative in radio astronomy, the Millimeter Array (MMA). The MMA will extend the powerful, high-resolution, imaging techniques of radio astronomy to millimeter wavelengths.

The millimeter wavelengths in the electromagnetic spectrum describe a boundary in astronomy, the margin where radio astronomy ends and infrared astronomy begins. The distinction is more than nomenclature: the richness of the radio sky is provided by non-thermal synchrotron radiation from relativistic electrons whereas the richness of the millimeter sky is a result of thermal emission from cool gas and dust, the latter being the same material that brightens the sky at infrared wavelengths. Fortunately, millimeter wavelengths do not mark a technological boundary in observational ground-based astronomy. The aperture synthesis techniques that were developed for radio astronomy and which permit precision astronomical imaging on sub-arcsecond angular scales are directly extendable to millimeter and submillimeter astronomy. The principal scientific requirement for the MMA is to apply the technological tools of radio astronomy to celestial imaging of thermal objects such as can only be studied now in the far-infrared from space with course angular resolution and limited sensitivity.

As a scientific complement to the next generation of space optical and infrared telescopes, the Millimeter Array will provide images at 1 mm wavelength with the same 0."1 resolution achieved by the Hubble Space Telescope (HST) at visible wavelengths. This is accomplished by means of an MMA antenna array configuration as large as 3 km in extent. Lower resolution imaging comes from more compact array configurations. With the MMA antennas packed-in closely together astronomers will make high fidelity images of astrophysical objects that are very much larger than the primary beam of the array antennas. Scientifically the MMA needed to be designed as a complete imaging instrument, the first such telescope in astronomy.

The MMA project will begin in 1998 with a three-year design and instrument prototyping phase referred to as MMA Design and Development (D&D). In this period (a) prototype hardware will be built of all the major MMA subsystems so that its performance can be assessed and its cost established; (b) a site will be selected and access to that site for the array confirmed; and (c) partnerships with other federal agencies or via international consortia will be sought.

MMA Design and Development: Organization

The design effort on the MMA is being done by the NRAO in concert with university-based astronomers and engineers associated with the Owens Valley Radio Observatory (OVRO) and the Berkeley-Illinois-Maryland Association (BIMA) array. The mechanism for this cooperation is the Millimeter Array Development Consortium (MDC) which is comprised of five topical design working groups overseen by a steering committee of four members (two from the NRAO and one each from OVRO and BIMA). All the MDC work, in turn, is reviewed annually by the Millimeter Array Advisory Committee (MAC), the membership for which is given in Appendix D.

As the MMA D&D work begins with its initial funding in FY98 the project will be organized as shown in Figure VI.1. The definition and oversight of all the activities will be the responsibility of individuals designated as project "Division Heads" and they will use as resources people and facilities at the NRAO and at the participating university groups. In the case of the latter, the BIMA and OVRO participation, funding to these university groups will be provided under contract from the project. However, the responsibility for their work will remain with the appropriate NRAO MMA Division Head.

MMA Design and Development: Hardware Design and Prototype

The realization of a major astronomical instrument such as the MMA inevitably requires a long process from conception through consensus building to design and construction. In order to achieve a significant advance in observational capabilities over existing instruments the new instruments require an extension of existing technology. This is as true for the MMA—with its densely packed mosaicing configuration, quantum-limited receivers, and precision antennas—as it was for the Keck telescope with its segmented, optical-quality primary mirror or for the Green Bank Telescope with its active, laser-guided, surface metrology. Application of significant technology advances is the sine qua non of the design of a forefront scientific instrument.

The MMA is being designed to take advantage of quantum-limited SIS (superconductor-insulator-superconductor) mixer receivers that are sufficiently wideband that 8 GHz of intermediate frequency (IF) bandwidth can be correlated and analyzed from each of the two orthogonal polarizations at each millimeter-wave and submillimeter-wave frequency band. The total of 16 GHz bandwidth is more than a factor of thirty greater than any existing interferometer is capable of achieving and it presents a challenge to mixer design, IF transmission capacity, and correlator throughput. Prototypes of all this hardware, at one frequency band, will be designed and fabricated during the three-year D&D phase of the MMA project. The goal of the prototyping is both to demonstrate that the hardware will function as desired but also the prototyping will establish a firm cost basis from which the total cost of the MMA receiving hardware can be estimated reliably.

The local oscillator presents a special challeng for the MMA and, indeed, for all millimeter and submillimeter telescopes. The traditional approach is to use a fundamental Gunn oscillator at 40-80 GHz and multiply that frequency with varactor diodes. Since the multipliers have a finite bandwidth, and there is no commercial source for multipliers at the frequencies needed by the MMA, the traditional LO design is unattractive for the MMA. Fortunately, recent work in photonic generation of microwave LO frequencies has been remarkably successful. An important goal of the MMA D&D work will be to accelerate the work on such a LO for the range 100-1000 GHz. If successful, a single broadband LO would serve all the MMA frequency bands at an enormous reduction in cost and complexity over the multiplied-Gunn solution. A prototype system will be fabricated early in the D&D phase for evaluation and costing.

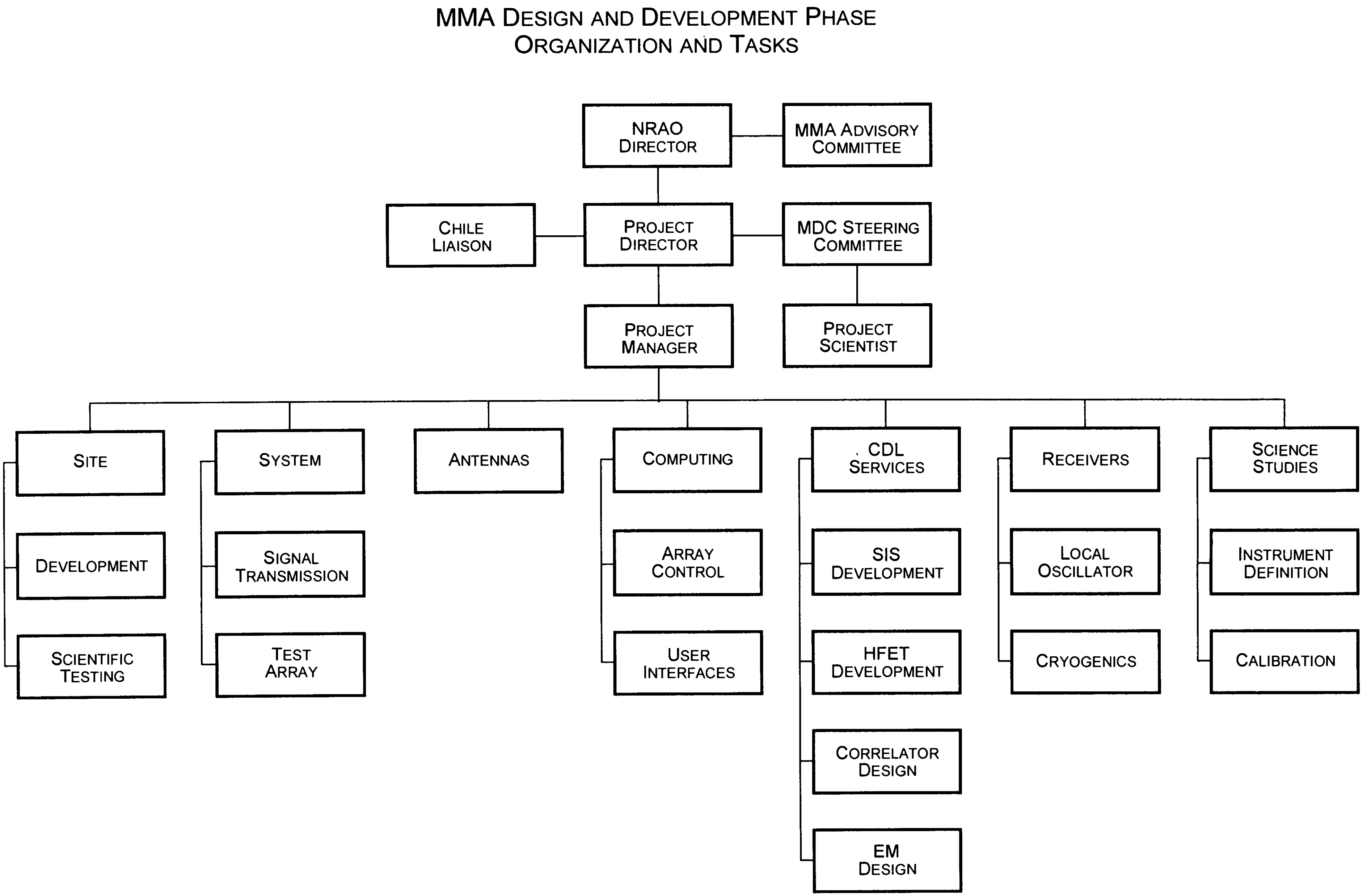


Figure VI.1. Organization of the MMA Project for the initial Design and Development Phase.

The MMA antennas are being designed with a surface precision of 25 microns or better and with a pointing specification of 1 arcsecond. The only existing antennas that achieve such performance are those built in an enclosure. The MMA antennas are in the open air, fully exposed to the environment, sun, and wind. This makes their design difficult. However, the more challenging specification for the MMA antennas to meet is that of having no more than four percent of their power received from "warm" surfaces. What this means is that the antenna "spillover" must be kept very low. Since spillover comes mainly from anything in front of the aperture that blocks the incoming astronomical signals, the antenna needs to be designed with exceptionally low blockage. Thus the MMA antenna must be high performance and low blockage. These specifications are difficult to achieve simultaneously. For this reason a prototype antenna, thoroughly tested, is one of the principal goals of the D&D effort. In fact, the plan is to build two such prototypes and connect them as a simple interferometer since the performance goals can be more reliably assessed with the antennas operating as an interferometer than they can by operating the antennas as single dishes. The reason for this is the atmosphere. Atmospheric fluctuations corrupt total power determinations of pointing; the interferometer is sensitive not to the fluctuations but only to those fluctuations that are correlated over the two antennas. The interferometer greatly reduces distortion of the quantities being measured.

An antenna design that meets the MMA specifications has been completed. It is shown in Figure VI.2, conceptually, on the preferred site for the MMA in Chile. Very early in the D&D phase this antenna design, and the antenna specifications for the MMA antenna, will be given to antenna contractors interested in bidding on the prototype antenna work. If this process can begin in the first quarter of 1998, the initial prototype antenna could be ready for testing in less than 24 months.

In three years it will be possible to assess prototypes of the receivers, the local oscillator, and the antennas. We will then be well-positioned to provide firm estimates of the cost and performance of the completed MMA.

MMA Design and Development: Site Selection

For the past decade tests and evaluations of possible sites for the MMA have been carried out in the continental United States, on Mauna Kea in Hawaii, and in Chile. In addition to clear and stable skies, the MMA requires a site at least 3 kilometers in extent and one that is sufficiently accessible that it can be provided easily with the infrastructure and logistical support needed by the array.

No site in the continental U.S. meets the MMA requirements. The frequent passage of winter storms combined with the summer incursion of moist Gulf air reduces to an unacceptable level the number of days on which observations are possible. Mauna Kea, on the island of Hawaii, and Llano de Chajnantor in the Altiplano of northern Chile both meet the minimum requirements for the MMA. However, the extensive site testing program clearly shows that the Llano de Chajnantor is the superior location. The reasons are:

- The Chilean site's atmospheric transmission is so much better that four times as much science can be achieved there as can be accomplished in the same amount of time at the Hawaii site.

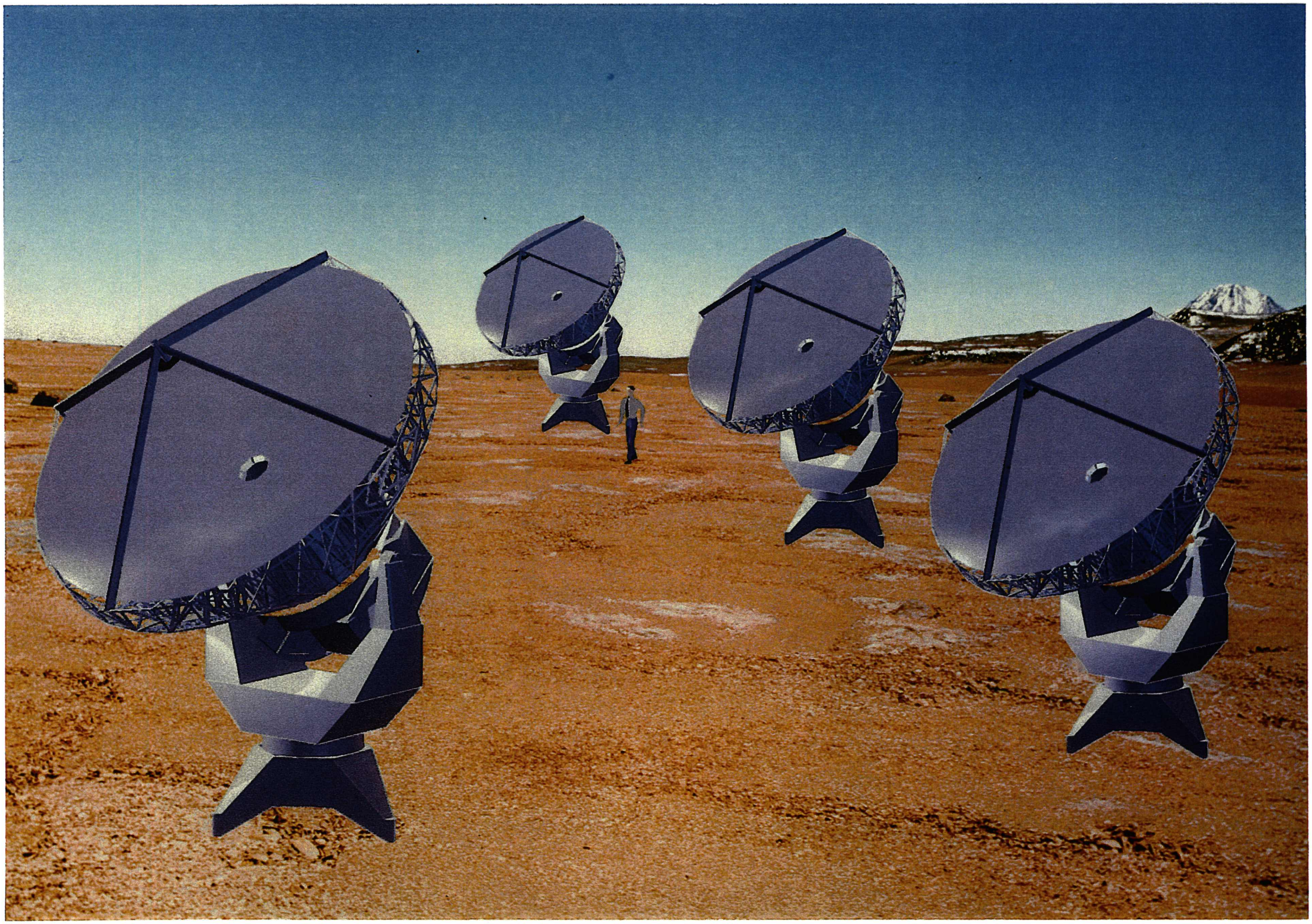


Figure VI.2. Computer rendering of the MMA antenna design shown on the site in Chile where they will be installed.

