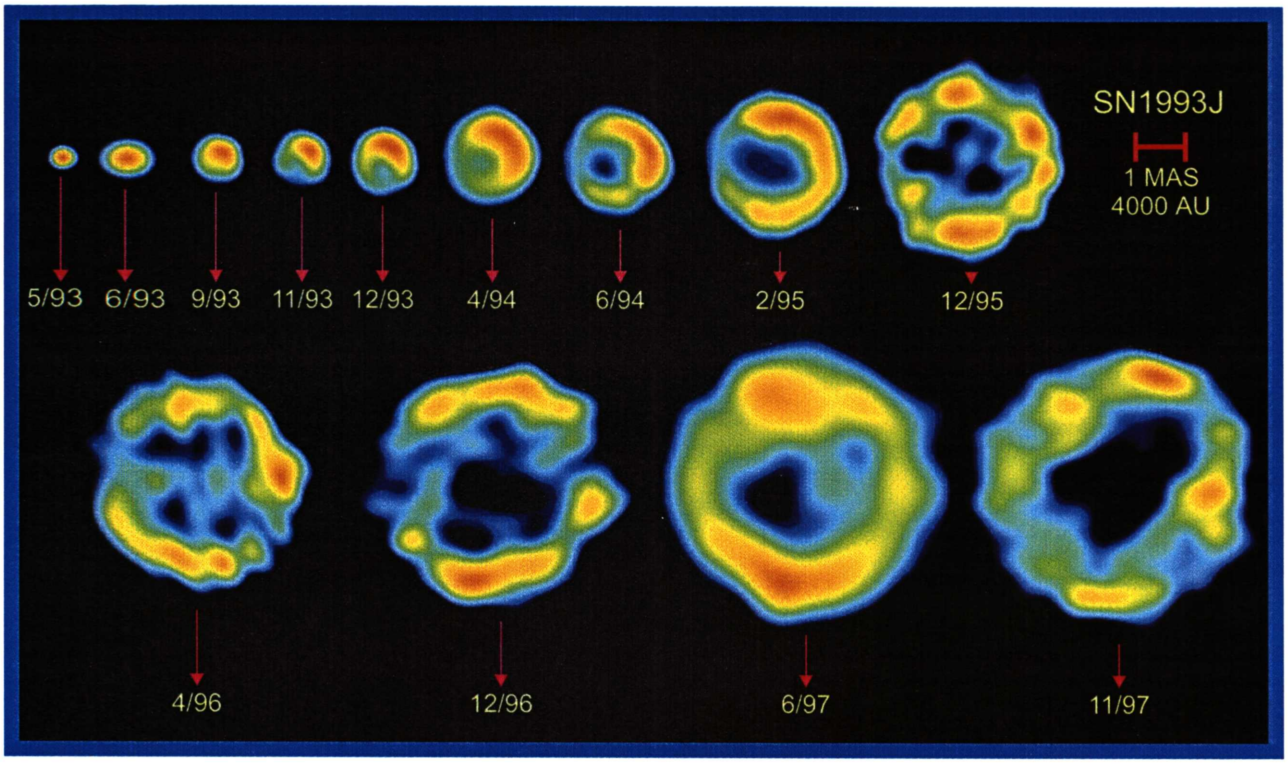

PROGRAM PLAN
1999

NRAO

NATIONAL RADIO ASTRONOMY OBSERVATORY

Cover: A "movie" of the radio emission from the exploding star Supernova 1993J in the galaxy M81. This time-sequence of images was made at a wavelength of 3.6 cm (8.3 Ghz) with a global array of telescopes that included the VLBA and the VLA. The resolution, or clarity of image detail, is 4000 AU (about 20 light-days), hundreds of times finer than can be achieved by optical telescopes on such a distant object. Observers: M. Rupen, N. Bartel, M. Bietenholz, T. Beasley.

NATIONAL RADIO ASTRONOMY OBSERVATORY

CALENDAR YEAR 1999

PROGRAM PLAN

NOVEMBER 1, 1998

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I. INTRODUCTION

The National Radio Astronomy Observatory (NRAO) plans for the penultimate year of this century are the culminations of a long effort preparing for the scientific requirements of the start of the new millennium. These plans call for the replacement or transformation of all current NRAO observing facilities. The new set of instruments is well matched to the instrumentation anticipated in other wavelength regions, enabling the multiwavelength studies increasingly demanded by research astronomers, and setting the standard for sensitivity, angular resolution, and quality of imaging. Projects in progress follow from the recommendations of past decade survey committees; we expect our proposed projects to gain the endorsement of the survey committee that is beginning.

Work by the contractor for the Green Bank Telescope (GBT) is expected to be completed by the end of 1999. This final year of construction will be accompanied by final testing of NRAO instrumentation in preparation for installation. The detailed plans for telescope commissioning will be completed, as will plans and procedures for use of the telescope by observers. A workshop held in July of 1998 discussed a wide variety of projects that are designed to exploit the enormous new scientific capability the GBT will provide.

The design and development phase of the Millimeter Array (MMA) will be in its second year in 1999. It will be a year of intense activity in designing and prototyping selected systems, most prominently a prototype antenna, and of planning and structuring the entire project. An important goal is the delivery of a sound cost estimate and schedule that the National Science Foundation (NSF) can use for budgetary planning. The year will also see intense activity on negotiations with international partners. The prospect of a merger between the MMA and the European Large Southern Array (LSA) shows strong promise, and we continue to discuss mechanisms for cooperation with the Japanese Large Millimeter and Submillimeter Array (LMSA).

Planning for an upgrade of the Very Large Array (VLA) will continue, following a workshop held in June 1998. These plans, to improve every VLA scientific specification by an order of magnitude through advanced instrumentation, will be presented to the Astronomy and Astrophysics Survey Committee. Some aspects of the upgrade have already begun using funds from the NSF Major Research Instrumentation (MRI) program. The construction of an optic fiber link between the VLA and the Pie Town antenna of the Very Long Baseline Array (VLBA) is well under way. The link will double the angular resolution of the VLA, and was made possible by an MRI grant with matching funds from Associated Universities, Inc., (AUI). The completion of a receiver system for the 40 GHz band on the VLA will be accomplished with a recently awarded MRI grant, the matching funds coming from the Max Planck Institüt für Radioastronomie (MPIfR). Guided by community input, we are planning a prioritized series of project phases to accomplish the rebuilding of the VLA and more closely couple it, technically and scientifically, to the VLBA.

In addition to these major programs of new construction and renovation, the operation of the Observatory's Central Development Laboratory (CDL) will expand to meet the needs of the construction projects, and the AIPS++ software development program will have its first public release. The operation and maintenance of the Observatory's telescopes will continue as the cornerstone of the NRAO, and these programs as well as those mentioned above are described in succeeding sections of this Plan.

II. 1999 SCIENTIFIC PROGRAM

1. The Very Large Array

With nearly 20 years of full operation, the VLA remains a vital tool at the forefront of many areas of astrophysics, including gamma ray burst afterglows, black hole x-ray binaries and various stages of stellar evolution. Its newer capabilities at both higher (40–50 GHz) and lower (74 MHz) frequencies are opening exciting new avenues of investigation for the user community. Data produced by the NVSS and FIRST surveys are seeing wide use in diverse fields, both by itself and as a spur to additional observation and study. Demand for VLA observing time is twice that available.

In 1998, 74 MHz capability was implemented on all VLA antennas, and in the first observing session with this system, numerous objects, including the Sun, galaxies and supernova remnants, were imaged successfully. Planned observations of radio galaxies and supernova remnants at 74 MHz will advance the scientific investigation of these objects as well as develop and refine the calibration methods peculiar to VLA observations at this frequency.

Solar System

As the level of solar activity rises toward the next maximum, the VLA will, as it has in the past, contribute to multiwavelength studies of solar phenomena. Researchers will use the VLA's capability to observe the Sun with both high temporal and spatial resolution to produce new information about the details of energy release in solar flares. This energy release appears to be highly "fragmentary," with numerous discrete release events during the flare. While previous studies have shown the temporal and spectral fragmentation of flare energy release, the new VLA studies will produce the first information about the spatial fragmentation.

Another study will seek to resolve questions about the fundamental character of solar Ellermann Bombs, short-lived bright optical features seen around the penumbra of sunspots and under arch filament systems. Multifrequency VLA observations of sunspot regions will coincide with optical, x-ray, and UV observations to investigate the physical mechanisms of Ellermann Bombs, observed in optical filter grams for many years but poorly understood.

The 7 mm systems of the VLA will be used to make what will be, if successful, the longest wavelength detections yet of Pluto, Charon and Neptune's moon Triton. Measuring Triton's brightness temperature at this wavelength will yield an estimate of its emissivity, since its physical temperature is known. Triton's emissivity can be used to determine the physical temperature of Pluto, a close analog to Triton, based on VLA measurements of Pluto's brightness temperature. Determining the surface temperatures of Pluto and Charon will provide constraints on the type of stable ices present, and thus the composition of the bodies. This, in turn, constrains models of solar-system formation.

Stars

Stars and the details of stellar evolution will be studied in a number of ways. Clumps of hot, dense molecular gas, called hot cores, found near water masers in massive star-forming regions, are thought to be the first manifestation of newly born or perhaps still-forming young massive stars. A recently-detected infrared source associated with a "textbook example" of a hot core challenges the standard interpretation, since extinction by the dense gas should prevent such a detection. Alternatively, the molecular clump could be heated externally by a massive young stellar object (YSO) or the infrared could be escaping along optically thin paths. VLA observations at 7 mm and 1.3 cm will seek to detect radio continuum emission that would be expected from an ultra-compact HII region produced by the YSO's ionizing radiation. In another case, 7 mm emission was detected by the VLA near the ultra-compact HII region NGC 6334F. This emission has been attributed to hot dust, suggesting that hot cores may exist without ionized components. Further observations with higher resolution will seek to resolve this question and provide new information about the physical relationships among masers, ultra-compact HII regions and other aspects of the early stages of massive star formation.

A 7 mm survey of circumstellar dust around young stars in nearby star-forming regions will produce data that, combined with infrared and submillimeter data on the same systems, will help characterize the size and radial structure of protoplanetary disks. Other 7 mm observations will help determine if the dust around Herbig Ae/Be stars, pre-main-sequence stars of intermediate mass, is in thin accretion disks or more extended spheroidal envelopes. A survey of protostellar disks in the Taurus cloud will yield information about the radial surface density of T-Tauri disks, and may reveal inner holes or gaps in the disks that could indicate planet formation.

As part of an international multiwavelength campaign, observers will use the VLA to study V4334 Sgr, a planetary nebula nucleus that has undergone a helium shell flash, making it swell into a "born again" giant star. This event is the final stage in the star's evolution before it reaches a stable planetary nebula nucleus state. Because of the rapidity of this process and the consequent lack of observable candidates, this is a poorly-studied point in stellar evolution. In fact, this is only the second such event detected this century and the first to be observed with nonoptical instruments.

A new observing strategy will be used in a search for pulsar wind nebulae. Such nebulae can provide insight into how pulsars couple to their surroundings and can be used to determine physical parameters such as the velocity and direction of motion of a pulsar, the pressure of the ambient medium and the properties of the pulsar wind. A new, low-frequency VLA survey using the VLA's pulsar gate to produce *off-pulse* images of candidate pulsars will be able to detect pulsar wind nebulae 100 times more faint than were detectable in previous searches.

Target-of-opportunity programs will provide rapid response to newly-discovered supernovae and outbursts of x-ray binaries. The VLA has contributed vital multifrequency radio light curves to the study of both types of objects, and has revealed the presence of expanding jets in x-ray binary systems, many of which are thought to include black holes as the compact component.

The Interstellar Medium

A 21 cm study of the Helix Nebula (NGC 7293) will seek to determine the velocity structure of HI in several of the nebula's most prominent cometary tails, in order to learn which of several proposed mechanisms produce such tails. Other 21 cm observations will map the HI toward the cometary-like HII region in GGD12-15. This HII region is excited by a B-type star, and the VLA observations will seek to determine the physical conditions and kinematics of the atomic hydrogen in the photo dissociation region surrounding the star.