- The greater atmospheric stability of the Chile site facilitates precision imaging; the combination of superior atmospheric transmission and stability allows the MMA to observe effectively at sub-millimeter wavelengths under median conditions on this site.
- Unlike the Hawaiian site, Llano de Chajnantor provides adequate space for expansion to larger MMA configurations for still higher resolution imaging in the future.
- The Chilean site can be accessed easily via a paved international highway.
- The southernly latitude of the Chilean site provides a full view of the entire disk of the Milky Way Galaxy, the Galactic center, and the Magellanic Clouds, the galaxies nearest our own.

Location of the site being studied in northern Chile is shown on the accompanying map (Figure VI.3). Construction and operating costs of the MMA in Chile are estimated to be comparable with those costs should the array be built in Hawaii.

In the D&D phase we will explore, with our Chilean colleagues and with the appropriate governmental agencies, the process and procedure by which the MMA may be constructed in Chile on the Chajnantor site. Detailed explorations of the soil conditions on the site will be made as well so as to assess any subsoil difficulties and to provide data necessary for the design of antenna and building foundations.

MMA Design and Development: Partnerships

Possibilities for a partnership arrangement in the MMA are being discussed with interested international groups, with two foreign synthesis array projects having scientific goals similar to those of the MMA and with NASA.

Among the countries presently active in millimeter-wave astronomical research—England, France, Germany, the Netherlands, Spain, Sweden, Canada, Australia, Finland, Chile, Korea, China, Taiwan, and Japan—are research groups interested in expanding their access to a sensitive imaging millimeter or submillimeter array such as the MMA. Several of these groups are discussing with their governments proposals to participate in the MMA as associate partners in the hope of negotiating observing time in exchange for capital and operating funds. Such discussions have taken on heightened importance with the commitment of the NSF to begin the MMA D&D phase in FY98. Talks will continue in the next year.

The Japanese National Astronomical Observatory is planning to build on their successful experience with the Nobeyama Millimeter Array and construct a 50-element array of 10 m antennas. This instrument, called the Large Millimeter and Submillimeter Array (LMSA), has similar requirements to the MMA. The astronomers developing the LMSA are studying sites in Chile, one of which is very near the site preferred for the MMA. Should the Japanese choose to locate the LMSA near the MMA there would be an opportunity to combine these two instruments together such that they could undertake scientific investigations at an angular resolution several times better than either instrument can pursue alone. A collaboration between the MMA and LMSA groups to study the feasibility of the combined instrument, known as the Atacama Array, has been

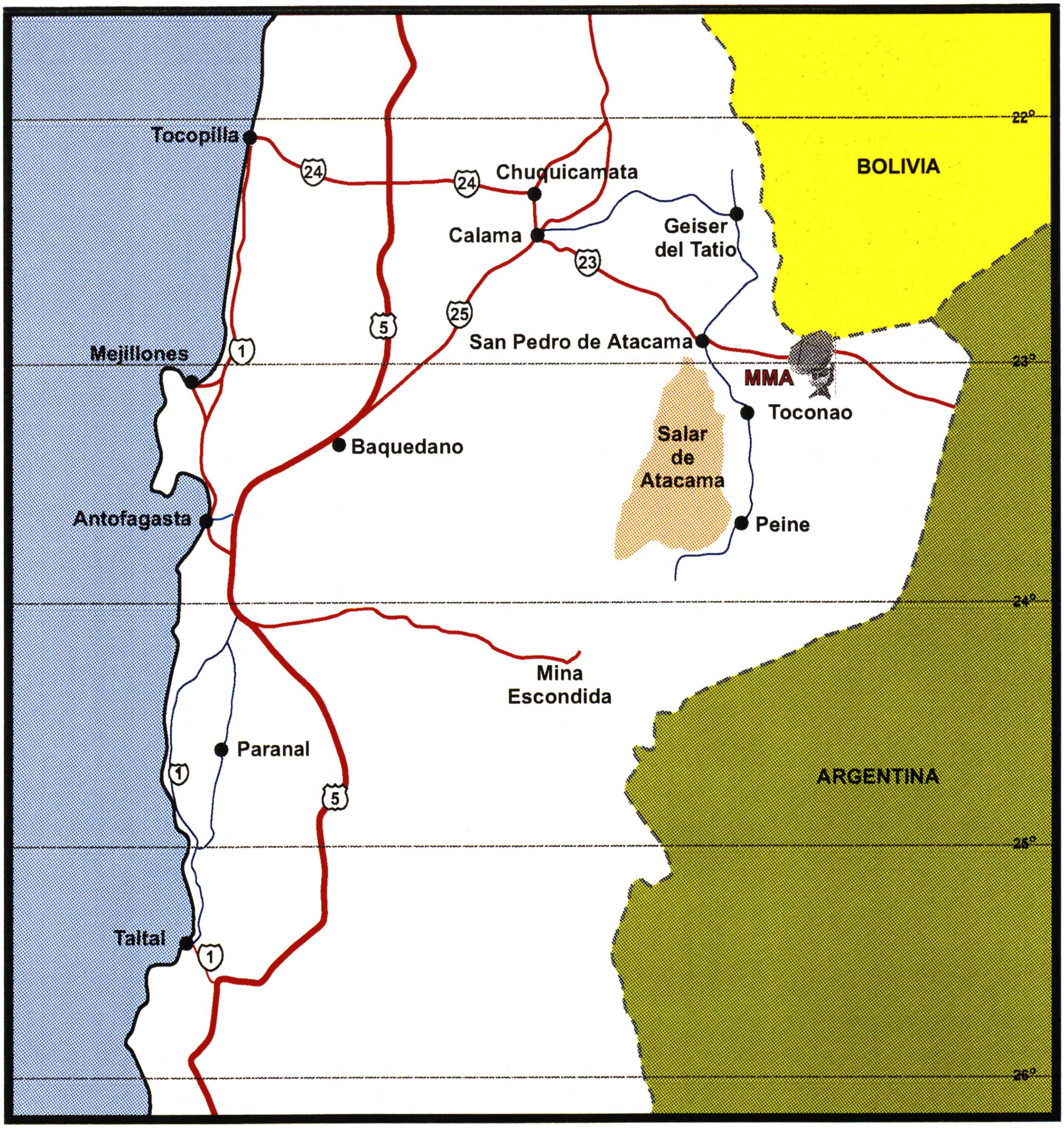


Figure VI.3. Location of the MMA site in the Altiplano of northern Chile approximately 50 km east of the historic village of San Pedro de Atacama.

active for three years. Such a collaboration offers the possibility for a significant cost savings through a sharing of support infrastructure in addition to providing new scientific capabilities. These discussions also will continue in 1998.

The Europeans are formulating plans in many ways similar to those of the MMA and LMSA groups. The concept in Europe is to build an array of very large collecting area, 10,000 square meters, that will operate at millimeter wavelengths and will be used for sensitive observations of compact objects (galaxies and protogalaxies) at cosmological distance. This array is referred to as the Large Southern Array (LSA); the intention is to locate it in Chile so that it can support, and be supported by, the Europeans Southern Observatory's Very Large Telescope (VLT). The focus on the cosmological problems makes the LSA in some respects complementary to the MMA and in others in provides a useful overlapping capability such that a partnership could increase the sensitivity of both arrays. Discussions are in progress between the MMA and LSA groups to identify whether and in what manner a collaboration between these two projects would be a worthwhile scientific asset.

Finally, NASA is now beginning a major sequence of scientific spacecraft known together as the "Origins" program. The goal of the program is to explore the beginnings of galaxy formation, the processes leading to the formation of stars and the origin of planets capable of supporting life. The "tool" to be used in these investigations is images of the visible and infrared light emitted by cosmic objects in formation. Since all such light-emitting objects arise from the gaseous environments that are probed effectively by the MMA, and at the same angular resolution as the space instruments, the MMA observations provide the earliest chapters to any story the NASA facilities may seek to write on "Origins." The astronomer needs both tools. A collaboration between the NASA facilities and the MMA is important and needed. We look forward to the chance to encourage this collaboration in 1998.

2. VLA Upgrade

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

The VLA upgrade will make possible a wide variety of new scientific programs by providing greatly increased sensitivity, much broader frequency coverage, enhanced spectral line capabilities, and better angular resolution. Factors of ten improvement in most of the critical areas can be attained at modest cost. It does so largely by returning the VLA to the state-of- the-art in receiver technology, in the transmission and processing of broadband signals, and in correlator design. The scientific potential also poses new technological challenges. How can optimum performance (polarization and sensitivity) be maintained across the large bandwidths now proposed? Can broadband, high-performance, low-frequency feeds be designed? What is the optimum way to transmit broadband signals from antennas hundreds of kilometers from the VLA for real-time ultra-high-resolution interferometry?

The impact on astrophysics of returning the VLA to the state-of-the-art will be profound. Many hard limitations now constraining VLA observations will be removed or greatly relaxed. The continuum sensitivity will increase tenfold in several bands. New frequency bands and increased bandwidth ratios could permit continuous frequency coverage. The bandwidth that can be processed by the spectrometer, and its spectral resolution, will simultaneously increase by about tenfold. The resolving power will improve fiftyfold. 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, compared to the present VLBA. The following technical capabilities are therefore key ingredients in a VLA development plan:

Phase 1: An Ultrasensitive Array

- New receivers: lower noise temperatures and much wider bandwidth performance (up to 4 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.
- 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 36 or more antennas, to process both broadband continuum signals and to provide improved resolution and flexibility for spectral line work.
- Improved low frequency (< 1 GHz) capability, using prime focus feeds and new receivers, with a goal of continuous frequency coverage from 200 to 1000 MHz.
- New antenna stations for a super-compact E configuration to enable fast mosaicing of large fields.

Phase 2: The VLA Expansion

- Additional new antennas to provide now unavailable baselines between those in the VLA and those in the VLBA.
- Fiber optic links between the VLA and the inner VLBA antennas, and between the VLA and the additional new antennas.

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 seven. 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.

Antenna and Receiver Improvements

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

Improved Low Noise Receivers

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 4 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). At present, only thirteen VLA antennas are outfitted for 45 GHz operation; this band will be made available on all antennas.

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 will allow the VLA to participate in bistatic planetary radar observations with Arecibo Observatory. The 33 GHz band also can support bistatic radar experiments, with the Goldstone 70 meter antenna, and it will allow imaging of many interesting molecular lines, including redshifted CO and O_2. Table VI.1 summarizes the proposed new and upgraded VLA Cassegrain observing bands.

Table VI.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

An alternate plan providing continuous frequency coverage from less than 1.0 GHz to 50 GHz is also being considered. This would require both a larger, new subreflector and ten frequency bands. Depending on the diameter of a new subreflector, optimum Cassegrain performance could be extended as low as ~700 MHz.

New Prime Focus Systems

Plans for new prime focus receiver systems are less well defined. A 330 MHz system is currently located at the prime focus. All twenty-eight VLA antennas will be equipped with 75 MHz receivers early in 1998.

Other specific proposals for prime focus systems include:

- A new system covering 580-640 MHz, matching that of the VLBA.
- A broadband UHF (150-600 MHz) system, including a simple system suitable for solar work.
- A sensitive 200 -1100 MHz system, comprised of three scalar feeds, mounted on the quadruped legs, which can individually be rotated into position.

The form of the low frequency, prime-focus system will critically depend on the Cassegrain systems, since in all cases the subreflector must be removed for prime focus operation.

Sensitivity Goals

Table VI.2 compares the continuum sensitivity of the current instrument to that we hope to achieve. 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

Table VI.2. VLA Sensitivity

Wavelength (cm)	$\Delta\upsilon$ (GHz)	Enhanced VLA T_{sys} (k)	Enhanced VLA δS (μJy)	Current VLA T_{sys} (K)	Current VLA δS (μJy)
90	0.1	80-135	15.00	150	170
50	0.1	55-90	13.25		
30	0.25	30-32	5.3		
20	0.5	25	1.6	32	5.7
11	1.5	25	0.9		
6	3.0	25	0.6	42	6.4
3.6	3.0	25	0.6	35	5.3
2	4.0	32	0.7	110	20
1.3	4.0	50-70	1.2	160	37
0.9	4.0	35	0.9		
0.7	4.0	55	1.8	90	60
0.6	3.0	120	6.0		

New LO/IF Transmission System

To transmit up to 8 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 specifications for a new correlator are still under discussion, as is the architecture best suited to meet them. It is not yet clear whether the more appropriate architecture is a lag correlator, as presently used at the VLA, or an FX correlator, as used by the VLBA. A detailed design study is needed to choose between the two options. Note that the product of the number of antennas, N, and the maximum bandwidth, B, analyzed by the correlator will be at least NB = 290 GHz. This figure of merit for the correlator is similar to the Millimeter Array (NB = 640 GHz); and nearly two orders of magnitude larger than the existing VLA correlator (NB = 5.4 GHz) or the VLBA correlator (NB = 2.6 GHz).

The new correlator should be able to process data from at least 36 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 six antennas on baselines between those in the VLA and in the VLBA.

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, e.g., 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 allowing some VLA, some VLBA, and some new antennas to be used interchangeably as members of either array. These 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 similar to that of the VLA; currently such a capability is lacking in the VLBA.

To fill this u-v gap, up to six new antennas would be built in New Mexico and Arizona to make the density of u-v coverage in the 40-400 km baseline range similar to the VLBA now beyond 400 km.

Early studies have indicated that six outrigger antennas would enable good u-v sampling over the 35-250 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.

Other Capabilities

Several other instrumental improvements that lead to new scientific capabilities also are being considered. They include: ultra-wide (35 percent) bandwidth at the highest frequencies, a robust total power system to support mosaicing and simultaneous multi-band performance (2.4 and 8.4 GHz or 4.9 and 15 GHz).

Table VI.3. Illustrative Budget

	Cost ($M)	Subtotal (SM)
PHASE 1:		
Antenna LO/IF	5.5	
Antenna Mechanical	2.3	
LO/IF Transmission	2.5	
Central LO/IF	2.5	
Correlator	7.5	
Test Equipment	0.2	
CASSEGRAIN:		
1.1 - 2.0 GHz	0.8	
2.0 - 4.0 GHz	1.6	
4.0 - 8.0 GHz	1.4	
12.0-18.0 GHz	1.5	
18.0-26.5 GHz	1.5	
26.5-40.0 GHz	2.2	
40.0-50.0 GHz	1.5	
NRE	0.5	
PRIME FOCUS:		
200-1000 MHz	3.5	
SUB-TOTAL		35
E CONFIGURATION:		
18 Stations	4.0	4
SUB-TOTAL PHASE 1		39
CONTINGENCY PHASE 1	6.0	
PHASE 1 TOTAL		**45**
PHASE 2:		
Six new antennas	30	
Fiber to VLBA antennas	2.0	
Fiber to new antennas	8.0	
SUB-TOTAL PHASE 2		40
CONTINGENCY PHASE 2		6
PHASE 2 TOTAL		**46**

3. AIPS++ Project

The AIPS++ Project is a collaborative initiative to develop a new data reduction and analsysis package for radio astronomy. Its origins can be traced to concerns within NRAO and other institutions that current data reduction packages do not provide the flexibility and future potential desired, despite the success of these packages at meeting some current needs. AIPS++ will be a considerable improvement in programmability (at various levels from astronomer to professional programmer), maintainability, portability, and exportability. Seven institutions are collaborating on AIPS++: The Australia National Telescope Facility (ATNF), The Berkeley-Illinois-Maryland Array (BIMA) consortium, the Canadian Herzberg Institute, the Netherlands Foundation for Radio Astronomy (NFRA), the Nuffield Radio Astronomy Laboratory, the National Center for Radio Astronomy in Pune, India, and the NRAO. Of these, ATNF, BIMA, NFRA, and NRAO are currently devoting substantial resources to the project, and so the Directors of these four institutions form an Executive Committee that oversees the project. The project is managed by an NRAO staff member and the project center is located at the Array Operations Center in Socorro.

The development version of AIPS++ is in active use at a number of consortium observatories for support of current activities:

- ATNF: At the Parkes telescope for Parkes Multi-beam observing of, for example, a HI survey of the southern sky.
- NRAO: At Green Bank, for support of the Green Bank Telescope engineering. In addition, AIPS++ has been adopted as the platform for GBT data analysis.
- NFRA: Integrated into the Telescope Management System of the Westerbork Synthesis Radio Telescope.

In addition, the Joint Institute for VLBI In Europe has decided to use AIPS++ as the platform for data acquisition and monitoring for the VLBI correlator now under development.

AIPS++ was first released for outside testing in February 1997, and a second subsequent release was made September 1997. In these two first releases, we learned a number of important lessons. Installation and setup of the system was straightforward for all testers but by universal reaction, the system was seen as very capable, but hard to learn to use and hard to use. Our major remedy to this problem is to write graphical user interfaces for major applications. This approach will be tested in one more beta release which is planned for late 1997 before a Limited Public Release is made in early 1998. In addition, a major new initiative in the development of the synthesis processing capabilities has just started with work proceeding simultaneously at different AIPS++ sites on cross-calibration, improved user interfaces, mosaicing support, wide-field imaging, and a number of other improvement. The first full release will have support for continuum and spectral line processing in all polarizations, for single-dish processing, for general processing of tabular information, and for display and analysis of images. Much of this functionality will be available both via command line and graphical user interfaces. Other capabilities such as VLBI processing and sophisticated image visualization will be added in a subsequent release in early 1999. The Limited Public Release will be targeted towards astronomers but a subsequent, intermediate release will be targeted towards aiding developers who wish to program within the system.

AIPS++ is advised by a Scientific and Technical Advisory Group, chaired by Robert Braun of NFRA. This group meets yearly and advises the Project on scientific and technical matters. The first meeting was held in November 1996, and the second meeting is expected to be held in February 1998, prior to the first limited public release.

VII. NON-NSF RESEARCH

1. United States Naval Observatory

The new 20-meter telescope has been in use for over a year with the USNO geodetic VLBI array. Other antennas used regularly by USNO in this array are located in Kauai (Hawaii), Forteleza (Brazil), Fairbanks (Alaska), and Wettzell (Germany). This array provides fundamental data on earth rotation and polar motion needed for timekeeping and navigation, and are essential to the analysis of observations from the VLA and VLBA. A weekly 24-hour observing run, along with daily two-hour runs, provides data for the IERS(International Earth Orientation Service) Bulletin A, published weekly by the USNO. The IERS bulletin lists the most recent polar motion and UT1 data and includes predictions for the next three months.

Current status and operational data on the 20-meter telescope are listed on the WWW at URL: http://www.gb.nrao.edu/gbint/GB20m.html.

The 20-meter is also used for other geodetic VLBI experiments, designed to explore geophysical effects on earth orientation, such as oceanic and atmospheric currents, plate tectonics, and core and mantle morphology. These are organized by the NASA geodetic group in cooperation with USNO.

In 1997 an addition to the Jansky Lab building funded by the U.S. Navy to support its activities in Green Bank will be completed. In early 1998 USNO telescope controls, as well as VLBI equipment, scientists, and personnel, will move into the new facility, which will also house orbiting VLBI related operations.

2. Green Bank Interferometer

The Green Bank Interferometer (GBI) resumed operation as a radio monitoring instrument on 22 November 1996, after a shutdown in early 1996 due to lack of funding. It is operated by NRAO with funding from the NASA High Energy Astrophysics program. The GBI consists of two 85-foot telescopes operating simultaneously at 2.7 and 8.3 GHz. During the last two decades the GBI program has evolved from doing radio astrometry and interstellar scintillation to observing x-ray binaries and x-ray active AGNs.

In 1998 the GBI will monitor both transient and persistent galactic x-ray and Gamma-ray sources, and x-ray stellar binary systems. Amongst the prime sources are GRS1915+105, GRO J1655-40, Cyg X-3, Cyg X-1, GRS1716-249, SS433, and LSI+61 303. Radio flaring episodes in x-ray binary sources correlate with the x-ray "high" and "low" states in ways that challenge our understanding of the radio and x-ray emission mechanisms. Studies of these objects at many wavelengths can help clarify the physics of mass transfer and dynamics in these rapidly evolving systems.

The monitoring program is open to all: instructions for proposing sources to be monitored may be found on the WWW at URL: http://www.gb.nrao.edu/gbint/GBINT.html. Recent results from monitoring data are also posted through the same web page.

3. Pulsar Monitoring

The third 85-foot telescope at Green Bank is being used to make daily observations of a set of 24 pulsars. The telescope is instrumented with two simple, uncooled receivers at 610 and 327 MHz and two back-ends: one a filter bank, and the other a digital de-disperser. This effort is supported by funds from NASA and by the individual investigators, who provide the back-ends and software support. The data are used to determine pulse arrival times for coordination with space-based pulsar observations, and to study time-dependent propagation conditions in the interstellar medium.

4. NASA – Green Bank Orbiting VLBI Earth Station

The primary goal of the Green Bank Earth Station is to support Space VLBI satellite experiments. This effort, funded by NASA, is expected to continue beyond the year 2000. The Japanese orbiting VLBI satellite, HALCA, was launched in 1997 and the Green Bank Earth Station has been successfully tracking it. The earth station transmits a precise timing tone to the satellite, records the downlink data on VLBA or S2 tape, and processes the downlink data to produce an accurate description of the satellite state and timing data during the pass. The data are sent to correlators in Socorro, New Mexico; Mitaka, Japan; or Penticton, Canada. The pace of these activities will increase in 1998 as HALCA finishes its in-orbit testing.

In addition to normal support of satellite operations, the earth station staff will continue to improve the operational software and the reliability of the station hardware in 1998. The earth station may also be used for occasional "target of opportunity" observations, such as monitoring variable radio sources.

5. NASA – Orbiting VLBI Science Support

The NRAO Space VLBI Project, based at the Array Operations Center in Socorro, New Mexico, includes the NRAO activities funded by NASA through the U.S. Space VLBI Project at JPL, in support of the international Space VLBI missions VSOP and Radioastron. The Project comprises the following tasks.

Management & Science

This activity, which continues throughout the duration of the project, involves management and scientific oversight by NRAO personnel with respect to project goals, implementation plans, and progress. Since both Space VLBI missions are international in scope, frequent interactions are necessary to maintain coherent interfaces with other mission elements. NRAO personnel are members of the two International Scientific Councils which serve as steering committees for the missions, of the VSOP Scientific Review Committee which performs peer review of submitted proposals, and of the VSOP In-Orbit Checkout and VSOP Science Operations groups.

VLBA Correlator Enhancements

Modification of the VLBA correlator to support Space VLBI observations is complete. First fringes with the VSOP mission's HALCA spacecraft were detected on June 12, 1997. It is anticipated that minor bug fixes may be required through the end of 1997, but that the correlator will require no further work thereafter until the launch of the Radioastron mission nears.

AIPS Enhancements

Modification of AIPS to support Space VLBI observations is substantially complete. These new features have been tested with simulated data but are only beginning to be used with real observations. It is expected that significant further modifications of the new AIPS tasks and, possibly, creation of additional tasks, will become necessary as experience in Space VLBI imaging is developed.

Operations Support

Most of the new operational functions and capabilities for support of Space VLBI observations already are in place, or nearing completion. Space VLBI operations cannot become routine, however, until the files of auxiliary data are provided routinely by the tracking stations and the VSOP Science Operations Group, without delay and in the correct format. Several new positions are budgeted to support Space VLBI operations, but will not be filled until further experience shows the optimal distribution of effort. Additional VLBA tapes, sufficient to accommodate the anticipated incremental requirements for Space VLBI observing, have been procured and are in service.

User Support

Two user support scientists have been hired on Space VLBI Project funding, and a third is employed by JIVE. All three currently contribute invaluably to the ongoing VSOP In-Orbit Checkout program. These activities also serve as the best training imaginable for their later responsibilities in assisting visiting scientists with analysis of their VSOP observations. A high-performance multi-processor computer server, presently the most capable image-processing system available in the Observatory, has been procured to support both the current tests and subsequent data analysis by visiting scientists.

6. SETI Institute – Project Phoenix

Project Phoenix, a SETI Institute funded search for radio signals of extraterrestrial origin, made its first observations with the NRAO 140 Foot Telescope in late 1996, and is expected to continue observing through 1998. Phoenix observations are designed to detect continuous wave (CW) signals in the direction of Sun-like stars. Each candidate star is tracked as long as it is above the local horizon. During this time, the entire passband of the receiver (1.0 - 1.8 GHz at L-band and 1.7 - 3 0 GHz at S-band) is swept in 10 MHz sections with a spectral resolution of about 1.0 Hz at the Phoenix spectrometer. Detections are checked in real time using a secondary antenna in Woodbury, Georgia. System integrity is checked with observations of space probes such as Pioneer.

When the 140 Foot Telescope is removed from active service as a user facility, the SETI Institute has proposed to use it as a dedicated instrument for their program, with all associated costs being paid by the SETI Institute.

VIII. EDUCATION PROGRAM

With observing sites and scientific offices located in ten states and the territory of the U.S. Virgin Islands, the NRAO has a public visibility that is being exploited to further science awareness and science education. Formal education in the form of supervised research experiences with the NRAO radio telescopes is provided to professional and pre-professional scientists. Programs that emphasize how scientists work and what they hope to accomplish are provided to secondary science teachers and interested amateur astronomy groups. Finally, public educational activities are sponsored at all the NRAO observing sites in the form of guided and self-guided tours, public access to the images of objects in the radio sky, and descriptions of the nature of objects studied by radio astronomers. A few of the highlights of the NRAO educational program are summarized below.

In an attempt to convey the excitement of scientific discovery in general and the rewards of astronomy in particular to the general public, the NRAO maintains visitor centers at the observing sites in Green Bank, West Virginia, and at the VLA site in New Mexico. Both of these centers are open year-around and each draws nearly 20,000 visitors annually from throughout the United States and around the world. The visitor centers feature automated slide presentations with audio narration, displays on the instrumentation and operation of NRAO radio telescopes, and illustrations of recent radio astronomical research. We hope to convey to the public visitors of the NRAO the following: (1) the value of astronomy to society and its importance among the sciences; (2) the place of radio astronomy and its value to astronomy as a whole; (3) the techniques of radio astronomical observations; and (4) the technology of radio astronomy and the operational basis of the NRAO instruments.