Observations of a hydrogen radio recombination line and of nitrogen lines toward the compact HII region G111.61+0.37 will produce detailed knowledge of the kinematics of ionized and molecular components of the region, knowledge that could confirm the presence of a neutral wind suggested by previous HI observations. The area of W49A, which contains a large number of ultra-compact HII regions, will be searched for carbon recombination lines in hope of detecting the dense molecular material presumed to be surrounding the HII regions.

Six sources in Sgr B2 that are strong candidates for NH_3 masers will be mapped at higher resolution. If they are confirmed as masers, this would be the highest concentration of such masers in the galaxy, probably related to large amounts of shocked material in the envelope of Sgr B2.

Several teams of observers will use the VLA to study supernova remnants. The Crab Nebula, a dynamic object showing structural changes on timescales as short as days, will be reimaged to study motions on different timescales. The observations, which will produce images to be compared with earlier VLA images, are expected to yield information about the expansion velocity and postacceleration of the radio-synchrotron component of the nebula; the velocity of radio features in the body of the nebula; and the wavelike motion of features near the pulsar. A nearby galactic supernova remnant recently discovered by the COMPTEL gamma ray spectrometer through radioactive decay of ^{44}Ti will be observed to image its environment, map its extended structure and search for a compact central source. If a radio pulsar is detected, it would probably be the youngest pulsar yet discovered. Seven selected supernova remnants will be used as background sources to investigate the properties of low-density ionized gas in the galactic plane.

A search for supernova remnants in M83 will be completed as part of a survey of ten nearby spiral and irregular galaxies aimed at compiling a large, statistically significant "super sample" of extragalactic supernova remnants that will contribute to understanding the role of the interstellar medium in the evolution of the SNRs and the role of SNRs in cosmic-ray production. This study also will use optical and x-ray data.

The galactic center, a longtime target of VLA observations, will come under new scrutiny. Hydrogen and helium recombination-line studies will seek to characterize the physical and dynamical conditions and ionization structure in the HII gas in the thermal Arched Filaments, one of two sets of unusual filamentary HII regions that are intersected by straight nonthermal filaments of the galactic center Radio Arc. The recombination-line studies also may show evidence of possible physical interactions between the thermal gas and the nonthermal filaments. Other observers will seek to confirm a previous detection of a new linear filament that, unlike other filaments near the galactic center, lies parallel to the plane of the galaxy. This structure could provide important new clues about the origin of the linear structures in the galactic center and the nature of the magnetic fields in the region.

The VLA's new 74 MHz capability will be used to make low-frequency images of the galactic center at unprecedented resolution. Expected results include detecting HII regions in absorption against the nonthermal emission; steep-spectrum emission from pulsars; low-surface-brightness supernova remnants; and possible radio relics of past activity in the galactic center.

Galaxies: Spectral-Line Observations

The VLA remains a premier tool for studying galaxies of all types. NGC 4258 will continue to serve as a remarkable laboratory for the study of accretion disks at the centers of galaxies. Earlier VLBA observations showed a sub-parsec scale disk of water masers in Keplerian rotation around a central compact object of 3.5×10^7 solar masses. New VLA observations will seek to measure the magnetic field strength in this disk by measuring Zeeman splitting in the maser emission. Competing models for the accretion process predict different magnetic field strengths; thus, these observations may help resolve controversies over the mode of accretion.

A sample of very compact, very luminous star-forming galaxies at low redshifts will be observed at 21 cm to measure their gas content. This information will allow a better characterization of their current nature and future evolutionary path, as well as placing constraints on the duty cycle of star formation in the "faint blue galaxy" population. High-resolution HI observations of four Blue Compact Dwarf galaxies will seek to test the hypothesis that these systems evolve into dwarf ellipticals through blow-away of their neutral gas. Detailed HI mapping of a pair of "transition" dwarf galaxies will be combined with broadband and spectroscopic optical data to determine their evolutionary status.

High-resolution, high spectral resolution studies of a sample of dwarf irregular galaxies with different amounts of current and recent star formation will seek evidence of cold and warm phases of HI to test a hypothesis that the cold HI phase is a precursor of star formation. Another study of dwarf irregulars will investigate the processes that control elemental enrichment in low-mass galaxies.

Two recently-discovered dwarf galaxies show peculiarities that will be investigated in detail by VLA observers. NGC 3800A, discovered with the VLA in 1997, has one of the most extended HI envelopes known, with respect to its optical size. The Antlia Dwarf Galaxy, a Local Group member, though noted in 1987, was "rediscovered" in 1997. New VLA observations will seek to accurately determine its dynamical mass and to detect cold HI. Investigators hope to understand the relatively low recent star formation rate in this galaxy, given its present gas content.

In the nearby spiral NGC 2403, previous observations indicate that either the HI layer is unusually thick or there is gas above and below the plane that rotates more slowly than that in the plane. New observations are planned to establish which of these is the case, throwing new light on the vertical structure of the HI disks in spirals. Many spirals, otherwise normal in morphology, are asymmetric in their optical surface brightness. VLA kinematic studies of isolated spirals, both symmetric and asymmetric, will reveal correlations between optical and kinematic asymmetry, as well as possible variations due to Hubble type and local environment. Results will be compared with numerical simulations of disk galaxies embedded in dark matter potentials that are not in a relaxed gravitational state.

The flocculent spiral NGC 7331 will be imaged with sufficient resolution to separate arm and interarm regions to search for evidence of tidal interaction and to examine the relative importance of small companions and nonaxisymmetric nuclear structures in producing weak but regular spiral structure in such galaxies. The unusually extended HI disk of DDO 154, extending far outside the region where any stars are detected, will be studied to learn if it contains filamentary structure such as that is seen in higher-density parts of nearby spirals. Understanding of such structure will be improved by learning if it occurs in DDO 154's disk, presumably more quiescent because it is far removed from star formation and tidal interactions.

The elliptical galaxy NGC 3108 is one of the few ellipticals for which an accurate HI rotation curve can be derived at a level comparable to that done for spirals. VLA observations will study the kinematics and mass distribution of this galaxy and contribute to a better understanding of the dark matter distribution in ellipticals. UGC 12695, a relatively isolated, remarkably unevolved system with possibly the bluest color of any known galaxy, is an excellent object for studying star formation in diffuse stellar systems. It will be imaged to determine its HI distribution and its gas kinematics. Previous VLA observations have revealed hydrogen radio recombination lines from starburst galaxies, and new observations will examine six different types of starburst galaxies to expand the sample of known starburst systems emitting recombination lines, to constrain the properties of higher-density ionized gas in the starburst region and to study the kinematics of the ionized gas.

Three pairs of very gas-rich luminous infrared galaxies will be imaged at 21 cm to characterize the stage of interaction in these systems. Other such systems that showed no evidence of a merger at optical wavelengths clearly showed merger or premerger when their HI was observed.

HI observations of three Hickson Compact Groups of galaxies will continue a long-running program and provide high-resolution data required to determine the gas kinematics of these groups. The new data, covering systems representing extreme stages in galaxy interactions, will enable a comprehensive analysis of the HI environment and evolution of such compact galaxy groups.

Studies of galaxies in dense clusters can yield a rich scientific return. Cluster members differ morphologically and in other respects from field galaxies and observations of clusters at different redshifts indicate that the cluster environment speeds the evolution of galaxies. Two observing teams will use the VLA to study extensively a pair of Abell clusters. Abell 2029 will be observed in HI over the full velocity range of the cluster to map both its core and outer portions. This will enable a study of possible spatial and kinematical segregation between gas-rich and gas-poor galaxies and provide constraints for dynamical modeling of the cluster. Another study, of Abell 1689, will seek to measure the HI content of galaxies in and around the cluster. This will constrain the accretion rate of gas-rich galaxies in clusters as a function of look-back time and help to establish how the evolution of gas disks determines the morphological content of clusters in the present epoch. The VLA is the only instrument capable of performing either of these studies.

A project will begin to obtain complete HI imaging data for 20 clusters covering a range of redshifts from zero to 0.2. Combined with deep optical multicolor imaging and spectroscopy, this will yield the most complete information yet on the evolution of clusters and their galaxy populations in the local universe. The HI observations will assess the evolution of individual galaxies as they enter the cluster potential and can put constraints on the 3-dimensional structure of the clusters.

Galaxies: Continuum Observations

Magnetic fields will be studied in galaxies for a variety of purposes. Polarimetry of the barred spiral NGC 1097 will measure the width of a shock front in the bar's compression region and also help determine the detailed structure of the velocity field. Observations of a gas-stripped Virgo Cluster galaxy (NGC 4254) will seek the signatures of dynamo-generated magnetic fields in the presence of highly disordered disk kinematics and peculiar flows induced by external interactions. This will serve as an observational test of the importance of turbulent processes in the generation of large-scale galactic magnetic fields. Data from new VLA observations of a nearby FRII radio galaxy will be combined with x-ray data to constrain the magnetic field and particle density in the radio lobes.

A number of observers will use the VLA to study radio galaxies and their jets. A new, four- configuration study of M87 will image not only the inner portion of the galaxy and jet, but the outer "halo." This will give a clearer picture of the galaxy, its environment and the energy budget of the jet and "cooling flow." Another study will involve observations of twin-jet galaxies to detect evidence that the jets may have two components, an inner, relativistic "spine" and an outer, slower "sheath." A sample of radio galaxies will be examined to see how the presence of inhomogeneous electron populations affects larger-scale observed spectra, and thus may lead to flawed estimates of age and flow speeds in such systems. The second-brightest classical double radio source, 3C 295, will be observed, in an effort to map the spectrum at high resolution and test models of particle energy loss. Following a ROSAT detection of x-ray emission from a hotspot in 3C 390.3, multiconfiguration VLA observations will seek to determine the radio spectrum and estimate the photon energy density in the areas of interest.

A sample of broad-line radio galaxies (BLRGs) will be studied to determine spectral and depolarization asymmetries. The data will be used in conjunction with optical and far-infrared information to compare these BLRGs with double-lobed quasars to address the place of BLRGs in AGN unification schemes. VLA images of a number of compact steep-spectrum radio galaxies, along with VLBI and MERLIN images, will help better define the relationships between compact steep-spectrum sources and FRII radio galaxies.

The cluster-wide radio halo of Abell 2163 will be observed to determine its properties and to improve the understanding of such large-scale radio halos, one of the most poorly understood phenomena in clusters of galaxies. The VLA data will be compared with x-ray data from the BeppoSAX satellite.

A sample of radio galaxies that are embedded in x-ray clusters will be observed to make detailed comparisons between the radio and x-ray emission with the goal of understanding the interactions between the radio source and its environment. The clusters in this study will be observed with the AXAF satellite. Other VLA observers will study the structure of the central galaxy and the diffuse emission in the most luminous known cluster at x-ray wavelengths, RXJ 1347.5-1145.

Cosmology

Target-of-opportunity and follow-up observations of gamma ray bursters (GRBs), now known to be at cosmological distances, will continue at the VLA. The VLA made the first-ever detection of a GRB radio afterglow in 1997 and has detected three more since then. VLA observations provided the first arcsecond-scale localization for two of those. In addition, VLA observations have provided multifrequency radio light curves and shown evidence of interstellar scintillation in some of these sources, thus constraining their sizes and expansion rates. One GRB (970508) has been observed for more than a year after the outburst, far longer than such objects are detectable at any other wavelength. The detection of radio and optical afterglows has fundamentally changed the character of GRB research, and radio observations will continue to provide information obtainable by no other means and which is crucial to distinguishing among competing models of GRBs.

Previous observations of three low-redshift quasars revealed spectacular tidal disruptions in the host galaxies, disruptions not apparent in optical images. This strongly supports the hypothesis that the quasar phenomenon is triggered by galaxy interactions. In order to test this hypothesis, another 20 nearby quasars will be observed to determine their HI environments. HI observations also will search for faint galaxies along the lines-of-sight to three quasars against which Lyα absorbers were found by HST.

A number of unresolved ultra steep spectrum sources found with the NRAO VLA Sky Survey (NVSS) and for which there are no optical counterparts will be observed to seek candidates for high redshift radio galaxies and their surrounding protoclusters.

Survey programs will address a variety of cosmological problems. The VLA will be used to survey four square degrees of sky that also will be surveyed by the Wide Field Infrared Explorer (WIRE) satellite. The combination of VLA and WIRE data, along with deep optical and near-infrared imaging and spectroscopy, will be able to uniquely identify AGN and starburst galaxies. This survey is expected to detect as many as 1,000 starburst galaxies, 200 AGN and 20 quasars. A sample of large angular size radio sources from the NVSS will be observed to study the implications of unification schemes for low power radio galaxies, the properties of giant radio galaxies and of their surrounding medium, and the possible effects of time evolution on the population of radio sources. Another sample of sources from the NVSS, this time faint sources, will be observed to select a smaller sample of flat spectrum sources for redshift determination. This will allow better interpretation of gravitational-lens statistics for estimating cosmological parameters.

2. The Very Long Baseline Array

As has been the case with the VLA, continued technical development of the VLBA has expanded its capabilities and made it an even more flexible tool for the observing community. In 1999, new capabilities will allow pulsar studies and limited observing at a wavelength of 3 mm.

For many observations, other radio telescopes are used in conjunction with the VLBA to enhance resolution or sensitivity. These now include the Japanese HALCA radio-astronomy satellite, with which a number of successful programs have been carried out.

Offering the routine capability to produce images with milliarcsecond resolution, 10 to 100 times better than that of the Hubble Space Telescope (HST), the VLBA is a valuable and popular tool for a wide range of astrophysical inquiries. Proposers now are requesting nearly twice as much observing time on the VLBA as can be allocated.

Stars

Star-forming regions and young stellar objects will be investigated with the VLBA through studies of various types of maser emission. One project will measure proper motions of water masers near four young stellar objects in the NGC 1333 region to help constrain locations of shocks generated by jets near the embedded objects. Other water-maser observations, of W3 IRS5, a newly-formed massive-star cluster, will reveal proper motions and yield information about magnetic fields around the compact region that will help in understanding the formation mechanism of both massive stars and their energetic outflows.

Observations of the Orion-KL nebula, a complex region of star formation, will compare SiO maser features at 43 and 86 GHz. These masers may trace a protoplanetary disk around a young star and can be used as sensitive probes of its kinematics and physical environment.

Methanol masers in the ultra-compact HII region W3(OH) will be observed to measure their proper motions and thus constrain the kinematics of molecular gas around a massive star. Observations of methanol masers in 1997 revealed methanol maser spots along a line in NGC 7538 that is consistent with a circumstellar disk with a diameter of about 1000 AU surrounding a 10-solar-mass young star. This area will be reobserved and other sources will be searched for similar features.

A newly-developed method of detecting Zeeman splitting in the emission of water masers will be used to study the circumstellar envelopes of four nearby stars to seek details of their magnetic fields in the extensive region between the inner area (2–5 AU) where SiO masers are found and the more distant (1000 AU) regions where OH masers are seen.

Several binary systems will be studied by the VLBA. The famous eclipsing binary Algol will be observed in conjunction with BeppoSAX x-ray observations to explore the relationship between the x-ray and radio emission regions. During a period in which BeppoSAX observes three eclipses of Algol, the VLBA will map the radio emission. Observations of the HR1099 binary system will seek to determine its orbital orientation and to test a model of polar radio emission developed as a result of earlier studies of Algol. The active giant star, l Andromeda, whose low-mass companion has not yet been detected, is close enough that the VLBA can resolve its radio corona. Observations will cover the orbital and rotational timescales of the system, and will explore the nature of the giant star's magnetic field. An observing campaign will follow the Wolf-Rayet and O-star binary WR140 to examine the structural and spectral evolution of the nonthermal radio emission from the wind-interaction region near the O star as it approaches periastron, with the hope of distinguishing between competing models for the cause of this emission.

The advent of pulsar gating for the VLBA allows new programs with rich scientific promise. Observers will work in the coming year to optimize the techniques required to make submilliarcsecond astrometric measurements of pulsar positions. This capability then will allow measuring proper motion and parallax for pulsars, producing new data on their motions and formation.

Interstellar Medium

VLBA studies will use absorption and interstellar scattering as tools for probing the interstellar medium. The galactic relativistic jet system SS433 will serve as a background source for mapping HI absorption in the plane of the Milky Way. Interstellar masers in four star-forming regions in the galactic center will probe scattering in that region as well as variations that may measure turbulence. A number of extragalactic sources will be used to probe the interstellar medium through measurement of scattering. These studies will help identify the mechanisms causing fluctuations of electron density and demonstrate the prevalence of turbulence in the interstellar medium.

Galaxies and Active Galactic Nuclei

A large number of researchers will use the high resolution of the VLBA to study the details of a variety of galaxies, active galactic nuclei (AGN) and jets. Studies of the galaxy NGC 4258 already have produced a rich yield of valuable information about its thin, warped disk of water masers orbiting a central black hole. A new program of monthly observations will help further utilize this unique laboratory for understanding the physics of accretion disks by providing the time resolution required to address several outstanding questions. Ongoing studies of the nearby radio galaxy 3C390.3 will provide the opportunity to study structural changes in an FRII object on the subparsec scale.

Study of a pair of Seyfert galaxies (Mrk 3 and Mrk 6) that appear quite similar in lower-resolution radio images even though one is Type 2 and the other Type 1, will seek to determine their radio properties, including spectral indices and brightness temperatures, at sub-parsec scales. Another Type 1/Type 2 pair of Seyferts (Mrk 231 and Mrk 348) will be observed at multiple epochs in an attempt to make the first-ever measurements of radio-component motions in Seyferts. An unusual, highly-variable radio galaxy (III Zw 2) that has been called a possible "blazar among Seyferts" will be observed following a recent major outburst. This is expected to provide an ideal case for observing the evolution of an isolated synchrotron- emitting blob.

VLBA polarization maps made the first unambiguous identifications of components and trajectories in the jet of BL Lac. This will be followed by monitoring of such superluminal components to study their movement and to refine a model for their production. Another BL Lac object, OJ287, like the namesake, shows helical motion in its jet. A monitoring program will seek to confirm this motion and to learn if ejected knots follow the same paths at all frequencies. Multifrequency observations of PKS 1413+135 will seek to detect motion and spectral changes in this object, one of the brightest red BL Lacs, and one which may have implications for AGN unification schemes.

VLBA polarimetry of a sample of blazars with low optical polarization will seek to learn if the differences in such objects with low and high optical polarization are due to intrinsic properties of their jets or extrinsic properties such as viewing angle. Four gamma ray blazars will be observed to resolve complex submilliarcsecond structure and determine their jet directions and other physical and morphological properties of the emitting material. The relationship of the complex structure to the likelihood of gamma ray emission is a principal focus of this study. Investigators will make multi-epoch studies of two gamma ray blazars that have undergone dramatic flares to determine the inner morphology of the objects, to observe the evolution of their cores and to track new components that may result from the flares.

The VLBA's extraordinary resolving power has made possible routine studies of extragalactic jets that identify individual components within jets, measure components' motions and show temporal evolution. This capability has attracted numerous investigators. The jet studies will target nearly the full range of AGN, including radio galaxies, quasars, and known superluminal sources. Some of these observations are expected to reveal sub-parsec scale features and thus shed new light on the morphology of jets. Other aspects of the jet phenomenon to be investigated include the relationships between core emission and jet power; the dependence of jet power on jet speed; opacity variations and pressure gradients along jets; spectral and polarization evolution in jets; the nature of plasma in jets; and hotspots and their magnetic fields. Several researchers will use the observational data to refine and constrain numerical models of jets.

A long-term project to study extragalactic radio sources in order to test physical models and AGN unification schemes will be continued with VLBA observations of a number of lobe-dominated quasars. These will include spectral imaging, second-epoch observations to search for superluminal motions, and studies of compact jet morphologies. Some of these high-resolution studies will be done using the HALCA satellite. Other quasars will be the targets of detailed polarization studies intended to probe their magnetic field topologies, relativistic aberrations and their thermal gas environments.

Cosmology

A recent discovery of molecular absorption by gas in the lensing galaxy of the Einstein ring source 1830-21 provides a unique opportunity to measure the temperature of the microwave background radiation at the redshift of the absorber. That redshift, a cosmologically significant 0.9, conveniently moves two transitions of HC_3N from 45 and 27 GHz into VLBA observing bands at 22 and 15 GHz. Since the excitation temperature of a gas can be calculated by measuring two transitions of a given molecule, these two lines can allow measurement of an upper limit for the temperature of the microwave background radiation field at that redshift to within a few percent. At a redshift of 0.9, that temperature is predicted to be approximately 5K.

The VLBA has detected two gamma-ray-burst afterglows, providing milliarcsecond astrometry of these sources, offering the possibility of localizing such objects within their host galaxies. The VLBA studies also can put severe limits on parallax and proper motion for the detected afterglow sources, helping to confirm their cosmological distances. In 1999, GRB afterglows will continue to be observed on a target-of-opportunity basis whenever a suitably strong candidate is found.

Observers will seek to confirm or refute a gravitational-lens explanation for PKS 1445-161, which, if confirmed, would be the most compact lens yet found, and could have advantages over larger-scale lens systems in measuring H_0. Finally, VLBA observers will seek to detect possible gravitational lensing by a foreground star that appears superimposed on the core of the radio galaxy 3C435B. If detected, such a lens system, which likely would change over the years because of the star's proper motion, could yield valuable information about both the radio galaxy and the foreground star.

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. On-the-fly 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 nearby spiral galaxies. 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 these galaxies.

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 the thioformyl radical, HCS, in the interstellar medium. This study will constrain some specific predictions of theories which describe sulfur chemistry in molecular clouds. 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 measure the 13CO 2-1/1-0 and HNC/HCN 1-0 line intensity ratios in a sample of luminous mergers with compact CO distributions. These observations will test the notion that the bulk gas kinetic temperatures are greater than 100 K in these objects. Another group will conduct an unbiased study of the total gas content of noninteracting SO galaxies through measurements of their CO emission. 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 microarcseconds. 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 1999 the 140 Foot Telescope will be used for galactic and extragalactic spectroscopy, for pulsar timing and studies of pulsar emission processes, and as an important element in U.S. and Global VLBI. There will be support for observations at all frequencies below 5 GHz, and at 8–10 GHz and 18–26 GHz. Proposals for the final months of observations with the telescope will be accepted until January 4, 1999. The use of the 140 Foot in 1999 will be affected by the schedule of outfitting of the GBT since by midyear, some 140 Foot equipment will be transferred to the lab for refurbishing and installation on the GBT.

Pulsar monitoring will continue to be a mainstay of 140 Foot efforts. PSR B1957+20 is an eclipsing millisecond pulsar in a binary system with a 9-hour orbit. There is evidence that the pulsar's companion is slowly evaporating and there are suggestions that the pulsar's orbital period may have variations that are cyclical in nature. Regular monitoring of this system can determine if the period variations are periodic or quasi-periodic and whether there is a long term trend. This project will take advantage of the bandwidths available at the 140 Foot Telescope, the sensitivity of the spectral processor, and the ability of the 140 Foot to track the pulsar through a complete orbit.

A number of pulsars are being studied to constrain long-term relativistic effects which yield refinements to the tests of general relativity and neutron-star mass measurements. Other pulsars are used as probes of the intervening interstellar medium—changes in the dispersion measure reflect structure in the ionized component, while changes in the HI absorption lines give information on fluctuations in the neutral component.