Green Bank Public Educational Programs

The NRAO in Green Bank, West Virginia is host to a number of educational activities. The largest of these is science teacher training, a series of programs conducted in partnership with West Virginia University. These programs have been in existence since 1987 and are supported by the Education Division of the National Science Foundation, and in 1990 by the Benedum Foundation. The training targets middle school and high school science teachers, from whom most students get their initial exposure to science. The goal is to increase teachers' understanding of science and technology, and their ability to teach it, by exposing them to real scientific research.

The science teacher training programs have brought more than 500 teachers to Green Bank for one to two week summer courses that involve lectures on astronomy, actual scientific research using a 40-foot diameter radio telescope, and detailed science education workshops. The teachers work closely with NRAO scientists, and also have a chance to interact with many professional astronomers who come from around the country and the world to use the telescopes at Green Bank. After participation in an NRAO training program, teachers host workshops for other teachers in their home district to spread information about effective ways to present science. It is estimated that more than 20,000 teachers have benefitted indirectly from our programs, and that the NRAO/WVU programs have improved the education of more than 100,000 students. Many teachers who received training at the Observatory return with groups of their students to use Observatory facilities. More than 1200 high school students have been able to gain first-hand research experience using the NRAO education facilities.

Teacher training initially concentrated on science teachers from West Virginia, then was broadened to include participants from the entire country. In 1994 the program was redesigned to focus on teachers and teachers-in-training from West Virginia and involves two West Virginia institutions of higher education: West Virginia University and Glenville State College. In September, 1997, NRAO Green Bank submitted a proposal to the NSF Teacher Enhancement Program to expand our summer institute program to include elementary teachers. If funded, this program will run from 1998-2003.

Chautauqua Workshops for College Teachers: The Observatory hosts two 3-day workshops each spring for science faculty of small colleges throughout the country to share results of current research in astronomy with as wide an audience as possible. This program is partially funded by the National Science Foundation (NSF). In 1997, 55 college teachers participated in a Chautauqua held at NRAO-Green Bank. Two workshops are planned for 1998.

Society of Amateur Radio Astronomers: This group has held an annual meeting at Green Bank for the past several years and will do so again in 1998.

High School Student Mentor Program: Local high school students who have interests in engineering, electronics, and astronomy can participate in a mentorship program at NRAO. These students spend one to two days per week at the Observatory working with a staff member (their mentor). In 1996/97 NRAO Green Bank staff mentored seven high school students. This year, six students have indicated an interest in working at NRAO.

Public Tour Program: The public is encouraged to visit the site. Hourly tours are given each day during the summer months, and tours can be scheduled for groups at any time of the year. Special in-depth tours are also occasionally arranged. In 1996/97 18,304 people visited the Observatory in Green Bank. School groups comprised 20 percent of the visitors.

Plans are underway to overhaul the Green Bank tour program. In June, 1997, NRAO submitted a proposal to the NSF Informal Education Program for funds to construct a series of interactive science exhibits which would allow the public to experience the ongoing research at NRAO more directly. If the proposal is successful, the project will proceed over three years. A year-round tour coordinator has been hired to expand the tour offerings and develop programs for the off-season.

Apple Computer Grant: Last year staff at the Observatory formed a Technology in Education Partnership with the neighboring elementary school and received one of only ten grants given nationally through the Apple Computer, Inc., "Partners in Education" program. The award consists of 16 Power Macintosh

Computers for the school, eight for the Observatory and a host of peripheral services. The Observatory will use its portion of hardware/software for exhibits in the Tour Program.

Socorro Educational Program

The Socorro educational program is a growing, multi-faceted effort that, while centered around the VLA Visitor Center, also includes cooperation with local and regional schools and colleges, public lectures, support for amateur events and organizations, and dissemination of scientific information to the public in a variety of ways.

The VLA Visitor Center has been a popular tourist attraction since its opening in 1983. Open year-round, the visitor center hosted at least 16,000 tourists in 1996. (It should be noted that this number represents those who signed an unattended guest book. Tourism experts contend that in such situations the actual number may be as much as three times higher. Thus, the VLA Visitor Center may be serving nearly 50,000 tourists annually.) Those tourists typically come from all 50 states and more than 40 foreign countries. The VLA and its visitor center have been featured in tourism-oriented television shows and in a number of regional and national publications. The Warner Brothers movie *Contact*, filmed in part at the VLA, was released in July of 1997, giving the facility significant additional exposure. The exposure from the movie has already produced record numbers of tourists and increased visibility in the media.

Currently, the visitor center features an automated slide show with audio narration, displays on the history of radio astronomy, the operation of the VLA and the VLBA, and changing displays on scientific results from both instruments. The visitor center is the starting point for a self-guided walking tour of the central portion of the VLA site. A free brochure provides background information and a map for visitors making the walking tour. Signs at stops on the walking tour explain the components of the VLA visible from each location. The walking tour provides visitors with close-up views of an antenna, the antenna assembly building, the transporter vehicles, and, from an outdoor balcony on the control building, views of the VLA electronics and control rooms.

Though the visitor center is not staffed, we provide regularly scheduled guided tours on summer weekends, using NRAO summer students as guides. Throughout the year, by appointment, we provide staff tour guides for educational and scientific organizations. The number of such guided tours averages about 50 annually.

We now are planning for a complete renovation and upgrade of the VLA Visitor Center that will include replacing and redesigning the scientific displays. We are applying for funding to support a detailed planning process that will use professional educators and museum specialists, and will include prototyping and testing of representative exhibits. With this complete, we will seek a larger grant to fund the actual production and installation of new exhibits.

A survey revealed that the vast majority of VLA visitors come with little or no detailed knowledge of astronomy, and a majority have no formal training in science. However, the visitors are remarkably well-educated, with a majority having college training. Based on analysis of the survey results, we feel that the VLA Visitor Center has the potential to have significant impact on public understanding of astronomy and its importance to society by effectively conveying this message to a geographically diverse audience of opinion leaders.

We will design, test, and refine our new exhibits with the aim of making the visitor center an effective, exciting center for informal science education. We will incorporate interactive techniques, new technology, and proven approaches to learning. We also will explore avenues of providing staffing for the visitor center, an addition that would significantly improve the quality of the experience for the visitor.

The VLA Visitor Center project as well as other educational efforts have benefitted from NRAO's membership in the recently-formed Southwestern Consortium of Observatories for Public Education (SCOPE). This organization, including, in addition to NRAO, Kitt Peak National Observatory, Lowell Observatory, Whipple Observatory, McDonald Observatory, Apache Point Observatory, and the National Solar Observatory, has quickly become an effective vehicle for cooperation and information exchange among its participants. Using funds obtained from government and private sources, SCOPE has produced educational materials on astronomy for distribution by all SCOPE institutions. NRAO distributed these materials—free of charge—through the VLA Visitor Center and all Socorro schools.

NRAO also is a member of Project ASTRO, an educational program of the Astronomical Society of the Pacific, funded by the National Science Foundation. This program links professional and amateur astronomers with teachers to bring astronomy into the classroom effectively. NRAO participates in Project ASTRO through that program's regional center in Alamogordo, New Mexico. NRAO staff members serve as team members with local school teachers, and we also support Project ASTRO by providing educational materials, information, and class tours for teachers in this program.

Both in Socorro and at the VLBA sites, NRAO staff members frequently give lectures at schools and to local organizations. Some area teachers regularly use NRAO staff members as guest speakers, and we attempt to make the availability of our staff well known to the schools. NRAO provides a display and staffing for career days at local 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. NRAO also contributes significant staff time to provide judges for area science fairs.

We widely distribute a pamphlet aimed at educators which outlines the NRAO services available to them. In this document, we offer tours, speakers, literature, and the assistance of our staff in serving as a resource for information about science, engineering, and computers. We have seen the effect of this effort in a continually increasing number of inquiries from educators not only from New Mexico but also from across the nation. In addition, 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.

With increasing public awareness of research results from the VLA and VLBA, NRAO has had greater opportunity to advance public education by teaching members of other organizations that have frequent contact with the public. We now regularly provide information on astronomy and NRAO's role to rangers and interpretive staff at parks and wildlife refuges. We provide brochures about the VLA Visitor Center to area hotels and to Chambers of Commerce and tourist welcoming stations around the state.

NRAO is ideally positioned to use the amateur radio community 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 on 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.

Amateur astronomers are another proven resource for public education, many of them showing great enthusiasm for bringing astronomical information to the public. NRAO has forged close ties with New Mexico's extensive amateur astronomy community. We regularly provide lectures and tours for amateur groups and provide displays at public events such as National Astronomy Day observances, held by these groups. In addition, NRAO provides staff assistance, VLA tours and lecturers for the annual Enchanted Skies Star Party, an amateur astronomy event that draws participants 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.

Undergraduate Research Program

The NRAO has sponsored a summer student program since 1959. For the last ten years support for the program has been derived from the NSF Research Experiences for Undergraduates (REU) program. Funds have been made available each year for the support of approximately twenty undergraduate students each of whom spends approximately twelve weeks in residence at one of the NRAO sites. In addition, for the past three years additional REU funds have been used to re-initiate a more comprehensive research program for cooperative education (co-op) undergraduate students.

The NRAO summer REU program is operated at the four major NRAO facilities: Charlottesville, VA; Green Bank, WV; Tucson, AZ; and Socorro, NM. The students are involved in all activities in the areas of astronomy, electrical engineering, and computer sciences. Students are treated as part of the organization and they are expected to participate fully in ongoing Observatory activities. In practice, students are mainly occupied with the research that they do with their advisor, but they are encouraged to attend scheduled scientific and technical colloquia, they have free use of the libraries and computing facilities, and they have the opportunity to interact with visiting astronomers. They are exposed to all aspects of the NRAO operation and are fully integrated into its research environment.

It is NRAO policy that the student programs are run primarily for the benefit of the students, and to a much lesser extent for the benefit of the NRAO staff. But students benefit most, we believe, by participating in real research or by building equipment that will be used by professional astronomers. The students are expected to contribute materially to the research that they are assigned by their advisor, and these contributions are often recognized by co-authorship of subsequent publications. There are no make-work assignments or exams. They contribute to real research projects in a real way. However, in recognition of the educational basis of the program, seminars, site tours, and a course of lectures is prepared each summer for them. Advisors are encouraged to involve their students in as large a cross-section of research as possible, from library reading through observing, data reduction, interpretation, and presentation.

The summer REU program is a worthwhile introduction to scientific research for the students and it provides the NRAO staff scientists with direct contact with what we hope will be the professionals of the future.

The twelve weeks that a summer REU student is in residence is often long enough for the student to make a substantive contribution to an astronomical research project. But it is usually not long enough for them to see to completion a task involving construction of instrumentation. For a subset of the technically-inclined students the co-op program is a more suitable learning environment. A number of colleges and universities have programs to place their technical students in a working environment for about a semester each year so that the students gain in-depth experience in a scientific and technical environment. Among the many benefits of the co-op program are these:

1. There are always research projects that are inappropriate for a summer undergraduate because by the time the student was taught the background necessary to do the work the summer would be over. Co-op students can participate in these more extensive research projects; this is particularly true for engineering and computer science students.
2. A twenty-four week co-op program allows a more in-depth participation than does the summer program of half this length. The greater involvement of the co-op often leads to publication with the student as a co-author, a valuable thing to have on one's curriculum vitae.
3. Co-op students are always fascinated by the application of technology to *pure* research such as astronomy. The co-op experience teaches them *why* they are studying some technical field. It occasionally happens that the student's experience is so rewarding that he or she will develop a professional interest in astronomy and will end up working professionally in the technical departments of the NRAO or some other observatory. Several of the present NRAO staff began as co-op students here.

With continuing NSF REU support we plan to continue the NRAO summer student and cooperative education program in 1998.

Graduate Education

As astronomy becomes a more phenomena-oriented discipline, and less divided by observing wavelengths, radio astronomical observations play an important role in a wide variety of astronomy Ph.D. theses. Some of the universities awarding degrees in astronomy have few, or no, radio astronomers to guide student research in radio astronomy. To rectify the situation and train students in the techniques of radio astronomy specifically needed for the individual student's research, the NRAO staff scientists collaborate with university astronomers in the supervision of Ph.D. thesis students. The students spend as long as twenty-four months in residence at the NRAO taking data, reducing it, and writing their theses—all with the guidance of NRAO staff scientists.

Presently there are five resident Ph.D. thesis students at the NRAO conducting research in astronomy, and one conducting research in instrumentation design (millimeter-wave local oscillators). This program principally benefits the student, but it has a salutary effect as well for the NRAO staff supervisor.

In addition to the thesis students resident at the NRAO, more than 150 Ph.D. thesis students use the NRAO facilities each year for their research. While these latter individuals receive no direct salary support from the NRAO, their stay of one to a few weeks at the Observatory is supported directly by a housing subsidy (in Socorro), travel reimbursement, computer time, and supplies; and it is indirectly supported by assistance from the NRAO scientists and staff as needed. Many of the students using NRAO facilities this year will receive their introduction to radio astronomy from NRAO staff scientists.

Postdoctoral Education

At the NRAO postdoctoral appointees are given Jansky Postdoctorals with a term of two years that may be extended an additional year. In the selection process recent graduates are given preference to those who are applying for their second postdoctoral position. Jansky Postdoctorals are available not only to those in radio astronomy but they are also available to recent Ph.D. recipients in engineering and computer science.

Postdoctorals 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 and become themselves better teachers of, and researchers in, radio astronomy. Approximately ten Jansky Postdoctorals are in residence at the NRAO at any time.