The 140 Foot Telescope will participate in a number of VLBI experiments in 1999. In addition to those scheduled in conjunction with the VLBA, there will be experiments with ad hoc arrays that exploit some feature of the instrument. Of particular interest are a set of observations that will be made in conjunction with European telescopes of strong, redshifted 21 cm lines seen in absorption against bright continuum sources. These data will provide the framework for measuring kinematics in the absorbing layers and isolating the absorption against background QSO cores for comparison with optical and UV spectroscopy. The 140 Foot will also continue to participate in space VLBI experiments with the Japanese HALCA satellite.

In 1999 a search will be made for the radio emission from spinning dust grains that has been predicted from several theoretical models. This novel emission mechanism might explain some of the anomalous diffuse emission detected in the short-centimeter wavelength range and previously attributed to free-free emission. The 140 Foot will be used to examine a number of molecular clouds for evidence of this phenomenon.

A major survey of galactic HI will be completed in 1999. It will cover the area within 10 degrees of the galactic plane at positive declinations. The region will be completely sampled at the Nyquist spatial frequency, yielding the most complete, most sensitive view of galactic HI to date. The data will be corrected for stray radiation using a new analysis of the 140 Foot beam pattern. This survey will be complementary to one being done at negative declinations at the Parkes Observatory, and, because of its extensive coverage and sensitivity, is unlikely to be superceded for many years. The 140 Foot will also be used for detailed HI studies of particular regions such as molecular clouds or supershells, in conjunction with studies of these objects in molecular lines, optical or UV absorption lines, or x-ray emission.

The new 800 MHz 256k channel GBT spectrometer has been tested successfully as a 140 Foot back-end, and in 1999 there will be several projects that take advantage of its broad bandwidth. A prime example will be searches for extragalactic H_2O masers, which require observations over many thousands of km/s to sample the entire velocity range of a nuclear disk at once. Other uses of the spectrometer will be for studies of radio recombination lines, where the broad bandwidth allows measurement of many separate transitions in a single spectrum, giving information on the helium abundance and physical conditions within HII regions.

III. USER FACILITIES

1. The Very Large Array

Present Status

More than 600 scientists used the VLA for their research work in 1998, and a similar or larger number will do so in 1999. Demand for the VLA arises both from the multiwavelength 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 are 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] 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.

Work has begun on the next generation of VLA receivers as proposed for the VLA Upgrade. Four of the new receivers covering the full waveguide bandwidth from 18 to 26.5 GHz will be on the VLA by the end of 1998. A minimum of six additional receivers will be installed by the end of 1999. The new receivers will have built-in radiometers which measure the strength of the 1.3 cm water vapor emission line. These line measurements will be used to correct phase errors in the VLA data due to atmospheric water vapor over the array. Testing and evaluation of this technique will be done with radiometers on the first six receivers.

A project is underway to connect the VLBA Pie Town antenna as a real-time active element of the VLA, thus doubling the maximum baseline of the VLA A configuration. This is now feasible since a fiber optic connection has recently been completed by the Western New Mexico Telephone Company, linking the VLA control building to the Pie Town antenna. A single IF demonstration interferometer should be available by the end of 1998, with full bandwidth testing by the end of 1999. This project is funded through an MRI proposal to the NSF.

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

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, plus better closure errors. Modifications on three antennas were prototyped in 1998 and have successfully demonstrated this concept. The upgrade of the full array will begin early in 1999. Going to the full 100 MHz bandwidth would require extensive modifications to the IF system and is not warranted at this time.

The two VLBA antennas at Pie Town and Los Alamos are currently outfitted with 80 to 90 GHz receivers. Receivers will be installed at the Fort Davis and Mauna Kea antennas by the end of 1998. A year-long period of testing and evaluation will likely proceed the next round of receiver installation.

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) errors in the setting of the surface panels of the primary reflectors. Holographic measurements of the antennas, with a 0.4 mm RMS, provided the corrections needed to bring the antenna surfaces closer 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 has continued with the other VLA antennas and 20 antennas will have been adjusted by the end of 1998.

The maintenance of the VLA infrastructure continues as a high priority. The major long-term projects are rail maintenance, antenna painting, and waveguide access port replacement. In 1998, most of the VLA effort went into rail maintenance with smaller programs in the other areas.

In 1998, rail system maintenance emphasized tie replacement and mainline leveling; 5,000 rail ties were replaced and one kilometer of rail between stations W5 and W14 was leveled. This involved aligning, gauging, and reballasting the rail track between these antenna stations. The two kilometers of rail line that were leveled earlier on the east arm have greatly reduced the swaying of the transporter during antenna moves. This level of effort on track maintenance should be continued indefinitely.

The aging of the VLA is seen clearly in the rust and staining on many 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 had been completely painted. This work is generally performed by a four-man NRAO summer crew. In 1998, with a smaller crew and a shorter work span, only the quadrupods on seven antennas were painted. The plan for 1999 is to return to full painting of three antennas over the summer.

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 was replaced in October 1997. Although several more antennas will need bearing replacements in the near future, no work was done in 1998 due to lack of funds. The azimuth bearing of one antenna should be replaced during the antenna overhauls in 1999.

There is a program to replace the waveguide access ports at the VLA with steel culverts. The existing concrete access ports are deteriorating. By the end of 1997, 51 access ports out of a total of 122 had been rebuilt. Due to a lack of funds, only one replacement was completed in 1998. This replacement program should be restarted in 1999 and continued for six more years 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. Generally, fourteen to eighteen temporary employees are hired for work on the rail and painting crews, and for carpentry, waveguide access, and vehicle maintenance. In 1998, only nine temporary employees were brought in for the full six-month period, although three more worked shorter periods on building repair.

2. The Very Long Baseline Array

Status

The percentage of VLBA observing time was increased during 1998 to about 60 percent of the available time, with a further 20–25 percent of time used for testing and maintenance. The implementation of automatic tape allocation during the year combined with the ability to write and correlate multiple projects per tape will allow us to increase the level of science observing to its maximum of 75 percent of available time in the near future. The rebuild of the VLBA operations software is well advanced. The completion of this system is required in order to reach the 75 percent target.

The long-awaited pulsar gate in the VLBA correlator was completed in 1998 and several observations have been made and are currently being correlated. Two Ph.D. students from U.S. pulsar groups are currently in Socorro working on data from the pulsar gate.

Space VLBI data from the Japanese HALCA/VSOP project have continued to flow through the VLBA correlator. A major success during the year was the detection of 1.3 cm fringes towards the flaring H_2O maser in Orion with HALCA. Due to a problem with the 1.3 cm feed resulting from vibration during launch, the effective diameter of the 8 m antenna is only 0.1 m. As a result, the only source detectable at this wavelength is the 2 x 10^6 Jy maser.

The VLBA now has two 90 GHz receivers (Pie Town and Los Alamos), and two more are due to be mounted on Fort Davis and Mauna Kea before November 1998. Fringes were obtained on the VLBA correlator at 90 GHz between Pie Town and Los Alamos, demonstrating that when four antennas are equipped, a new waveband will be opened up for the VLBA.

Initial tests have been performed using the VLBA's maximum recording rate of 512 Mb/s. The results of these tests are encouraging and we hope to allow users to use this feature within the next few months.

Present Instrumentation

The VLBA is a dedicated instrument for very long baseline interferometry. The ten antennas are distributed about the U.S. in a configuration designed to optimize the distribution of baseline lengths and orientations (u-v coverage). Baselines between 200 and 9000 km are covered, which provides resolution as fine as 0.1 milliarcseconds at 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 90 GHz. The antennas are designed for remote operation from the Array Operations Center (AOC). Local intervention is required only for changing tapes, regular maintenance, and fixing problems.

The VLBA is outfitted for observations in twelve 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.

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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, 1,024 spectral channels can be provided for each input channel. The correlator is of a novel design, pioneered by the Nobeyama Radio Observatory in Japan, in which each bit stream is Fourier transformed to a spectrum before cross correlation (the "FX" architecture). Output data 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 rewritten 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. Much work has been done to make the AIPS VLBI sub-system more robust and user-friendly. Astrometric/geodetic processing is done primarily in the system developed by the Crustal Dynamics Project, now Dynamics of Solid Earth (DOSE), at NASA. The in-house computing for the VLBA is done mainly on workstations of the SUN Sparc 20, Ultra and SGI Origin 2000 classes.

Future Plans

Major milestones for the VLBA for the next year include:

(a) Two additional 90 GHz receivers for the VLBA are expected to be installed before the end of this year. If funding allows, the current receivers may be redesigned to lower the system temperature by ~50 K and/or more receivers may be built. Once four (or more) receivers are in place, important SiO maser and AGN studies can begin at 90 micro-arcsecond resolution.

(b) The software and information-handling methods of the VLBA Operations group are currently undergoing major revision. Although progress has been good, the project is expected to continue next year. A new database design and suite of user interfaces are under construction. This project is aimed at overcoming the current information-handling approach, which evolved during the commissioning phase of the VLBA correlator and is now a major limitation to increasing the level of observing on the VLBA.

(c) AIPS development and support of VLBA data reduction continue. A transition to AIPS++ is planned for sometime in the future.

(d) 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.

(e) Further tests and full implementation of the maximum recording rate of the VLBA will occur in the next six to nine months. This will provide high-sensitivity (512 Mb/s) recording for approximately six hours (two tape recorders operating simultaneously). This feature is expected to be particularly useful for millimeter observing.

3. The 12 Meter Telescope

The 12 Meter Telescope began as the 36 Foot Telescope, the telescope responsible for the birth of millimeter-wavelength molecular astronomy. Following a period of explosive growth in this new area of astronomical research, during which most of the dozens of molecular species known to exist in the interstellar medium were first detected at the 36 Foot, the telescope's reflecting surface and surface support structure were replaced and the 36 Foot was re-christened in 1984 as the 12 Meter. Subsequently, the scientific program has evolved from one dominated by observing programs in astrochemistry to one with a broader mix of studies of molecular clouds and galactic star formation, evolved stars, astrochemistry, and external galaxies. The

12 Meter is the only millimeter-wavelength telescope in the U.S. operated full-time as a national facility. More than 150 visitors make use of the telescope annually. It offers users flexibility and the opportunity to respond quickly to new scientific developments. Low-noise receiving systems at a wide range of frequencies, currently covering all atmospheric windows from 68 GHz to 300 GHz, are maintained. Operational reliability throughout 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 cost effective, simplifying operations.

Table III.3. 12 Meter Receiver List

Frequency Range (GHz)	Mixer	SSB Receiver Temperature (K) Per Polarization Channel
68 - 116	SIS	60 - 90
130 - 170	SIS	120
200 - 260	SIS	200 - 400
260 - 300	SIS	400 - 500
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

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

To enhance the telescope's spectroscopic capability and to accommodate the array receivers, a new autocorrelator, which is a clone of the GBT correlator, will be available in the coming year. Its instrumental parameters are given in Table III.4.

Table III.4. 12 Meter Correlator Specification

IF Channels: 8/4/2 IF BW (Bandwidth): 800–1600 MHz Sample Rate: 1600 MHz Correlator Clock: 100 MHz Usable bandwidth assumes a 75 percent efficiency factor for analog filters.			
Total BW (GHz)	Usable BW/Channel (MHz)	Lags/IF	Freq Res/IF
	A) 8 Active Samplers		
6.4	600	1024	0.781 MHz
3.2	300	2048	0.195 MHz
1.6	150	4096	48.830 KHz
0.8	75	8192	12.200 KHz
	B) 4 Active Samplers		
3.2	600	2048	0.390 MHz
1.6	300	4096	0.097 MHz
0.8	150	8192	24.410 KHz
0.4	75	16384	6.100 KHz
	C) 2 Active Samplers		
1.6	600	4096	0.195 MHz
0.8	300	8192	48.830 KHz
0.4	150	16384	12.200 KHz
0.2	75	32768	3.050 KHz

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.

A New 8-Feed SIS System for 3 mm

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

4. The 140 Foot Telescope

The 140 Foot Telescope will continue to be operated as a user facility until mid-1999, at which time it is expected to be closed so that efforts can concentrate on outfitting and commissioning the GBT. In the first part of 1999 the telescope may be operated for only five days each week so that personnel can be shifted to the GBT. Exceptions will be made for special experiments and observations of transient phenomena.

Some modest improvements will be made to 140 Foot Telescope systems in 1999, including replacement of old telescope operator computers with more modern models, and implementation of a new interference database which will be used to document signals that are detected by observers. The database uses AIPS++ tables and will allow users to help identify possible sources of interference.

The 140 Foot currently has a suite of prime-focus receivers that cover 250 MHz to 5 GHz, and three receivers at the Cassegrain focus covering 4–6, 8–10 and 18–26 GHz. The Cassegrain receivers are those which have been built for the GBT. They have been performing quite well on the 140 Foot after predictable start-up problems were resolved. Switching between the Cassegrain receivers can be accomplished in a few minutes, and this has allowed us to begin scheduling a more varied mix of programs than was previously possible. The new flexibility also gives a considerable increase in efficient use of the Telescope. The experience derived on the 140 Foot will be carried over to GBT operations.

Back-ends at the 140 Foot include a digital continuum receiver, the Model IV autocorrelation spectrometer, the Spectral Processor, which is useful for pulsar observations and low frequency spectroscopy, a VLBA DAR, and an S2 recording system on loan from the Canadian Space Agency for VLBI. For a few programs it will be possible to use the new GBT spectrometer by sending the IF over fiber to the lab, though this configuration is experimental and will require substantial effort on the part of the observer.

A 86 GHz tipper has been in operation at Green Bank since early 1998 and will continue through 1999. Its data are posted on the NRAO web site in near real-time, allowing observers to have information about the atmospheric opacity at the site. In 1999 these data will be used to test several contingency scheduling plans, in which a weather-dependent (generally high-frequency) program shares the telescope with one which is less sensitive to the weather. Use of the 140 Foot by either program will be decided each day based on weather information.

Spectrum Management and RFI Control

The 140 Foot will be used occasionally for spectrum monitoring, as well as for targeted programs on individual sources of interference where appropriate. The Interference Office will continue to administer the National Radio Quiet Zone, which grows in importance each day as pressures on the spectrum increase. In 1999 we will make special efforts to improve the smooth processing of applications for transmitters within the Zone, and to upgrade our terrain and propagation models where appropriate. In addition, we will attempt to identify sites within the area covered by the Quiet Zone which are suitable locations for transmitters, but which are also well-shielded from Green Bank. Companies or agencies who wish to place new facilities within the Quiet Zone will be encouraged to consider these locations first.

It seems clear that spectrum management activities must become part of daily life at NRAO if any windows for radio astronomy are to be preserved into the future. For this reason every scientist at Green Bank will have some spectrum management responsibility in addition to other duties. The Interference Protection

Group will remain the nucleus for local interference suppression efforts, and will lead the development of devices and techniques for mitigating the effects of interference.

An interference monitoring station is being assembled, and will eventually consist of antennas on the GBT arm and an extensive suite of receivers and detectors. This will enhance the real-time ability to identify and possibly mitigate sources of interference that are detected by observers.

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 1999, a major goal is to build an integrated IF amplifier into an SIS mixer, covering a 4–12 GHz IF band. This large instantaneous bandwidth will be needed for maximum continuum sensitivity by the MMA.

Major effort was expended during 1998 on the development and production for the Microwave Anisotropy Probe (MAP) project, a joint effort with Princeton and NASA Goddard Space Flight Center. This work was carried out primarily by M. Pospieszalski, E. Wollack, N. Bailey, S. Thacker, W. Lakatosh, W. Wireman, R. Harris, and T. Boyd. The receivers at 22, 30, 40, 60, and 90 GHz will be used in a new satellite to be launched in 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.

A variant of the MAP amplifier design will be produced in 1999 which is optimized for the band 80–95 GHz for use by the VLBA. This will replace the MAP prototypes now in use at 86 GHz on VLBA antennas with a better design having more gain and better impedance match over the target band, thus improving the sensitivity of VLBA observations at 86 GHz.

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

A variant of the MAP amplifier design for 18–26 GHz will be produced for the continued upgrade of the VLA at K-band, for which funds for six new receivers have been allocated. The existing four new K-band receivers on the VLA will be upgraded with the new amplifier as well, thus bringing the total of VLA antennas with state-of-the-art receivers to ten.

Low-frequency balanced amplifiers for frequencies up to 1.2 GHz have now been developed which have octave bandwidths; for example, amplifiers for 500–1000 MHz and 600–1200 MHz with about 3 K noise temperature are now incorporated into GBT receivers. In 1999, this technology will be pushed into higher bands, with the goal of producing a prototype for the VLA upgrade which has excellent performance from about 1.2 to 2 GHz.

In preparation for work on an internal IF amplifier for SIS mixers (described below), M. Pospieszalski will design InP amplifiers to work in the frequency range 2–18 GHz, thus extending knowledge of how to stabilize InP designs at frequencies lower than the MAP bands.

Millimeter-Wave Receiver Development

The design and fabrication of SIS (Superconductor-Insulator-Superconductor) mixers covering the frequency range 68–300 GHz are done by A. Kerr and S. Pan of 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, and also with the Jet Propulsion Laboratory (JPL) and SUNY (Stony Brook). Mixers have been produced not only for the 12 Meter and MMA applications, but for other radio astronomy organizations as well. The noise temperatures now being attained in laboratory receivers are only three to six times the photon temperature *hf/k*, so in many cases the dominant noise sources are external to the mixers.

Spectral line observations require only a single sideband response, whereas mixers typically provide a double sideband response. At the 12 Meter Telescope, zenith system temperature is typically 60 K at 230 GHz, of which about 30 percent is due to unwanted image noise. Tests will continue 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. A new wafer manufactured by JPL's Center for Space Microelectronics Technology will be used in a refined design.

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 90-degree hybrid. These will incorporate the same design principles and structures already proven in the image separating mixer. The work will continue in 1999.

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 under way to achieve an IF bandwidth of 8 GHz for use by the MMA. An MMIC design by S. Weinreb (University of Massachusetts) will be used in initial tests, followed by tests of a design using discrete InP devices by M. Pospieszalski.

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.

Emphasis on developments for the MMA strongly brings to our attention the need to improve the speed at which SIS mixers can be built and tested. At present, it is possible to produce one fully tested SIS mixer in approximately two months, given all the workloads of existing personnel. For the MMA, we must achieve about two SIS mixers *per week* during the construction phase. For this reason, new techniques for assembling and automating the testing of SIS mixers must be developed, and this process, which began seriously in 1998, will continue throughout 1999. The improvements include fabricating test evaluation structures on the Nb wafers and placing most of the mixer testing under computer control.

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 by E. Wollack for the 18–26 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. 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 by S. Srikanth. The new electroformed version of this device is now in production for the VLA and is in use in the new K-band receivers.

This work, as well as other electromagnetic calculations, has been greatly advanced by the purchase of a commercial finite-difference time domain solver, Quickwave. For certain classes of problems, this program is many times faster than HP's HFSS. Throughout 1999, we will continue to learn how to apply this new technique to the solution of problems of interest at the CDL.

A new OMT for the 75–110 GHz band was also built and tested in 1998, and this work will continue through 1999. It appears practical to perform polarization separation in this fashion up to about 200 GHz; for higher frequencies, quasi-optical techniques will be required. However, the use of OMTs below 200 GHz will greatly simplify the optics of the MMA receiver layout.

A new OMT and polarizer for the 26–40 GHz band were under development in 1998 and are expected to be completed and put into production status in 1999.

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. To aid in the analysis, a program capable of simulating this geometry has been obtained from JPL.

Digital Correlators

The 262,144-channel GBT spectrometer, which can analyze instantaneous bandwidths up to 800 MHz, was delivered to the telescope by R. Escoffier and W. Brown in 1998 for integrated testing. Software for operation in more of the possible modes will be written and undergo integrated testing in 1999 in preparation for GBT operation.

A duplicate of the Green Bank spectrometer was built at the MPIfR. Another duplicate was built in 1998 at the CDL for use with the 12 Meter antenna; the IF electronics were built in Tucson. A third, smaller copy was built for use by the University of Massachusetts. In 1999, another copy will be built for use as a test correlator for the prototype MMA interferometer.

The time-slice principle of the GBT spectrometer will be used in the MMA correlator design. This will require a new correlator chip to be developed. In 1999, all the system design and some of the detailed board design will be carried out, with the goal of producing an initial test version of the MMA correlator by 2002.

Millimeter-Wave Local Oscillators

The LO requirements for the MMA receivers include all-electronic wideband tunability, low amplitude and phase noise, sufficient power to drive SIS mixers, high reliability, and low cost. This excludes use of the traditional second harmonic Gunn diode oscillators followed by frequency multipliers employing whisker-contacted diodes which are used in most millimeter receivers. Two areas of research are under way: LO multiplier chains using YIG oscillators, amplifiers, and frequency multipliers; and a photonic system using two phase-locked lasers.

New frequency multipliers have been developed in collaboration with the University of Virginia(UVA) by D. Porterfield (UVA) and R. Bradley (NRAO). These employ new, UVA-developed planar diodes fabricated on monolithic chips, and have been successful in 40–80 and 80–160 GHz frequency multipliers. These devices have a 3 dB bandwidth frequency ratio of 1.15:1, and appear to be easily modified to achieve an even broader bandwidth with slightly less overall efficiency. New frequency doublers of similar design for 55–110 and 110–220 GHz are in fabrication and should be complete in early 1999. When the performance of these components has been optimized for MMA use, it will be possible to determine the practical tuning range for a given system, and this information will be used in deciding the exact MMA frequency bands.

For frequencies above about 300 GHz, it is probably impractical to build efficient frequency multipliers using even the advanced planar diodes. We are therefore working on MMIC frequency multiplier designs for these critical higher frequencies, in collaboration with JPL. A doubler for 200–400 GHz has been designed, and a tripler for 220–660 GHz is under way. These will require the development by JPL of techniques to produce via holes and backside etching, a process which is expected to be completed in early 1999; following this, the prototype high frequency multipliers will be fabricated.

In addition to the actual multipliers, an electronically tunable LO chain requires a phase-locked source. We propose to assemble such a source using a YIG oscillator in the range 10–15 GHz and a combination of multipliers and MMIC amplifiers to generate enough power in the range 60–110 GHz to drive the next multiplier stages. Phase-locking will occur at a frequency in the range 60–110 GHz. In 1999, we will assemble such sources using commercially-available components and MMIC amplifiers in the range 80–110 GHz which are being developed by JPL and TRW.

In collaboration with Tucson personnel and UCLA, we are 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 a photomixer which will couple sufficient energy out of the structure to drive an SIS mixer. In 1998, design studies are continuing 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; some experimental structures will be evaluated to test the computer models. This will provide a prediction of the output power and usable bandwidth. Experiments to fabricate and test an actual device will occur in 1999.

Other Hardware Developments

The search for the ultimate vacuum window, required for cryogenic receivers, inevitably results in a compromise between leak rate and electrical loss. The CDL millimeter wave group has developed and tested a prototype broadband vacuum window for the 75–110 GHz band using crystalline quartz. This window works well (although not as well as theory predicts) and has been incorporated into a VLBA receiver. Further research will continue in 1999.

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

Adaptive Interference Excision

During the first half of 1998, the current adaptive filter system, intended to reduce the effects of interference, was subjected to laboratory-based measurements to determine the dynamic range, noise injection, and tracking effectiveness of the filter for various types of stationary and nonstationary interference signals. Also, a detailed paper, describing the proof-of-concept system and its initial evaluation, was written and accepted for publication in the *Astronomical Journal*. Throughout the second half of 1998 and into 1999, the original system will be modified to improve upon the analog filtering, create a more robust interface between the adaptive system and the spectral processor, and increase the effectiveness of RF shielding within the adaptive system. The number of reference channels will be increased to four. The improved and enhanced adaptive system will be set up in Green Bank for extended field studies. The polarization and other properties of the interference signals, as well as the response of the adaptive technique to signal polarization, will be investigated. The measurements will be compared with the results from ongoing simulations.