IX. 1998 PRELIMINARY FINANCIAL PLAN

by Budget Category

(NSF Funds, $ in thousands)

	New Funds	Uncommitted Carryover of 1997 Funds	Total Available for Commitment	Commitments Carried Over from 1997 Funds	Available for Expenditure
Operations					
Personnel Compensation	$18,500		$18,500		$18,500
Personnel Benefits	5365		5365		5365
Travel	770		770		770
Material & Service	5600	400	6000	800	6800
Management Fee	615		615		615
Common Cost Recovery	-700		-700		-700
CDL Device Revenue	-150		-150		-150
Total Operations	$30,000	400	$30,400	$800	$31,200
Research & Operating Equipment	0	0	0	100	100
Total NSF Operations	$30,000	400	$30,400	$900	$31,300
MMA Design & Development	9000	0	9000	0	9000
GBT	0	1000	1000	500	1500
TOTAL NSF PLAN	$39,000	$1,400	$40,400	$1,400	$41,800

IX. 1998 PRELIMINARY FINANCIAL PLAN

NRAO Non-NSF Funding

($ in 000's)

Organization/Project	1998 Funds
USNO:	
Ops & Maintenance	$420
GB/HA Repairs	200
NASA:	
Science OVLBI	983
Earth Station OVLBI	759
MAPS	300
SETI:	550
Miscellaneous:	100
TOTAL	$3,312

IX. 1998 PRELIMINARY FINANCIAL PLAN

by Function/Site

(NSF Funds, $ in 000's)

	Personnel	Salaries, Wages, & Benefits	Materials, Supplies, & Services	Travel	Total
Operations					
General and Administrative	24	1669	865	140	2674
Research Support	58	4748	450	280	5478
Central Development Lab	26	1419	100	30	1549
Green Bank Operations	81	4303	465	40	4808
Tucson Operations	25	1599	317	45	1961
Socorro Operations	191	10127	3403	235	13765
Management Fee			615		615
Common Cost Recovery/ CDL Device Revenue			-850		-850
Research and Operating Equipment					
Total NSF Operations	405	$23,865	$5,365	$770	$30,000

APPENDIX A – NRAO SCIENTIFIC STAFF ACTIVITIES

The approximately 80 individuals with Ph.D. degrees at the NRAO each maintain a vigorous program of research, ranging from antenna and instrumentation design and development of new techniques for the analysis of radio astronomy data, to a wide range of astronomical research programs. Many of the astronomical 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.

The planned astronomical research program of the scientific staff for 1998, which is subject to the same competitive review as all NRAO observing programs, is summarized below.

1. The Solar System

Passive radio observations of solar system objects allow properties of their atmospheres, surfaces, and magnetic fields to be inferred. Active radio observations (radar) allow additional properties of surfaces and magnetic fields to be inferred, and can also give insights into the rotation of the probed body. Radio wavelengths are unique in their ability to probe into regions inaccessible to shorter wavelengths, e.g., into the deep atmospheres and into the subsurfaces of planets. They are also unique in their ability to observe in conditions which would make shorter wavelength observations useless (daylight, cloud cover, etc.). They have therefore made, and continue to make, very important contributions to planetary astronomy and planetary science in general.

With the recent visit of comets Hyakutake and Hale-Bopp, interest in the molecular spectral line emission from comets has increased dramatically. Observations of comets at radio wavelengths yield important information on the state of the cometarynucleus, on the production of volatiles from the nucleus surface, and on the composition and structure of the comae, among other things. Ammonia, OH, methanol, and formaldehyde were detected and will form the basis to study the development of the molecular production rates with heliocentric distance, and the thermal development of the coma. Attempts to directly detect the thermal emission of cometary nuclei at longer wavelengths will continue, following the first such successful detection of Hale-Bopp, from the VLA. The newly developed technique of observing the occultation of bright background sources by the OH in cometary comae will also be continued, with special attention paid to comet 9P/Tempel 1, which is the target of the NASA Deep Space 4/Champollion mission.

The arrival of the Mars Global Surveyor spacecraft at Mars will initiate an important program of global imaging at many wavelengths, both from the spacecraft itself, and from ground-based observatories. High resolution radio and radar observations of the planet will help place important constraints on the interpretation of these global images. Programs to do such observations from the VLA will continue, most notably during the next Martian opposition.

The current state of the water in the atmosphere of Mars is an important clue to the past water budget and climate of the planet. This information may yield insight into the question of past life on the planet. The amount and vertical structure of water in the Martian atmosphere can be probed via spectroscopic observations of various water (and deuterated water) lines. This will continue at both the 12 Meter Telescope and at the VLA.

Sulfur compounds play an important role in the atmosphere of Venus, most noticeably through the formation of the H_2SO_4 clouds which mask the surface at optical wavelengths. In addition to supplying important information on atmospheric composition and chemistry, observations of these compounds might be used to imply active volcanism on the surface, if their abundances changed significantly over short time periods. These compounds can be probed through multi-wavelength radio wavelength observations, combined with very accurate lab measurements of the constituent gas opacities. A program to do this type of observation will continue at the VLA.

2. Stars and Stellar Evolution

Radio emission is observed from stars throughout their life cycle. Young stars are commonly associated with maser emission from OH, water, and methanol, whereas in more evolved stars radiation from the molecular gas and thermal dust emission dominate. Some stars, such as x-ray binaries, also have intense non-thermal radio emission reflecting intense magnetic fields and the production of relativistic particles.

GRS 1915+105 is a galactic x-ray binary discovered in 1992 by the Granat satellite. VLA observations subsequently showed superluminal motion of the ejecta. VLBA images of the core show an elongated structure with the major axis aligned with the arcsecond-scale ejecta. The radio flux may be associated with x-ray bursts of the same period, corresponding to activity in the accretion disk at ~ 1 light second radius. IR and x-ray observations, coordinated with the VLA and VLBA in the radio, will continue on a target-of-opportunity basis in an attempt to connect disk and jet behavior and to interpret the behavior in terms of incoherent synchrotron emission models

The VLA is involved in regular monitoring of the active, or potentially active, x-ray binaries and x-ray transients to find and study the radio counterparts of new transients detected by the RXTE ASM and the CGRO BATSE x-ray instruments. These sources are amongst the prime objects on the NASA-funded Green Bank Interferometer program where daily, and hourly, monitoring is done when appropriate. Following major flares detected with the Green Bank Interferometer or with the VLA, imaging sequences for the relativistic and often superluminal motion in GRO J1655-40, GRO J1719-24, and Cyg X-3 will be obtained with the VLBA.

The ejection of relativistic jets, and related particle acceleration is probably due to magnetically collimated jets produced by winds from accretion disks and advection dominated accretion flows for the black hole systems that are predominate amongst these objects. These studies are addressing, with more easily observable objects, the fundamental problems of accretion-induced jets and outflows that also occur in quasars and AGN.

Planned theoretical modeling of both the basic physics and the appearance of relativistic distorted jet structures will be fundamental to interpreting the highly relativistic jet sources.

An intensive monitoring campaign of the v=1, J=1-0 SiO maser emission towards the late-type star TX Cam was begun in September 1997 with the VLBA. This project consists of a series of polarization observations using the VLBA, every two weeks, and is planned to cover a full pulsation period of the Mira variable. These observations allow the study of the kinematics and dynamics of the extended atmosphere, as well as providing fine-scale information of the distribution of the magnetic field in this environment. The full determination of polarization properties and proper motion will constrain models for mass-loss from late-type stars. In addition, work is planned to continue in the numerical modeling of maser kinematics using a generalized ellipsoid model.

Theoretical studies of stellar evolution will concentrate on chemical morphologies in young stellar regions and stellar evolution mixing theories through observations of isotopic abundances in planetary nebulae.

Several studies of the molecular abundances, physical characteristics and morphologies of young stellar regions have been done which highlight the chemical complexity of the circumstellar environment and the physical processes controlling it. This study forms significant tests of chemical models which consider gas-phase depletion of molecules and atoms onto grains during the collapse phase, grain surface reactions resulting in more complex species, and subsequent release of molecules back to the gas phase by shock and radiative heating after the young stellar object has formed. Overall a chemical evolutionary sequence is being developed for young stellar objects which parallels the dynamical evolutionary sequence but addresses more the physical processes that determine the observable morphology and chemical abundances of the circumstellar environment.

3. Supernovae and Supernova Remnants

Supernovae studies include observations of recent extragalactic supernovae as well as studies of historical supernovae remnants in our Galaxy.

A program to detect and monitor radio emission from young extragalactic supernovae will continue at the VLA. This radio emission arises from the interaction of the supernova ejecta and the circumstellar medium, and offers a means to study the final mass loss rate of the pre-supernova star. New optically discovered supernovae will be observed for radio emission, and if detected, will be monitored to establish multi- frequency radio light curves. Five older supernovae, SN 79C, 80K, 86J, 88Z, and 93J, remain radio bright. VLA observations will continue to trace their decay many years after the supernova explosion. Twenty-four radio supernovae have been detected to date, 14 of which were strong enough to have established radio light curves. When the next bright nova appears, extensive radio observations are planned with the VLA and the VLBA to determine light curves and evolutionary image sequences as was done very successfully for Nova Cygni 1992.

SN 1992J in M81 is unique among supernovae due to its proximity and level of radio emission. For over 45 months the shell has expanded uniformly with circular symmetry in complete agreement with models of shock excited emission. VLBA observations of SN 1993J will continue to follow the observed expansion to search for departures from circular symmetry due to hydrodynamical instabilities. Comparison of the angular expansion rate with spectroscopically determined radial velocity may lead to a measure of the distance to M81 more accurate than that obtained from classical methods such as the HST Cepheid program.

The availability of efficient continuum mapping with the 12 Meter will allow the exploration of the millimeter spectrum of some of the brighter Crab-like supernova remnants important to the study of evolutionary effects along with the intrinsic spectrum of the radiating electrons.

4. Pulsars

Pulsar observations have been enormously productive in teaching us about the physics of neutron stars, in exploring properties of the interstellar medium, and as the only experimental probe of gravitational radiation.

Polarization observations of the individual pulses from pulsars indicate that their radio emission consists of the simultaneous interaction of two modes of orthogonally-polarized radiation. The individual modes are highly linearly-polarized. A statistical model for the individual pulses of pulsar radio emission based upon these observed properties is able to replicate the histograms of total intensity, linear polarization, fractional linear polarization, and position angle that are observed in PSR B2020+28. Future research, based on this model and existing data will be aimed toward demonstrating that the pulsar radio emission depolarizes by superposed orthogonally polarized radiation, and will be crucial to our understanding of the radio emission mechanism of pulsars.

Pulsars lose a large fraction of their rotational energy in the form of a relativistic pair-loaded wind. How this wind is generated, its composition, and how it interacts with the surrounding medium (i.e., geometry) are poorly understood problems. Studying this weakly radiating wind has proven difficult. One productive approach, done particularly at optical and x-ray wavelengths, has been through a study of the nebulae formed by the action of the wind, where it first begins to interact with the surrounding environment as it is shocked. A program is in place at the VLA to make multi-frequency observations of both known pulsar wind nebulae and several promising candidates. The physical sizes and shapes of these nebulae as well as their spectra can be used to put constraints on the energetics of the nebula and to derive the parameters of the pulsar wind.

Strong scintillations of many pulsars has been observed towards the inner galaxy. These pulsars also have anonymously high dispersion measures. New measurements will investigate a recently discovered new class of diffuse HIM regions in the inner galaxy which could be the source of the enhanced scattering and the higher than expected dispersion measures.

5. Molecular Clouds, Star Formation, and Cosmic Masers

Star formation is complex process as it involves the chemistry, density, temperature, magnetic field, and kinematics of the material that will make up the star. Radio observations of molecular clouds on large scales and of young stars on the smallest scales characteristic of the protostars themselves contribute to our understanding of the fundamental questions involved in star formation.

High resolution mapping of regions of star formation will emphasize the environments surrounding jets and outflows from protostars. Of particular excitement is the newly discovered protostellar jet Herbig-Haro 212 which is so deeply embedded in molecular gas that it is visible only in infrared shock line emission. Images of the dense molecular gas surrounding this jet using the VLA may lead to an understanding of how a jet can retain high symmetry while tunneling through very dense molecular gas which is typically clumpy.

The ammonia (3,3) line is now known to be excited in regions of protostellar outflows. A VLA image of ammonia (3,3) emission surrounding the Orion-KL core will be used to study the outflow region in Orion (OMC-1). This image will then be compared to previous ammonia (1,1) and ammonia (2,2) studies which map the dense, unaccelerated gas around the outflow source. Such high resolution information covering a large (9') spatial scale, may show for the first time how outflows chisel their way out of their parent molecular cloud cores. The resulting disruption, shocking, and heating of the surrounding environment can affect the character of the next generation of stars that will form.

Dense pre-stellar cores of molecular gas in the northern region of the Orion Molecular Cloud (OMC-1) show some unusual properties including very fast rotation and unusual chemistry. Images of CS emission in these northern cores, observed with the IRAM interferometer, will be used to compare with high resolution ammonia maps of the cores observed with the VLA. The combined data-set should help us discern whether these are indeed collapsing cores that are "spinning-up" as they conserve angular momentum.

Other studies will concentrate on the earliest and latest stages of stellar evolution and will investigate 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 a VLA ammonia survey. Curiously, these objects tend to occur gregariously, with several cases of multiple objects within a single core known. Studies concentrate on these, both because of the usefulness of having more than one object in a field of view, and to study reasons why some cloud cores give birth to more than a single star at nearly the same epoch. In these images, differences among the objects become quite apparent. In objects so young that no bipolar flow has commenced, ammonia structures are readily discerned. In another group of objects, very cold ammonia exists, but shows only subtle correlation with cold dust structures enveloping the star. During the coming year, a high resolution ammonia study of HH212 will continue. The study of the Ophiuchus A molecular core, in which four dense clumps have formed a single star, maybe in the earliest formative stages of star production, will be concluded. The protostar VLA1623 will be shown to be an example of star formation induced in a cold molecular core by expansion of the wind from HD147889, a nearby O star.