Fully Sampled, Focal Plane Array Receiver

A paper describing the theory of focal plane array feed signal processing and the technical details of the original proof-of-concept system and its evaluation on the 140 Foot Telescope is currently being written. Throughout the last half of 1998 and into 1999, a low noise array element will be developed. This room temperature element will operate from 1.2–1.7 GHz with a gain of 30 dB and a noise temperature of under 50 K, and will easily be switched between a dual linear or a dual circular polarization mode. The RF design is currently under way. Twenty elements will be built and fitted to the existing array receiver for system evaluation on the 140 Foot sometime during the first half of 1999. Cryogenic cooling of the array element will be investigated. A compact, 70 K refrigeration system will be purchased and evaluated for this purpose.

Spectrum Protection and Radio Frequency Interference

The CDL contributes to frequency coordination and spectrum protection for radio astronomy through the activities of A. R. Thompson, who is Chairman of U.S. Working Party 7D (Radio and Radar Astronomy) of the ITU Radiocommunication Sector. During February and March of 1998, tests of the emission of an IRIDIUM satellite in the band 1610.6–1613.8 MHz, made in cooperation with IRIDIUM/Motorola, were completed and a report was issued. An important current concern is the preparation for the World Radiocommunication Conference of year 2000, at which allocations of the spectrum above 71 GHz, including radio astronomy, are to be reviewed. Input documentation providing support and protection for radio astronomy is under preparation and will be an important concern of international meetings of the working parties of ITU-R Study Group 7 to be held September–October 1998 and March 1999. Meetings of U.S. Working Party 7D are being held at approximately monthly intervals at the NSF building in Ballston, VA. Issues of concern include studies of the effects upon radio astronomy of transmissions from atmospheric platforms which are proposed to be located above major population centers to provide communications, etc. Also, proposals are under study for allocations in the bands 1390–1393 MHz and 1429–1432 MHz to feeder links for low-earth orbit satellites. Intense pressure for increased use of the spectrum, especially for space-to-earth transmissions from satellites, will continue to be a major threat to radio astronomy.

2. Computing

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

Computing systems at NRAO must satisfy strong demands in the face of constrained budgets. Over the past year NRAO made considerable progress in addressing many of the problems of its aging computing infrastructure. The combination of a reasonable level of funds in 1998 and steadily improving capability for modestly priced workstations allowed us to continue with vitally needed upgrades for approximately 20 percent of the workstations on the desks of NRAO's staff. Significant investments in local networking infrastructure have been possible in Green Bank and Charlottesville, and to a lesser extent in New Mexico.

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 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.

High-resolution spectral-line VLBI is one area where improvements in computing capabilities are having a noticeable effect. These observations, and others such as VLBI, work on gravitational lenses, which result in very large monolithic files. Traditionally, the size of an individual file has been limited under UNIX to 2 gigabytes, except on a very few specialized hardware architectures. This capability is now supported on the most common AIPS platform, Sun/Solaris. Without it, processing these datasets is extremely labor-intensive and takes many times longer to perform; in many cases this has meant that the science was simply not done. Several experiments have already taken advantage of this support, and it is likely that the number of projects requiring it will increase over the next few years. The availability of large-file support on Silicon Graphics systems has also been crucial to data analysis for the Japanese VLBI satellite mission, HALCA, for which facilities at NRAO handle most of the processing.

NRAO's partnership with the National Computational Science Alliance (NCSA - formerly the National Center for Supercomputing Applications) is now in full swing. 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, pulsar searching, and analysis of large spectral-line data cubes, can require computing resources beyond what NRAO, and most other research institutions, can provide. The NCSA collaboration focuses on implementing parallelization techniques in selected AIPS++ tasks which, combined with improved access to NCSA's facilities, we hope will allow radio astronomers to take advantage of powerful parallel architectures.

NRAO's program to assess, test, and correct software and hardware bugs related to the change of the century on January 1, 2000, has made excellent progress. Following tests and upgrades of some key software, it now appears that critical functions at the Observatory, such as financial and telescope operations, will be largely unaffected. Nonetheless, the effort involved in this process is having an impact on the workload of a number of NRAO staff.

For 1999, 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 a little more than one year, 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 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.

The assessment phase of NRAO's preparations was completed almost a year ago. Several key tests, including those of VLA, VLBA, and the 12 Meter Telescope operations with the date set to 2000, have been made successfully during 1998. Additional tests will be carried out in 1999 (primarily those involving the VLBA which cannot be done until closer to the actual date). The primary fileserver at the AOC, which is almost seven years old, cannot be made Y2K-compliant and will be replaced in late 1998.

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; detailed testing done so far has verified this estimation. Clearly we must also evaluate our dependencies on outside services in these areas, and have already taken steps to do so.
- Telescope Operations: Detailed testing revealed only a few small errors in the real-time control systems and data processing software, all of which have now been repaired. Further testing of VLBA operations software will be performed in early 1999. Currently it is expected that the 140 Foot Telescope in Green Bank will cease operations before the end of 1999. A major effort would be required to bring it into compliance if that proves necessary.
- Embedded PCs: Many of our most complex electronics systems use embedded PCs and chips which may not be Y2K compliant. While many of these do not rely on the date to perform their tasks, further testing is required to see which systems are affected, and where updates or replacement might be needed.
- Communications: Only minor problems exist in our own telephone, intranet, and Internet-related equipment, which will be easy to solve. As with our business systems, we need to evaluate the potential for problems in outside services, and develop contingency plans in case important communications services are unavailable or crippled in the first part of 2000.
- Utilities and Other Key Outside Requirements: Our planning will include possible disruptions in power delivery to NRAO sites. Other services to be concerned about are being identified.

Detailed assessment and testing of PC systems and evaluation of third-party software are underway; only limited testing of the latter can be performed. At this time, it appears unlikely that Y2K fixes at NRAO will require substantial resources from the Research Equipment budget in 1998 and 1999. 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-fifth of the workstations at NRAO are expected to be upgraded to more capable systems. At least this level of replacement must be maintained in 1999 and beyond, to allow NRAO to continue retiring now-obsolete workstations purchased as early as 1992. These older machines have reached the end of their operational lifetimes, and will no longer be supported by the manufacturer beyond mid-1999. Their upgrading or replacement is also required by the increasing demands on computational capability at NRAO from both increased demands by NRAO users and increased observational capabilities brought about by technological advances and enhanced processing techniques. These upgrades will allow most workstations at NRAO to be replaced or upgraded by the end of their useful lives (typically no more than four years for scientific workstations). They also allow us to upgrade the smaller network server systems at sites such as Tucson and Green Bank.

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 about $250,000 for hardware acquisition during 1999. This level of investment will accomplish three goals:

- Reduce any 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 resources are constrained during 1999, 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.

While NRAO must provide AIPS support for a broad range of UNIX systems, we must also be careful not to strain our resources by attempting to maintain too much diversity. The field of viable platforms for scientific workstations has narrowed somewhat in the past year, with a few leading manufacturers making significant changes in strategic direction. This has been slightly offset by radical improvements in performance on very inexpensive Intel hardware running Linux, giving it a favorable price/performance margin over the more traditional UNIX platforms at NRAO. While Linux cannot replace all other UNIX systems in our installations—it does not have support for large files, and some of the commercial software we require is not available—it is an extremely attractive and cost-effective desktop for many purposes, and is likely to remain so.

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 maintain a large number of computers. The tightly networked computing systems at NRAO also allow the Observatory to provide significant support to its users, especially outside users. For example, 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 web 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 completed NRAO VLA Sky Survey (NVSS) and the ongoing 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.

Beginning in 1996, we were able to start the process of modernizing NRAO's network infrastructure. This process is proceeding during 1998 with the completion of local-area network connections to outlying buildings at the VLA, installation of fiber-based networking in the Jansky Lab at Green Bank (the only medium that can be used for high-speed communications there because of RFI considerations), the purchase of a reliable Ethernet switch in Charlottesville, and much-needed troubleshooting equipment in Socorro. It must continue in 1999 with further upgrades in Green Bank, in Charlottesville to prepare for the likely merging of the Ivy Road and Edgemont Road facilities, and in Tucson with new facilities to accommodate expansion due to MMA development. A related goal is to provide high speed links between NRAO sites, and between NRAO and external institutions. Current network connections only allow limited access for remote observers; the pioneering efforts at the 12 Meter to provide support for remote observers should be enhanced and expanded to provide such capabilities for remote observer access for NRAO's other instruments.

The estimated cost for completing improvements in the performance of the internal computer networks at NRAO will be $200,000 in 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 Millimeter Array, and the proposed VLA upgrade. These projects, like many ongoing engineering tasks for existing instruments, are heavily dependent on the use of advanced engineering workstations to carry out various aspects of design and fabrication. If engineers at NRAO are faced with carrying out their work using obsolete or inadequate workstations and PC's, their productivity will suffer. Improvements in this area continued in 1998 and will need further investment in 1999. Special efforts are also being made to ensure that all engineering staff have access to current releases of major software packages to reduce the difficulty that has been encountered in exchanging information. The estimated cost of these undertakings during 1999 will be approximately $50,000. This will allow the acquisition of both 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 1999 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 used in the system are nearly 11 years old, and represent an expensive maintenance problem. In the spring of 1998, NRAO was informed by the manufacturer of these computers that support can be guaranteed only for approximately two more years. At this time, it appears that two viable options are available. First, it is possible to buy newer models of the same type of computers, which are slightly more powerful, could be installed in a relatively short time with minimal software effort, and would be supported for at least another ten years. Alternatively, the current on-line system could be redesigned with the intention of basing the new system on a more modern and cost-efficient hardware platform such as that used in the VLBA, GBT, and 12 Meter telescopes, which has considerably better performance at much lower cost.

While the first option is in many ways the simpler one, it still leaves us dependent on an expensive proprietary architecture for which it is difficult to find experienced programmers. In addition, considerable development effort would still be needed to support new instrumentational capabilities, particularly those that result from the proposed VLA upgrade. We have therefore chosen the second option. While it will take much longer to implement, it will produce a system that is easier to support, is compatible with other NRAO control systems for which we have considerable in-house expertise as well as a larger pool of potential applicants, carries much more reasonable maintenance costs, and can be designed from the start with many of the requirements of the upgrade and other planned enhancements in mind.

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

In addition to storage issues related to data processing, we must also consider the requirements of archiving very large volumes of raw data. This will be particularly important for the data produced by the GBT and 12 Meter spectrometers. The VLBA archive currently contains more than 4 terabytes of data, stored on 2-gigabyte DAT tapes. The accumulated data archive of the VLA, spanning 22 years, is over 1.5 terabytes, increasing by about ten percent per year; this rate will go up considerably when the proposed VLA Upgrade is implemented. Clearly, the tape media currently being used for this purpose have neither the capacity nor the longevity required for permanent archives. Alternatives will need to be investigated.

A desirable level of expenditure for data storage and handling facilities at NRAO during 1999 would be $100,000. This would allow significant enhancement of current facilities and add new capabilities for especially large scientific problems. Individual tape systems with the required capacity and transfer rates are somewhat costly, and adding enough drives to create a useful capability at NRAO requires significant resources. Deferring this expenditure is possible, but NRAO users will have to curtail certain types of experiments on various instruments, and continue to spend large amounts of time shuffling data instead of performing scientific analysis.

Computing Personnel

Some reorganization occurred during the past year which will have an impact on future computing activities at the NRAO. First, on the advice of a special review committee, a new management position was created to oversee all GBT software development; this position was filled by the then Deputy Assistant Director for Computing. Second, the Assistant Director for Computing joined the MMA project management team. To fill these vacancies, a new approach to Observatory-wide computing was announced in March 1998 with the formation of a Computing Council, composed of the site and MMA computing division heads, the directors of NRAO's two major software projects (AIPS and AIPS++), and a senior member of the scientific staff as chair. To implement the decisions of the Council, and to coordinate Observatory-wide computing efforts—including major purchases, contracts, support initiatives, policies, and Y2K efforts—an assistant to the director of NRAO was appointed to act as Executive Officer of the Council.

The current level of personnel for computing support at the Observatory continues to be sufficient only to meet critical needs, and is not adequate to pursue advanced developments in computing. A consequence is that NRAO is not maximizing the scientific return from our observing facilities. Unfortunately, lean budgets at NRAO during the past few years have led to reduced personnel, particularly in software development. As a result, NRAO is barely able to provide essential support to its computer users, and must neglect them in certain areas. Support personnel in computing are often forced to work in crisis mode, and must neglect long term planning and enhancements in computing support. Scientific staff are sometimes called upon for such tasks as WWW page development and local maintenance of important astronomical data analysis packages written outside of NRAO.

During 1999 NRAO will move to address critical shortages in certain areas of computing support. Particular needs for support and programming personnel exist at all four of the NRAO sites. The initial Design and Development phase of the MMA, which extends through mid-2001, is in reasonable shape with funding for five and one-half full time employees. But significant software challenges face our plans to get the VLBA and the GBT fully operational, and to modernize the VLA control systems. Increased personnel for software development for the VLBA would dramatically enhance the observational capabilities of the VLBA, while additional personnel for the GBT will reduce the time required to bring the GBT laser ranging system into full operation. Although badly needed for these and other tasks, no new positions are currently budgeted for FY99.

V. GREEN BANK TELESCOPE

Antenna Construction

The accompanying photograph, taken this September, shows that the Green Bank Telescope is actually beginning to resemble it's concept drawings now that the reflector back-up structure (BUS) has been fully installed and the vertical feed arm started.

In October 1997, six of the BUS modules had been installed on the supporting box girder structure while the balance (16 modules) remained on the ground. A 310-ton mobile crane was brought to the site to accomplish ground repositioning of modules so they could be handled directly by the S70 tower derrick. The mobile crane brought a resultant schedule and cost advantage.

Concurrent with the erection of the BUS modules, the 1,036 intermodule members were reinstalled and welded. The intermodule members are needed to give the BUS its integrity. To accomplish this task, three additional tower cranes were brought in. The extra tower cranes have been in constant use since acquisition, expediting the various erection functions. Temporary walkways were put up along the perimeter top and bottom chords of the modules in order to properly position and weld the intermodule members.

Eight of the 22 reflector backup structure modules are supported by one or two temporary supports. When the first two modules went up, provisions were made to land the modules in their correct location by putting rollers (pipes) under the support point plates. When it was found that the support points were in line with the temporaries within one-half an inch, the rollers were discarded. This indicated three things: first, the rigging of the units had been done correctly; second, the modules were somewhat stiffer than anticipated; third, no erection stresses were being built into the backup structure due to pulling or jacking at the support points. The average time for installation of each of the 22 modules was 2–2.5 weeks. The planning and careful execution of the erection of the BUS has paid-off in the accuracy achieved in the RMS of the actuator support points, i.e., 3/4″ RMS (19.5 mm RMS).

Actuators

Most of the active surface actuators were installed on the front chords of the BUS modules prior to lifting. As the modules were placed at the base of the S70 tower derrick, several of the small mobile cranes were used to expedite this operation. Actuators which would interfere with the installation of the intermodule members or obstructed target areas were left off. These actuators were filled-in when the modules were in place atop the box structure. This fill-in operation started in April of 1998 and lasted until mid-August. Today, all 2,209 of the active surface actuators are in place while over 300 have been accurately positioned. Accurate positioning is presently constrained to the area of the BUS, directly over the rigid support of the box structure. It was originally specified that the surface panel actuators be aligned on the top chords of the BUS to a positional accuracy of one degree. To insure the proper alignment of the 2,004 surface panels, and to

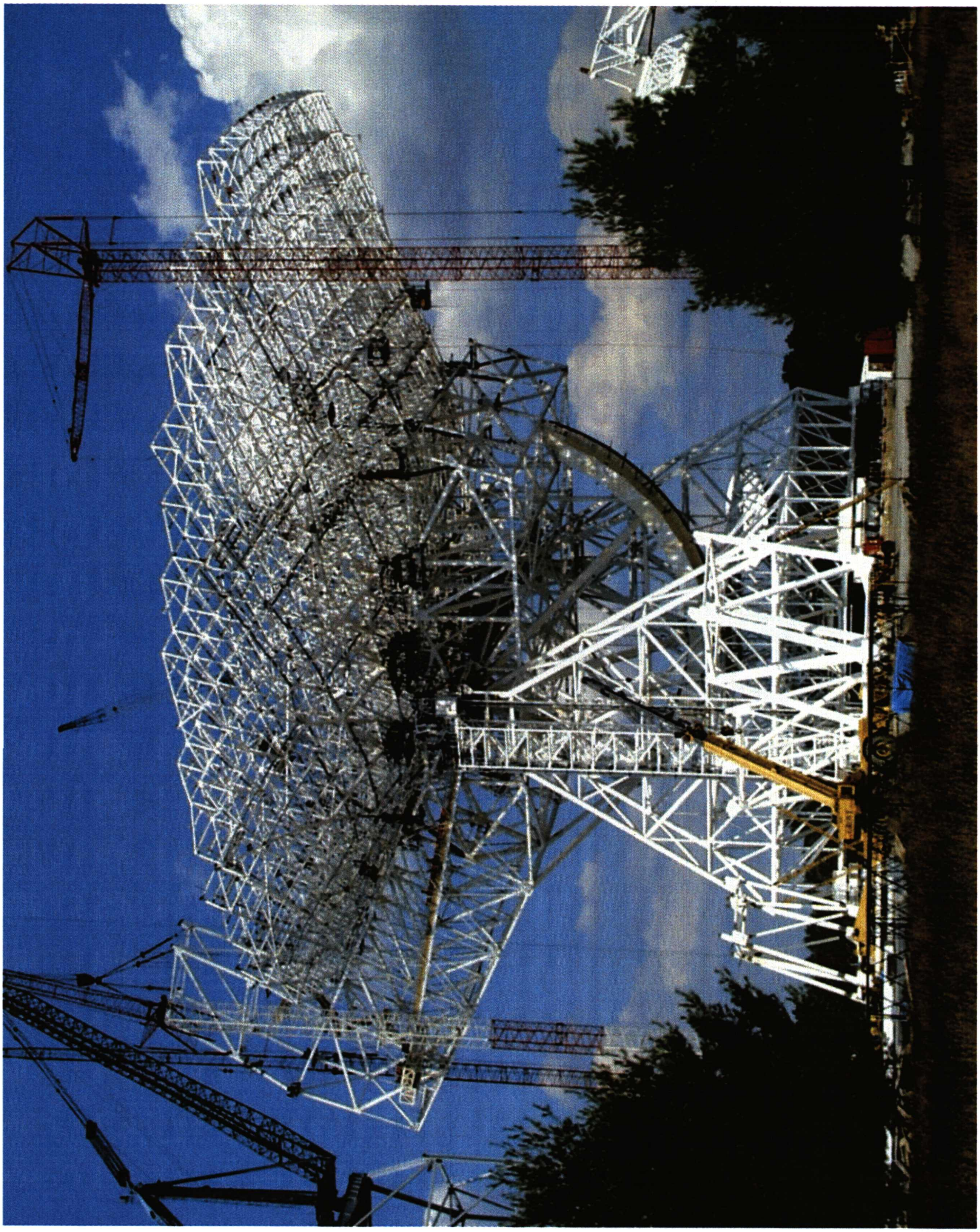


Photo taken September 1998 showing construction progress of the Green Bank Telescope (GBT).

maintain the nominal two millimeter panel gaps, the contractor has elected to reduce the allowable positional accuracy of the actuators to one tenth of a degree. This means that the top of each actuator will be aligned normal to the surface to within one millimeter (0.40"). Regarding the translational accuracies (six degrees of freedom) the target at the top of each actuator must fall within a 1/8" diameter cylinder, 1/4" long. These tolerances are being achieved presently in the alignment of the actuators installed on that portion of the BUS, which is directly above the box support structure. Obviously, this area has been selected as it will have the rigidity to avoid changes in actuator alignment when the BUS loads are transferred from the temporary to permanent supports.

Permanent Supports

The permanent supports function to carry the live and dead loads incident upon the BUS back, or down, to the box girder structure and thereby to the elevation shaft which is supported by the alidade and the foundation/ground. Under certain conditions loads incident upon the BUS are carried to the box girder which transfers the loads through the elevation wheel and gear to the alidade and thus to the foundation/ground. There are sixteen joints welded to the back of the various BUS modules. Of these, thirteen needed to be redesigned, either to reconfigure the joint to achieve greater stress path efficiency or to correct bad welding. Rework of the BUS joints began in May 1998 and is now 84 percent complete. There are 20 welded joints on the box structure at various levels. Rework of these joints is 26 percent complete. There are 30 permanent beams carrying loads between the BUS and box joints. Six percent of these have been installed.

Surface — Actuator Cables

Actuator cable runs are currently being installed in the cable raceways, from the proximate vicinity of the actuators to the actuator control room. More than 50 percent have been installed. Run installation is ahead of schedule. The cabling installation is expected to be complete before contractor acceptance testing of the telescope.

Vertical Feed Arm

In December 1997, preparations began for installation of the vertical feed arm. This component consists of 13 modules plus the feed/receiver room and upper feed arm. By the end of September 1998, the bottom two sections on each side of the 200-foot vertical feed arm will be in place on the outboard end of the horizontal feed arm. Two additional sections, and the platform which supports the feed/receiver room, have been assembled and await erection along with the upper feed arm and feed/receiver building. The upper 60-foot portion of the feed arm has been trial erected at site including the deployable prime focus boom, the prime focus rotation mount, the subreflector, and the subreflector adjustment mechanism. The feed arm servo, which controls the above equipment had been installed and preliminary tests run. The feed/receiver room, which is located directly below the upper feed arm, has been located nearby with the secondary focus feed turret in its roof. In early 1998, additional servo tests were conducted and the photogrammetric setting of the subreflector surface and calibration of the six subreflector "Stewart platform" actuators was accomplished. In October-November 1998, the upper feed arm servo will be operated continuously for at least a month. Additional photogrammetric measurements will be made to allow final setting of the subreflector surface to a tolerance somewhat better than 0.004 inches RMS.

The Vertex Platform has been installed on the telescope and the access walkways to the vertical feed arm have been installed.

Recently, the contractor sent 20 surface panels to the site to test shipping, handling, installation, and alignment procedures. The panels were unpainted so that they might be returned to contractor's plant for re-measurement on the contour measurement machine (CMM). This will provide an evaluation of the above procedures with respect to any deteriorations of surface tolerances. NRAO has provided a prototype Panel corner setting tool which the contractor is using to familiarize his personnel with its operation. Initial experiments with the panel setting tool revealed that the primary obstacle to achieving the desired panel-to-panel setting accuracy of 0.001" is the mechanical adjustment, not the measurement instrument. It was pointed out to the contractor that in order to realize the benefits of the 0.004" accuracy of the individual panels, and to fit the (CMM) data, the corner-to-corner accuracy of 0.001" must be achieved. Moreover, if their mechanics could not adjust the panels to this accuracy, neither could NRAO, and thus the surface would be out of spec. This forced a closer examination of the panel adjustment mechanism and the procedure. A number of ideas are being investigated and NRAO is optimistic that a solution will be found.