The evolution of chemical morphologies in young stellar regions will receive special attention. Several studies of the molecular abundances, physical characteristics and morphologies of young stellar regions have been done which highlight the chemical complexity of the circumstellar environment and the physical processes controlling it. This study forms significant tests of chemical models which consider gas-phase depletion of molecules and atoms onto grains during the collapse phase, grain surface reactions resulting in more complex species, and subsequent release of molecules back to the gas phase by shock and radiative heating after the young stellar object has formed. Overall a chemical evolutionary sequence is being developed for young stellar objects which parallels the dynamical evolutionary sequence but addresses more the physical processes that determine the observable morphology and chemical abundances of the circumstellar environment.

Stellar evolution mixing theories through observations of isotopic abundances in planetary nebulae will also be important. Observations of carbon isotopic ratios ($^{12}C/^{13}C$) in evolved stars suggest that non-standard mixing occurs in some low-mass stars which decreases this ratio from ~ 25 to five. During the red giant branch (RGB) phase the deepening convective envelope brings material to the surface which has undergone nuclear processing over the main-sequence life-time of the star. Standard theories predict that for stars with masses greater than two solar masses, the $^{12}C/^{13}C$ ratio should be about 25. As the mass decreases below two solar masses the $^{12}C/^{13}C$ should increase. Observations of carbon in the surface of red giant stars are consistent with the models for the higher mass stars; however, these observations reveal lower $^{12}C/^{13}C$ ratios for stars below two solar masses. This study will test these predicted results from stellar evolution mixing theories.

Some galaxies have been identified as undergoing bursts of star formation for the first time. Of these galaxies, the HI-rich, low luminosity dwarfs may be precursors of normal spiral and elliptical galaxies. A systematic study with the 140 Foot Telescope of the HI envelopes of low-luminosity galaxies is expected to determine which dwarf galaxies are the best examples of the precursors of normal elliptical and spiral galaxies. The crux of the project requires devising and testing methods for measuring the absolute flux of extragalactic HI emission to an unprecedented accuracy of a few percent

The extended HI material associated with galaxies may act as a reservoir of material that may fuel star formation within galaxies. Very high signal-to-noise HI observations of galaxies are being made with the 140 Foot. The galaxies under study are isolated, have no known companions, and have diverse properties The observations should help evaluate the reservoir of gas. In particular, any observed anomalies in the profiles may arise from HI concentrations or peculiar kinematics, the latter probably because of tidal interactions with a companion.

The IRAM Interferometer and 30-meter radio telescope will be used to study the chemistry of local diffuse and translucent clouds by observing millimeter-wave molecular absorption spectra against compact extragalactic radio continuum sources. Past results showed that the relative abundances of trace molecules in these clouds resemble those in dark clouds, even though (i) the material is exposed to the interstellar uv radiation field; (ii) most of the carbon is not in CO; (iii) the ambient density of electrons must be relatively high. The absolute abundances of most of these molecules is hundreds or thousands of times larger than can be explained by conventional models of such gas. New results include a chemical survey of C_2H in 20 directions and smaller surveys of C_3H_2, HCN, HNC, CN, CS, SO, H_2S, among other species which is being used to investigate carbon, sulfur and nitrogen isotope ratios in the local ISM; the excitation and fractionation of CO; the statistics of C_2H absorption; and on the comparative chemistry of the many species we have observed.

The circumnuclear disk in Cen A was mapped in the CO J=3-2 line using the JCMT, and resolved for the first time. It is well modeled by a uniform flat disk in rigid-body rotation, implying the existence of a constant-density core. Such cores are now commonly observed in high-luminosity ellipticals, but the optical morphology of the core of Cen A is inaccessible owing to the prominent dust lane. The CO is now being compared with VLA HI data to see if CO mapping of the large-scale dust lane is warranted.

Images of the continuum distribution at 3.2 mm and 1.3 mm of J=2-1 CO emission over the face of Cas A will be used as a finding chart for the study of molecular absorption across Cas A but the continuum will be separately useful to constrain models of the supernova remnant.

Methanol masers bring unique information about physical conditions of the densest part of the cores of molecular clouds. Since these sites are the places where new massive stars are being formed a lot can be learned about the process from methanol masers observation. Previous VLA observations left many methanol condensations unresolved. Planned VLBA observations will allow for more detailed investigation of these clumps.

The OH (1720 MHz) masers have proven to be excellent tools for studying the interaction of supernova remnant shocks with molecular clouds. Future research will study individual objects identified in previous surveys. High angular resolution observations with the VLA and VLBA will be used to measure the angular size and position of the maser spots and Zeeman splitting will be used to measure the magnetic field strength in the post shock gas. Millimeter and sub-millimeter observations are planned to constrain the density and temperature of the gas from which the masers originate.

The search for water masers in the direction of the galactic center using the 140 Foot Telescope and the VLA will continue to concentrate on far-infrared (IRAS) sources. The ultimate goals of this systematic search are i) to study the kinematics of the late-type stellar population within and outside of the inner few hundred parsecs of the Galaxy; ii) to thereby constrain the galactic mass distribution; and iii) to assay the prevalence of star formation in the huge reservoir of galactic center gas, inasmuch as water masers detected in the vicinity of HII regions and from protostellar sources embedded in clouds can be used to locate and enumerate the sites of star formation.

Water maser monitoring in low mass stars, a continuing project on the 140 Foot and the VLA, has revealed some interesting parameterizations of low mass stellar masers. Most of these masers occur within 100 AU of the protostar, as revealed by millimeter continuum positions, whereas centimeter continuum positions appear to frequently locate the outflow, rather than the star. Even on these scales, the velocity shifts associated with the bipolar flows are evident. How then, does the maser emission arise? Perhaps it arises at the working surface of the bipolar jet on the ambient molecular cloud or it occurs where material entrained in or along the jet interacts with the surface of a protoplanetary disk. VLBA images will map the proper motions of the masers, and therefore explore the kinematics of outflow gas.

VLBA polarization observations of the OH maser emission towards a sample of possible post-AGB or pre-planetary nebulae have unusual spectral properties. Planned study of the OH maser morphology will assist in determining the nature of stellar evolution of late-type stars towards planetary nebulae.

6. The Interstellar Medium

Radio observations of the interstellar medium are used to study the distribution of cold atomic and molecular gas as well as the hot gas ionized by starlight.

Neutral hydrogen gas is found throughout the Galaxy. Planned observations of interstellar neutral hydrogen will focus on at high galactic latitudes where it is the dominant species in the interstellar medium, and on low latitudes where it is useful as a tracer of supershells and other organized energetic events. Previous VLA observations demonstrate the turbulence of HI which may extend from parsec scales down to AU scales. The observed AU scale features seen in absorption against pulsars and extragalactic sources could be part of this turbulence. This relationship will be investigated by further observations along lines of sights where the AU scale features have been seen.

The galactic fountain model predicts that energetic stellar winds and supernovae in OB associations produce superbubbles of hot gas that breaks out of the galactic disk, cools radiatively as it rises upward, and recombines and returns to the disk ballistically. The cool returning neutral hydrogen would be detectable as 21 cm emission from high-velocity clouds, while the hot million degree gas can be observed by x-ray telescopes. ROSAT observations will be used to search for x-ray emitting superbubbles in M33.

The observed properties of the galactic diffuse ionized gas are not easily reconcilable with simple photoionization models, unlike classical HII regions. A model of the diffuse ionized gas has been developed whereby it is ionized by a relatively soft ionizing spectrum and is also heated by an additional thermal mechanism: the dissipation of turbulence. This model has been fairly successful in describing the observed properties of the ionized gas in our Galaxy. Plans are underway to extend this calculation to other components of the Galaxy as well as to the diffuse gas in several well-studied extragalactic objects.

The large-scale distribution of more diffuse gas in the galactic center is poorly understood. Studies of the large-scale comparison of CO and H I emission over the inner 25 degrees of longitude will be made in an attempt to determine its properties.

High resolution, deep images of ^{4}He in several Galactic HII regions are planned with the VLA. ^{4}He radio recombination lines can provide important cosmological information about the early stages of element formation and are important diagnostic tools in the determination of the physical conditions in HII regions. Temperatures in the HII regions, the excitation temperature of the exciting stars, and local enhancements in y^+ ($^4He^+/H^+$) due to mass loss from evolved stellar objects are examples of the possible properties that can be determined.

Observations are also planned to measure the carbon isotopic abundance ratio, $^{12}C/^{13}C$, by using the millimeter transitions of CO in planetary nebulae at the 12 Meter Telescope and possibly the HHT. These data will constrain mixing theories in stellar evolution models and provide a connection between similar measurements in red giant branch stars and the interstellar medium. They will also compliment the observations of ^3He in PNe and may give insight into the "The ^3He Problem"—the discrepancy between the abundances of ^3He in PNe and HII regions. A resolution to this problem has implications to Big Bang nucleosynthesis.

The study of physical and chemical conditions in small translucent molecule clouds will continue. Physically self-consistent models (hydrostatic equilibrium polytropes) have been fit to extensive observations of $C^{18}O$ and ^{13}CO, which include the effects of external radiation fields and provide the radial distributions of all physical quantities including electrons. Once these conditions are known, the chemistry of other molecules can be derived. We have completed an extensive study of ion-molecule chemistry with detailed modeling of the species H_2CO, NH_3, HCO^+, N_2H^+, SO, SO_2, SO^+, HCS^+, CS, H_2S, HCN, HNC, C_3H_2, HC_3N, C_2S, SiO in an ensemble of 38 translucent objects. Ion-molecule chemistry is found to describe all of the species except H_2CO, H_2S, and SiO, which require photocatalysis on grains. This work will continue with an analysis of observations of more complex species (CH_3OH, H_2CCO, HCOOH, HNCO) which already shows that the slow radiative association reactions cannot match observed abundances, and that grain formation must be effective. Observations of the complex species (CH_3CHO, NH_2CHO, EtOH, EtCN, $(CH_3)^2O$, and CH_3OHCO will be used to set limits for the complexity of molecules detectable in translucent clouds.

An unambiguous example of a molecular cloud impacted by a violent shock, W51C, has been recently discovered. After IC443, this is only the second clear example of a shocked molecular cloud. Thus shock chemistry is poorly understood from the observational point of view. Sensitive observations of ^{13}CO and $C^{18}O$ rotational lines in the interface region have discovered very optically thin, very hot CO gas. Detailed modeling techniques to this object will be used to derive physical conditions, and to study its chemistry.

The transition between diffuse atomic gas and molecular gas is not well understood, the relation between HI, CO, and IRAS 100 um emission being highly complex. A key missing species in these studies is OH known to be the first molecule formed in gas phase (after H_2 on grains). The Polaris Flare Cloud is a well-mapped object in HI, CO, and at 100 mcicrons with IRAS. Images of this cloud in OH will be used to explore the idea that OH is detectable in regions where CO is not; the OH images should act as an excellent tracer of H_2, which OH requires for its formation.

7. Normal Galaxies and Clusters

Radio telescopes study the properties and evolution of galaxies and clusters of galaxies by observations of their continuum emission as well as spectroscopic observations of atoms and molecules. Of special interest are neutral hydrogen, HI, and carbon dioxide, CO, which are found in great abundance throughout the universe. Studies of the distribution and interaction between hot (x-ray) and cool (HI, CO) gas within early type galaxies will be continued. Particular attention will be given to study the cosmic evolution of gas in galaxies through observation of redshifted radio emission and absorption lines, including: low frequency observations of the HI and OH lines using the VLA, Effelsberg, and the up-graded WSRT; and high frequency observations of transitions from various molecules using the VLA and the VLBA.

Galaxy interactions in clusters, mergers and groups are an important probe of star forming activity in distant galaxies. Observations of the cluster Abell 2029 which is one of the densest clusters known, will teach us about ongoing evolution by detecting galaxies in their first approach to the cluster center as their neutral hydrogen is stripped by ram pressure as well as through the tidal interaction with the cluster. At a redshift of 0.08, Abell 2029 is one of the most distant clusters that can be studied with the VLA.

Merging galaxies often possess long dynamically cold tidal features stretching tens to hundreds of kpcs from the host systems. Therefore, HI data cubes of such systems are also uniquely suited to constraining numerical simulations of the interaction. An automated model-matching process is expected to constrain the structure of the halo of the progenitors (and hence of their dark matter content) over much larger radial scales than can be traced with normal HI rotation curves.

Observations of galaxy mergers frequently reveal curious offsets between the faint optical and HI tidal features. In each of these cases the host systems show evidence of the "blowout" phenomena, whereby the nuclear starbursts imparts so much kinetic energy into the surrounding ISM that it is heated to several million degrees, expands, and flows out of the Galaxy in a galactic wind. These observations suggest that there is often an interaction between the cold tidal HI and the hot expanding wind material. New HI observations of two well known "blowout" candidates will test this these theories.

One goal of these investigations is to understand whether disks resulting from a merger will eventually resemble normal ellipticals, or if these systems will be anomalous in some way. Observations trace the cold and hot gas phases in a sample of six ellipticals with evidence of a past merger or accretion event. Elliptical galaxies as a class are relatively bright, and there is some suggestion that recent merger remnants may be x-ray underluminous. Planned observations will span a range of x-ray luminosities, and will investigate whether there is a relationship between the amount of tidal HI and the x-ray luminosity of the remnant.

Observations of infrared galaxies with an on-going starburst, but with none of the more obvious morphological signatures of a past interaction or merger suggest that tidal HI may leave the longest lived signatures of past encounters. New observations will search for such relic tidal features. If they are not found, we would conclude that such active starbursts may be fueled by process other than mergers. High quality HI data cubes on 20 mergers will be used to assess the contribution of merging galaxies to the absorption line features seen in optical and UV spectra

Recent VLA observations of the "Antennae," galaxies NGC 4038/4039, which is the best known example of a merging system, show a large amount of compact radio emission in the galaxy, distributed along the tidal tails, near the two galaxy nuclei, and in several loops or shells of sources. Further VLA data will be obtained, and the resulting images compared to high resolution optical and UV photos from the HST and Astro-2. The radio observations will be used in conjunction with those at the shorter wavelengths in order to identify HII regions and supernova remnants, as well as to probe the regions of high obscuration in the Antennae galaxies.

HI, optical, and Owens Valley Radio Observatory (OVRO) millimeter observations of seven luminous infrared galaxies, which are the most active starbursts in the nearby universe, have been completed. All are on-going mergers of gas rich systems. The distribution and kinematics of the HI gas bears the imprint of the encounter geometry and provides clues as to the Hubble types of the progenitors. These observations will be compared with similar observations of mergers with lower characteristic star formation rates to see if there are specific requirements (e.g., gas content, spin geometry) for a merger to experience a highly elevated episode of star formation.

The asymmetrical distribution of cool gas within disk galaxies is long recognized but little studied. It occurs frequently but is poorly understood. The differential rotation within these systems should have smoothed out such asymmetries on a time scale of one to two rotation periods. The study of such asymmetries in an ongoing project in which an initial data set of ~ 100 isolated galaxies were observed with the 140 Foot Telescope. A subset of these galaxies will be observed with the VLA to locate the spatial distribution and hopefully the origin of such asymmetries.

Amorphous galaxies are rare, approximately one percent of catalog entries, but appear to represent an important step in the evolution of interacting systems. These systems will be studied to see if they are on a poorly populated "branch" of such evolution or on a main stream "trunk." Synthesis HI maps will give detailed information on the distribution of HI as well as the kinematics within these systems. An initial study of the amorphous system NGC 2777 uncovered an HI bridge to an uncataloged faint galaxy nearby.

Several other projects will focus on understanding the relationship between the neutral gas and the star formation process in galaxies. One involves an investigation of the correlation between metallicity and the empirical critical gas density for star formation. For instance, the extremely high peak column density associated with star formation in the most metal-poor known star-forming galaxy, I Zw 18, suggests that the empirical threshold density increases at low metalicities. High spatial and spectral resolution of five low metallicity actively forming stars were obtained using the VLA to look for a correlation between high gas column density and low metallicity and to further our understanding of the role neutral gas plays in regulating star formation activity in low mass galaxies.

ROSAT observations designed to map the distribution of x-ray emission around two Sa galaxies NGC 2775 and NGC 3263 have now been completed. Coupled with observations of the cool gas, the x-ray data will be used to explore the spatial correlation between the hot and cold gas. Current indications are that the hot gas is a bulge phenomenon and the cold gas is concentrated to the disk. The analysis of these data, and of HI synthesis data, will concentrate on the region where the cold and hot components apparently come together, to search for a signature of interaction between the two components.

It has been more than 30 years since the discovery of the high-velocity clouds of neutral hydrogen that dominate the kinetic energy of neutral hydrogen in non-circular motion in our Galaxy. Despite progress in the last three decades, the unknown distances to almost all galactic high-velocity clouds prevent the determination of their masses, linear diameters, or densities, which makes it difficult to understand their nature and origin. Deep VLA observations of high-velocity clouds of neutral hydrogen galaxies will concentrate on two nearby disk galaxies with large high-velocity mass fractions. These observations will establish whether the high-velocity neutral hydrogen is due to internal processes such as a galactic fountain, external processes such as infall or past interactions, or a combination of the two. The two galaxies are in different environments, so the observations will also test whether the nature of the high-velocity clouds depends on the presence of nearby galaxies.

8. Radio Galaxies, Active Galaxies, and QSOs

Radio emission from distant galaxies and quasars is due primarily to synchrotron radiation from highly relativistic particles moving in weak magnetic fields. In many of the lower luminosity objects, the source of energy is believed to be in due to active star formation accompanied by multiple supernovae activity which excites the interstellar medium. But in the more powerful radio galaxies and quasars, the energy source is believed to lie in a massive central engine, probably a black hole which supplies relativistic electrons to the distant radio lobes along a narrow jet. How the energy is transformed into a highly focused beam of relativistic particles is unknown, and this question forms the focus of much of the work on extragalactic radio sources.

Continued work on understanding the large scale structure of powerful radio galaxies will concentrate on i) high resolution polarimetric imaging surveys of a large sample of high redshift radio galaxies, ii) x-ray observations of select sources, iii) detailed studies of Cygnus A with the VLBA, the VLA, and ROSAT, and iv) ISO and HST observations of selected sources.

High dynamic range submilli-arcsecond imaging of quasars and AGN including polarizations structure is now feasible with completion of the VLBA and numerous programs are planned to exploit these opportunities. Quasars and AGN are being imaged with submilli-arcsecond resolution, in order to better understand their morphological structure and how this relates to the larger arcsecond structure and optical counterparts. Polarization imaging will give new insight to the ordering of magnetic fields in quasars and AGN, and continuing observations of internal motions in quasars and AGN may lead to a better understanding of the mechanism by which relativistic electrons are accelerated and focused into narrow beams within regions as small as one parsec or less.

Special attention will be given to Seyfert galaxies to: investigate the sub-parsec-scale radio structure, and to look for absorption effects that might indicate the presence of the obscuring torus required by the standard model of orientation unification; investigate the properties of parsec-scale radio jets in Seyfert galaxy cores, including their strengths, curvature, and speeds; and search for direct evidence of parsec-scale tori or accretion disks in Seyfert nuclei. Particular attention will be given to multi-frequency observations to search for the presence of jets, and to image the spectral index gradient along possible jets. The spectral index gradient should carry a characteristic imprint near the jet base left by free-free absorption from the ionized inner edge of the torus.

A second-epoch observation of NGC 4151 will be made to look for proper motions in the newly discovered sub-parsec jet. These observations will provide one of the first measurements of the speed of components in a radio-quiet AGN. The observation will involve a long integration to achieve good surface brightness sensitivity, to search for direct thermal emission from the hypothesized torus, such as has been found recently in NGC 1068. Deep integrations will be made of other Seyfert galaxies to further the search for thermal emission from obscuring tori.

Also of great interest will be VLBA observations of Compact Symmetric Objects discovered in surveys over a wide range in frequencies which will pinpoint the center of activity in these objects and yield further knowledge about the evolution of radio galaxies. The VLA, VLBA, and WSRT telescopes have revealed a remarkably high incidence of redshifted HI absorption in Compact Symmetric Objects and will be used to further pursue this line of research.

Special attention is being given to the radio galaxies 3C 84 (NG1275) and 3C 120. Multi-wavelength VLBA observations are being used to image 3C84 in order to study the free-free absorption from a putative obscuring disk, and to follow subluminal motions in the jet and counter-jet at 0.05 parsec resolution. Further monitoring is expected to refine the constraints on the geometry and kinematics of this jet, which is apparently accelerating and has multiple bends. Questions that will be addressed are: Is the fluid motion ballistic or along a helical channel? Do individual plasma blobs survive the sharp bends? What is the physical nature of the transition region where the jet apparently accelerates to its terminal velocity of 0.5c? Which components are moving? Is there a counter-jet in the core?

The first VLBA 18 cm image of 3C120 shows a continuous jet structure over 0.5 arcseconds long. A 19-station global VLBI observation should provide an even better image, and should provide full polarization information, and will be further enhanced by planned observations with the Japanese HALCA space VLBI mission. Recent results with the VLA suggest that the motions have slowed by the time the jet reaches 4 arcseconds (about 2 kpc). It is of interest to find where the slowing occurs.

9. Radio Surveys, Gravitational Lensing, Gamma-Ray Bursts, and Cosmology

As new radio facilities are put into operation, or older facilities are given new capabilities, sky surveys have traditionally uncovered unexpected new phenomena such as radio galaxies, quasars, pulsars, gravitational lensing, and cosmic masers which have changed, in fundamental ways, the course of astronomical research. Surveys to ever improving depths are also important to determine the luminosity function and its evolution for different populations of radio sources. In 1998 the NRAO team will complete the NVSS which will be an order of magnitude more sensitive than any previous survey of this kind, and which will provide users with an invaluable catalogue of some two million radio sources. Complementing this are the very deep VLA surveys of selected regions including the Hubble Deep Field which are leading to a new understanding of the history of star formation in the early universe, as the radio emission is an accurate measure of star formation unimpeded by obscuration or orientation effects which plague optical studies.

The early Universe will also be probed using the VLA to search for proto-clusters of galaxies through the observation of their redshifted 21 cm emission at a frequency in the range of 305 MHz to 335 MHz. The VLA has been pushed to a sensitivity of better than 0.8 mJy/synthesized-beam for spectral channels of width 100 kHz. A number of tests have located sources of systematic errors (interference, pointing) and ways have been found to correct them or eliminate their effects. Indeed, signal-free images are free of artifacts and achieve the theoretical sensitivity which corresponds to an rms sensitivity value of about 4×10^{12} $M_{\odot}$.

Research on high energy transients (soft gamma-ray repeaters and classical gamma-ray bursters) will continue, building on the success at determining the counterparts to these intriguing objects. VLA observations of the known soft-gamma ray repeaters will be made to understand the central energy source that gives rise to these bursts. For gamma-ray bursters, the successful counterpart program at the VLA and elsewhere will continue. Important goals of these radio observations include the testing of the predictions of the "fireball" model with the light curves and an attempt to resolve the expanding fireball either directly with the VLBA or by interstellar scintillation. The radio counterpart to the gamma-ray burst of May 8, 1997, will continue to be monitored using both the VLA and VLBA. Upper limits on the angular size and proper motion place limits that can already be used to eliminate some theoretical models. Other gamma-ray bursts will probably have radio counterparts and will be followed-up with VLA and VLBA observations as appropriate.

VLBA polarization observations of gravitational lens systems will focus on the highly polarized source B0218+35.7. These observations have been shown to be technically feasible and offer the opportunity to study the invariance of polarization under gravitational lensing, to study Faraday rotation in the intervening lens galaxies and to provide additional constraints on gravitational lens models.

A number of observational programs will 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. VLBA observations will search for milli-arcsecond lensing expected from lenses of the order of 10^6 $M_{\odot}$.

10. Instrumentation, Geodesy, and Observing Techniques

The continued increase in use of radio frequencies to fulfill a multitude of commercial and communication needs, especially from satellite-born transmitters, threatens the future of radio astronomy. Research to develop techniques to suppress the effects of interference are receiving increased attention.

Considerable effort by many NRAO staff is being devoted to preparing for the MMA development. Particular attention is being paid to the design of antennas, methods of obtaining precise amplitude calibration of the array and the use of radiometric techniques to correct for tropospheric phase fluctuations.

Many members of the scientific staff are also engaged in preliminary studies for the VLA/VLBA upgrade. Major goals are to improve the sensitivity, frequency coverage, and spectroscopic capability. Emphasis during the coming year will be to develop the real-time local oscillator and IF links between the VLBA Pie Town antenna and the VLA as a prototype to prepare for later linking other nearby VLBA antennas to the VLA to allow real-time operation of the VLA with enhanced resolution.

Other programs by the scientific staff will provide for various improvements in VLA performance. Polarization calibration at the VLA will be supplemented by GPS measurements of the ionospheric Faraday rotation. Antenna pointing performance will continue to be improved and work on the 43 GHz system at the VLA will implement and test phase calibration techniques for obtaining images with diffraction limited spatial resolution on arbitrarily long baselines at 43 GHz. Special attention will be given to use of the site testing interferometer at the VLA for real-time monitoring of phase stability to be used by observers for making decisions on observing strategies while observing at high frequency at the VLA. Work will also be started to develop a tipping radiometer to measure the atmospheric opacity, as an important input for future possible dynamic scheduling at the VLA.

Much of the staff research on VLBA instrumentation will be devoted toward implementing the 3 mm observing system which will effectively double the resolution of the VLBA. As part of this effort, the VLBA antenna optics have been aligned for maximum efficiency, and the active rotation of the subreflector has been used to compensate for the gravity-induced quadrupod sag. Pointing and thermal effects at millimeter wavelengths are also under ongoing investigation, as more of the VLBA antennas get receivers for the 3 mm band during 1998. Other activities include implementing pulsar-gating for improved sensitivity for pulsar observations.

In the effort to make the VLBA a phase-stable instrument, experiments will be carried out using GPS receivers to measure the ionospheric contribution to path length variations. These should improve the dynamic range achievable through phase referencing. The use of phase-referencing to extend coherent integration times on the VLBA requires a dense grid of VLBI-compact calibrator sources. An all-sky survey of potential calibrators using geodetic-mode snapshot observations of 2236 flat-spectrum sources selected from the MERLIN Calibrator list has been completed with a typical positional accuracy better than 1 mas. These observations are being used to define the VLBA astrometric reference frame.

1998 should see increased use of the HALCA space VLBI satellite in cooperation with the VLBA and other ground-based radio telescopes. Considerable effort is being expended toward optimizing the performance of the Green Bank earth station, the VLBA correlator, and post-correlation algorithms to maximize the returns from planned space VLBI observations by the NRAO staff as well as users worldwide. Plans are also being formulated to develop the concept for a future space VLBI mission which is aimed at launching an orbiting radio telescope with capabilities similar to a VLBA telescope.

Observations with single-dish antennas have been traditionally limited due to the limited number of beams, typically only one, placed in the sky. Full-sampling of the aperture plane using array feeds have demonstrated the feasibility of forming multiple, closely spaced, beams on the 140 Foot. The next step is to improve the receiver's sensitivity to optimize the beam-forming algorithm and to study the effects of mutual coupling between the array elements. These topics will be among those explored and developed by the NRAO staff in 1998.

APPENDIX B – SCIENTIFIC STAFF

(Does not include visiting appointments)

D. S. Balser — Galaxy: Abundance, Structure – ISM: HII Regions, Planetary Nebulae – Radio Sources: Continuum, Line.

T. S. Bastian — Solar/stellar radio physics; interferometry; image deconvolution and reconstruction.

A. J. Beasley — Radio interferometry; VLBI observing techniques.

J. M. Benson — Extragalactic radio sources; VLBI image processing.

R. C. Bignell — Polarization and imaging of extragalactic radio sources; planetary nebulae; supernovae remnants.

J. Braatz — Galaxies; interacting galaxies.

A. H. Bridle — Extragalactic radio sources.

R. L. Brown — Theoretical astrophysics; interstellar medium; quasar absorption lines.

B. J. Butler — Using observations of the planets and their atmospheres at radio wavelengths to deduce information about them.

C. Carilli — Radio galaxies; QSO absorption lines; magnetic fields in galaxies; tropospheric effects on interferometer phases.

J. Cheng — Structural engineering, antenna design theory.

B. G. Clark — VLBA control; software development.

M. J. Claussen — Masers; HII regions; molecular spectroscopy; spectropolarimetry; radio recombination lines.

J. J. Condon — QSOs; normal galaxies; extragalactic radio sources.

T. J. Cornwell — Interferometry; image reconstruction methods; coherence theory; radio source scintillation.

W. D. Cotton — Extragalactic radio sources; interferometry; computational techniques for data analysis.

L. R. D'Addario — Telescope design, correlators, millimeter-wavelength receivers, cryogenics, radio astronomy from space.

K. M. Desai — Space VLBI; development of VLBI imaging algorithms.

V. Dhawan — Extragalactic and galactic jets; millimeter VLBI development.

P. J. Diamond — Spectral line interferometry; VLBI; software development.

D. T. Emerson — Nearby galaxies; short wavelength millimeter VLBI observations; millimeter-wave instrumentation; history of millimeter-wave research.

J. R. Fisher — Cosmology; signal processing; antenna design.

C. Flatters — VLBI polarization studies of extragalactic radio sources.

E. B. Fomalont — Interferometry; extragalactic radio sources; relativity tests.

D. A. Frail — Interstellar medium; pulsars; supernova and nova remnants; radio stars.

R. W. Garwood — Galactic 21-cm line absorption; interstellar medium; high redshift 21 cm line absorption.

F. D. Ghigo — Interacting galaxies; extragalactic radio sources; interferometry.

B. E. Glendenning — Starburst galaxies; scientific visualization.

M. A. Gordon — CO; galactic structure; gas-rich galaxies; interstellar medium.

W. M. Goss — Galactic line studies; pulsars; nearby galaxies.

E. W. Greisen — Structure of the interstellar medium; computer analysis of astronomical data.

J. R. Herrnstein — VLBI spectroscopy of galactic nuclei; interstellar masers.

J. E. Hibbard — Extragalactic HI, galaxy evolution, merging galaxies.

R. M. Hjellming — Radio stars; radio and x-ray observations of x-ray binaries; interstellar medium.

D. E. Hogg — Radio stars and stellar winds; early-type galaxies.

M. A. Holdaway — Image reconstruction methods; VLBI polarimetry.

K. I. Kellermann — Radio Galaxies, Quasars, Cosmology, Radio Telescopes.

A. J. Kemball — Spectroscopy and polarimetry in VLBI; interstellar masers; astronomical software.

A. R. Kerr — Millimeter-wave instrument development.

L. J. King — Antenna structural/mechanical analysis and design; optimization methods for antenna structural performance.

L. Kogan — Maser radio sources; theory of interferometry; software for data reduction of VLBI.

G. I. Langston — Gravitational lenses; computational techniques for synthesis imaging.

H. S. Liszt — Molecular lines; galactic structure.

F. J. Lockman — Galactic structure; interstellar medium; HII regions.

R. J. Maddalena — Molecular clouds; galactic structure; interstellar medium.

J. G. Mangum — Star formation; astrochemistry; molecular spectroscopy of comets.

R. G. Marson — Aperture synthesis algorithms; optical aperture synthesis; imaging stellar surfaces.

M. M. McKinnon — Pulsar astrophysics; polarimetry; stochastic processes.

J. M. McMullin — Astronomical software systems.

A. H. Minter — Interstellar turbulence; space VLBI.

A. Mioduszewski — Radio galaxies; techniques for space VLBI.

P. J. Napier — Antenna and instrumentation systems for radio astronomy.

F. N. Owen — Clusters of galaxies; QSOs; radio stars.

S. K. Pan — Design of superconducting circuits; SIS devices.

J. M. Payne — Telescope optics; millimeter-wave receivers; cryogenic systems.

R. A. Perley — Radio galaxies; QSOs; interferometer techniques.

M. Pospieszalski — Low noise front-ends and amplifiers; theory and measurement of noise in electronic devices and circuits.

S.J.E. Radford — Starburst galaxies, millimeter interferometry.

M. S. Roberts — Properties and kinematics of galaxies.

J. D. Romney — Active extragalactic radio sources; VLBI; interferometer imaging.

A. Roy — Starburst galaxies; active galactic nuclei; radio recombination lines; instrumentation..

M. P. Rupen — Interstellar medium of early type galaxies; galaxy dynamics; supernovae; steep spectrum sources.

E. R. Schulman — The disk-halo connection in spiral and starburst galaxies; the properties and kinematics of spiral galaxies.

R. A. Simon — Theory of interferometry; computational imaging; VLBI.

R. A. Sramek — Normal galaxies; quasars; supernovae, aperture synthesis techniques.

G. Taylor —Active galactic nuclei and their environments; Faraday rotation measures; HI absorption; gamma-ray bursters.

A. R. Thompson — Interferometry; frequency coordination and atmospheric effects; distant extragalactic sources.

B. E. Turner — Galactic and extragalactic interstellar molecules; interstellar chemistry; galactic structure.

J. Ulvestad — Seyfert and starburst galaxies; blazars; space VLBI.

J. M. Uson — Clusters of galaxies; cosmology.

P. A. Vanden Bout — Interstellar medium; molecular clouds; star formation.

G. A. Van Moorsel — Dynamics of galaxies and groups of galaxies; techniques for astronomical image analysis.

L. E. Van Zee — Extragalactic HI; galaxy evolution; star formation; elemental enrichment.

M. Verheijen — Radio galaxies.

R. C. Walker — Extragalactic radio sources; VLBI; VLBA development.

J. C. Webber — VLBI and Space VLBI; superluminal radio source structure.

D. C. Wells — Digital image processing; extragalactic research.

J. J. Wiseman – Star formation; structure and fragmentation of molecular clouds; protostellar outflows; radio image mosaics.

E. J. Wollack — Cosmic microwave background; instrumentation for radio astronomy.

A. H. Wootten — Star formation; structure, and chemistry of the interstellar medium in galaxies; circumstellar material.

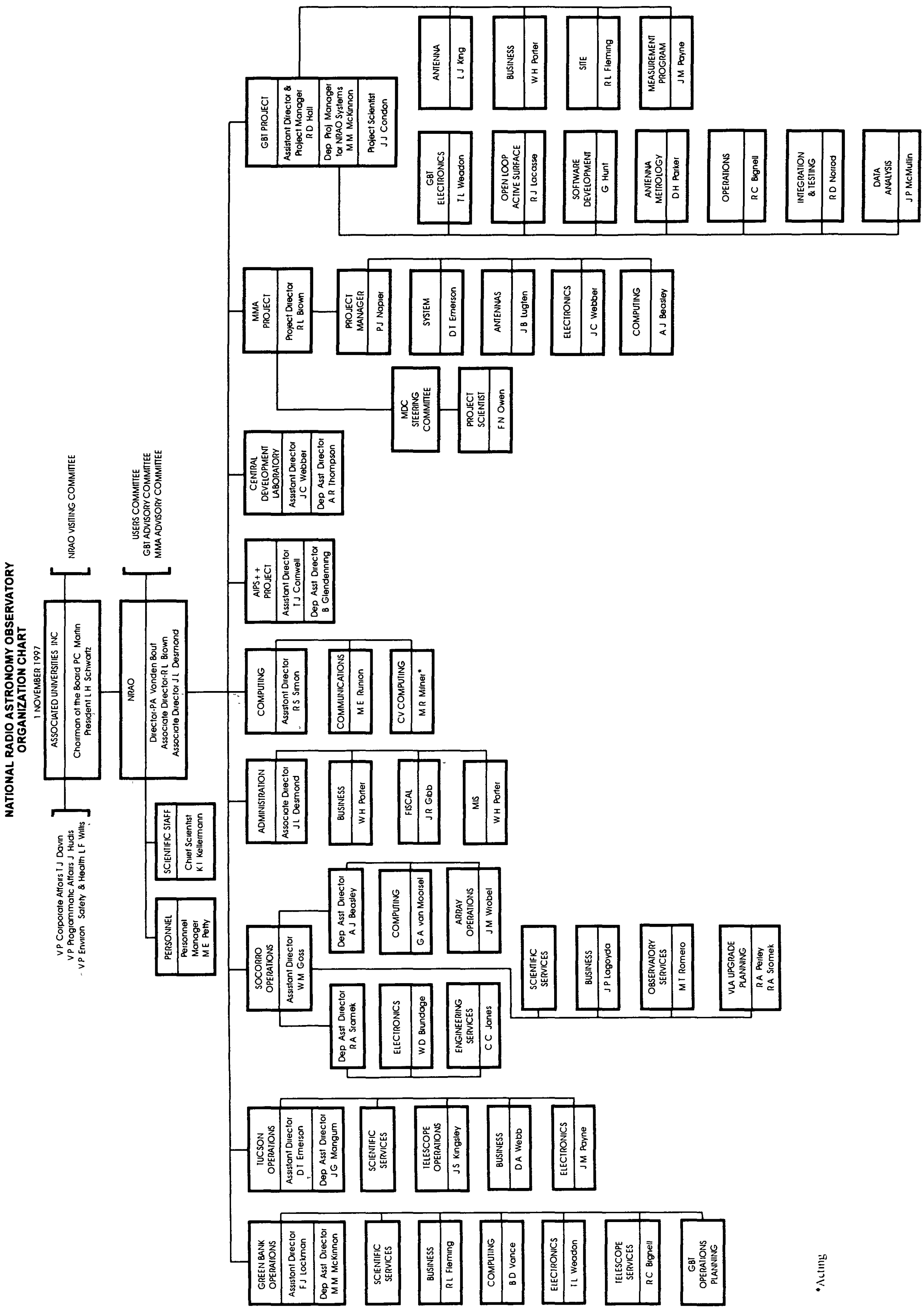
J. M. Wrobel — Normal galaxies; active galaxies; polarimetry.

Q.-F. Yin — Normal galaxies; imaging techniques.

M. S. Yun — Extragalactic radio sources; star formation.

Q. Zhang — Star formation; physical processes in molecular clouds.

APPENDIX C - ORGANIZATION CHART



APPENDIX D - 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:

T. M. Bania	Boston University	Term Expires 2000
J. E. Carlstrom	University of Chicago	Term Expires 2000
D. B. Campbell	Cornell University	Term Expires 1999
N. J. Evans	University of Texas, Austin	Term Expires 1997
R. Hanisch	Space Telescope Science Institute	Term Expires 1999
K. Y. Lo	University of Illinois	Term Expires 1997
J. Pipher	University of Rochester	Term Expires 1997
M. J. Reid	Center for Astrophysics	Term Expires 1998
L. F. Rodriguez	Instituto de Astronomia UNAM	Term Expires 1998

2. NRAO Users Committee

The Users Committee is made up of users and potential users of NRAO facilities from throughout the scientific community. It advises the Director and the Observatory staff on all aspects of Observatory activities that affect the users of the telescopes (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:

A. Arzoumanian	Cornell University
D. C. Backer	University of California, Berkeley
R. Barvainis	MIT Haystack Observatory
M. Bell	Herzberg Institute of Astrophysics
R. T. Clancy	University of Colorado
I. de Pater	University of California, Berkeley
M. Elvis	Center for Astrophysics
A. L. Fey	U.S. Naval Observatory
R. S. Foster	Naval Research Laboratory
R. Giovanelli	Cornell University

L. Greenhill	Center for Astrophysics
C. E. Heiles	University of California, Berkeley
L. A. Higgs	Dominion Radio Astrophysical Observatory
D. Hough	Trinity University
J. D. Kenney	Yale University
E. A. Lada	University of Florida
R. Mutel	University of Iowa
S. T. Myers	University of Pennsylvania
C. P. O'Dea	Space Telescope Science Institute
P. Palmer	University of Chicago
E. Skillman	University of Minnesota
J. Van Gorkom	Columbia University

3. 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:

F. C. Adams	University of Michigan
T. M. Bania	Boston University
J. H. Bieging	University of Arizona, Steward Observatory
E. B. Churchwell	University of Wisconsin
E. Erickson	University of Massachusetts
N. J. Evans	University of Texas, Austin
P. Goldsmith	Cornell University
R. Hills	Cavendish Laboratory
G. R. Knapp	Princeton University
C. R. Masson	Center for Astrophysics
F. P. Schloerb	University of Massachusetts
P. Solomon	State University of New York
J. Turner	University of California, Los Angeles
E. van Dishoeck	University of Leiden
R. W. Wilson	Smithsonian Astrophysical Observatory
G. Wynn-Williams	University of Hawaii

4. GBT Advisory Committee

This committee periodically reviews the GBT Project. Initially the committee advised the Director on critical design issues facing the GBT project. Review of construction progress and expected telescope performance is the present charge to the committee. The committee is appointed by the Director. Current membership is:

T. M. Bania	Boston University
J. Baars	University of Massachusetts
C. E. Heiles	University of California, Berkeley
R. Hills	Cavendish Laboratory, UK
J. E. Nelson	University of California, Santa Cruz
V. Radhakrishnan	Raman Research Institute
S. Von Hoerner	NRAO, Retired
S. Weinreb	University of Massachusetts
R. W. Wilson	Smithsonian Astrophysical Observatory

5. AIPS++ Scientific Advisory Committee

This 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
R. Foster	Naval Research Laboratory
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 Laboratories, UK
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