Schedule

The schedule for the GBT construction has undergone updates as the construction has proceeded. The work on the permanent supports continues to be time-consuming but steady progress is reported. A few tasks have been accelerated. Overall, the goal of completing the construction of the telescope itself by the end of 1999 continues to appear to be reasonable.

The current goal is to install the Upper Feed Arm late in the winter of 1998/99. When that has been completed, it will then be possible to complete the alignment of the actuators and the installation of the actuator cables. Installation of the panels themselves can begin after the actuators are in place, in the late spring of 1999, and will continue through the summer. The accurate alignment will employ photogrammetry, and will occur in the fall of 1999.

Receivers

All GBT receivers have been built and tested with the exception of the S-band, Q-band, and prime focus receivers. The GBT L-band receiver was completed and tested this year. The receivers for C-, X-, K-, and Ku- bands have been used at the 140 Foot Telescope for general user observations, and their system temperatures are comparable with predicted values. System temperatures on the GBT will, of course, improve because of the unblocked aperture of the new telescope.

The design for the S-band receiver is complete and all of its electrical components have been purchased and tested. The Central Development Laboratory (CDL) has delivered the S-band cryogenic amplifiers to Green Bank. The orthomode transducer (OMT) for the receiver was fabricated in the Green Bank machine shop, and the receiver feed is currently under construction. Once the feed is completed, the shop will proceed with the fabrication of the receiver dewar and chassis.

A test dewar for the Q-band receiver is being assembled to test the mechanical design and RF/IF performance of one of the four RF/IF receiver quadrants. The three remaining quadrants will be assembled once the testing is satisfactorily completed. Two low noise amplifiers have been borrowed from the VLBA for testing, and the eight amplifiers that will actually be used in the receiver, along with two operational spares, will be manufactured in the CDL as part of its MAP Project.

The mechanical design of the prime focus receiver is complicated because it is actually five receivers combined in a single box. Consequently, progress on the construction of the prime focus receiver has lagged behind that of the other GBT receivers. However, the prime focus receiver will play a key role in the commissioning of the GBT, so we have dedicated significant resources to the receiver to finish it in time for commissioning. The OMT and feed for the 910–1230 MHz observing band were completed by the shop. S. Srikanth has made significant progress in the design, construction, and testing of the cavity-backed dipole feeds that will be used at the lower frequency bands of the receiver. Richard Bradley has developed balanced amplifiers for the prime focus receiver. This new design of amplifier provides a good input match, thus eliminating the need for an isolator in front of the low noise amplifier, and improves the receiver's dynamic range, which ultimately makes the receiver more resistant to the interference that is likely to be encountered at low radio frequencies. All amplifiers for the prime focus receiver are on hand.

Funds from the NRAO Research Equipment (RE) budget have been allocated for a new 26–40 GHz receiver and an L-band focal plane array receiver.

Amplitude Instabilities of the GBT IF in the Optical Fiber

The GBT IF will be transmitted from the Receiver Room on the telescope to the Electronics Room in the Jansky Laboratory in an optical fiber. Initial tests of fiber optic links showed gain fluctuations as high as one percent, which is significantly larger than the amplitude stability required by a continuum observation (about one part in 10^4). The gain fluctuations will also affect spectral line observations. Tests made by Steve White and Roger Norrod over the past year have shown that the amplitude instability is due to a combination of stress-induced changes in the birefringence of the optical fiber and the polarization sensitivity of the photodetectors at the end of the fiber. Mechanical stress in the fiber alters the birefringence of the fiber and thus the polarization of the light at the photodetector. The polarization of the light changes with time because the stress in the fiber can vary due to various telescope motions. The changes in polarization appear as gain fluctuations because the photodetector is polarization sensitive.

Our solution to the problem with the optical fiber is multi-faceted. First, we have selected photodetectors that are least susceptible to polarization changes. Second, additional tests by Norrod and White indicate that the dominant source of stress in the fiber would occur at the azimuth cable wrap of the telescope. (The elevation cable wrap is of a different design and maintains a constant tension on the fiber). A new azimuth cable wrap, which also maintains constant tension on the fiber, is being built for the optical fiber cable. Third, automatic level control will be applied to the drive laser on the fiber to remove the amplitude fluctuations which arise from vibrations on the telescope. Recent tests of the level control scheme by White indicate that it works well. Fourth, we are exercising special precautions in the installation of the fiber. For example, the loose tube buffering of the fiber we have selected minimizes external forces on the individual fibers. Additionally, fiber splices will be mechanically stabilized, and the fiber transmitter/receivers will be located in temperature-controlled areas. Finally, we are locating the GBT total power detectors in the Receiver Room, instead of at the end of the fiber, so that continuum observations will not be affected by IF transmission through the fiber. Laboratory tests indicate that our solutions will provide the amplitude stability that is required for astronomical observations.

Green Bank Spectrometer

Ray Escoffier and Walter Brown completed the construction and initial testing of the GBT spectrometer. The spectrometer was moved to Green Bank in January 1998. A large portion of the spectrometer's observing modes have been programmed, and the machine is being integrated into the GBT monitor and control system. Large heat sinks are being attached to the correlator chips to improve spectrometer cooling. Additional tests of the spectrometer will be conducted in the GBT Electronics Room.

Water Vapor Radiometer

An 86 GHz water vapor radiometer was designed and built by Mike Stennes and Lisa Wray. The radiometer was integrated into the GBT monitor and control system by John Ford, and, using software tools available in AIPS++, Joe McMullin developed a data analysis package for the radiometer data. We began collecting meaningful statistics on the atmospheric opacity due to water vapor before the onset of winter, when atmospheric conditions are expected to be most favorable for high frequency observations. We have found that the zenith opacity at 86 GHz can be less than 0.1 for extended periods of time (days).

RFI Testing

The radio frequency interference (RFI) that is generated by GBT hardware is measured in an anechoic chamber. Engineers and technicians make modifications to their hardware if the RFI is found to be excessive. We are currently sealing the GBT Receiver Room so that we can measure the RFI attenuation provided by the room.

Integrated Testing

An integrated testbed, or mock-up, of the GBT Electronics and Monitor and Control systems has been assembled in the GBT Electronics Room, and we are now realizing the benefits of integrated testing in the Mock-up. For example, Roger Norrod found that the electronics in the IF racks are sensitive to changes in ambient temperature. Consequently, we have modified the temperature control scheme in the Electronics Room. Norrod also found that the noise in the detected total power from the GBT IF did not integrate down as the square root of bandwidth or time. Further investigations showed that the excess noise was due to excessive gain fluctuations in a certain type of IF amplifier. Additional tests in the Mock-up are high priority objectives because the time required to commission the GBT can be minimized by identifying and solving problems in the Mock-up now.

Operations

The GBT operations group now consists of three full-time personnel. Carl Bignell transferred from VLA/VLBA Operations to lead the Telescope Services Division in Green Bank. Jerry Lawrence, who has extensive experience in the commissioning of radar installations for the United States Air Force, was hired as the GBT Operations Supervisor. Steve Reeves transferred from his position as an operator of the 140 Foot Telescope to become our first GBT operator. A great deal of effort is being dedicated to hiring additional operators.

The operations group is focusing its efforts on developing plans and procedures for operating and maintaining the GBT. The group developed a manpower transition plan which identifies the manpower needed to operate and maintain the GBT and describes how operations and maintenance manpower will shift from the 140 Foot Telescope to the GBT as 140 Foot operations come to a close. Many items needed to operate the GBT (e.g., communications hardware, safety equipment, and optical fiber between the telescope and the control room) are not provided by the GBT construction contract, and the operations group has initiated the necessary procedures to acquire essential items this year. The group is also prioritizing a list of GBT spare parts to insure that the most critical spares are purchased with our limited budget. Lawrence has specified the communication requirements for the GBT and has written the job description for GBT operators. Members of the operations group are also interacting with the software development group to insure that the operator's interface to the telescope provides the basic functionality they need.

In November of 1997, we decided to operate the GBT from the new addition to the Jansky Laboratory instead of a new local control building. The GBT operations group quickly developed a plan for occupying the space in the new addition in such a way that would accommodate site-wide telescope operations.

Metrology

The metrology group reached a significant milestone during the past year by fabricating and assembling the components which make up the production laser rangefinders. Eventually, these rangefinders will be mounted on both the telescope feed arm and on the ground around the telescope perimeter and will be used to measure the locations of retroreflectors on the structure. Most of the rangefinders have been optically aligned and calibrated for pointing and mechanical offsets.

Bob Hall, David Parker, John Payne, and Michael Goldman documented the GBT Measurement Program, with which the group continues its experimental work with prototype laser rangefinders. The group has monitored the deflections in the GBT derrick as a large section of the reflector back-up structure was lifted on to the telescope structure. The prototype instruments are capable of measuring submillimeter deflections over distances of hundreds of meters. Ambient air conditions are monitored in these and other experiments to better understand how distance measurements are affected by changing ambient conditions. Four rangefinders were used to track three retroreflectors on the 140 Foot Telescope in November 1997. The tests demonstrated the ability of the rangefinders to track moving targets and illustrated the need for an accurate telescope model to point the lasers. The measurement program plan describes how the rangefinders, in conjunction with other metrology instruments, can be used to check critical alignments; to test finite element models of the structure; to identify structural anomalies and fault conditions; to provide useful data for optimization of servo algorithms, to allow independent measurements of acceptance criteria; to aid in expediting outfitting and commissioning operations; to improve setting accuracy, servo performance and pointing accuracy; to provide a basis for on-going trend analysis and to be of service in development of a GBT maintenance program. The program document outlines in detail how rangefinder measurements can be used to determine telescope pointing coefficients. The GBT will probably be the first radio telescope to have its pointing characterized prior to the use of receivers. The measurements proposed in the document are being incorporated into the GBT commissioning plan. Goldman has also made detailed recommendations on how the rangefinder measurements, finite element model, and surface panel and retroreflector data bases should be integrated into the telescope monitor and control system for precision pointing and surface shaping. His recommendations will be evaluated and incorporated in detailed commissioning plans for Phase 3 operations (closed loop, active surface) of the telescope.

Active Surface

The active surface system is capable of shaping the primary reflector of the GBT and consists of 2209 actuators and their individual control computers. The development of the active surface hardware has been complete for some time. We are coordinating the installation of the actuators and the actuator cabling with the contractor. NRAO personnel are routing the cables inside the actuator room on the telescope as the contractor runs them to the actuators. Rich Lacasse has concentrated his efforts over the past year on designing the monitoring software for the active surface, and Amy Shelton, a recent addition to the digital electronics group, is completing the programming of the active surface software.

Software Development

An NRAO internal review of GBT software was also conducted in the fall of 1997. The review committee identified a need for a software development manager in the project, and Gareth Hunt was appointed as Software Development Manager for the GBT. Hunt has already addressed many of the issues raised by the software review committee. For example, he has established priorities for the software development group and is tracking progress of the group. He has been instrumental in encouraging communication between programmers, hardware engineers, and software engineers. He also selected a software tool for building graphical user interfaces to the telescope.

Project Coordination

Over 50 people participated in a workshop on First Science with the GBT on July 27–29. Capabilities of the GBT were discussed by the Green Bank staff on the first day of the workshop, and science with the GBT was discussed by potential users on the second day. GBT commissioning issues were discussed on the final day of the workshop. Workshop participants made specific recommendations on priorities for commissioning, priorities for spectrometer observing modes, integrated software and hardware testing, and the development of future hardware.

A preliminary plan for commissioning the GBT was developed. Requirements were written for the data analysis software that will be needed at commissioning, and the programming of this software is well underway.

VI. MAJOR INITIATIVES

1. The Millimeter Array

Introduction

The Millimeter Array (MMA) project will bring to millimeter and sub-millimeter astronomy the aperture synthesis techniques of radio astronomy which enables precision imaging to be done on sub-arcsecond angular scales. The richness of the celestial sky at millimeter wavelengths is provided by thermal emission from cool gas, dust, and solid bodies, the same material that shines brightly at far infrared wavelengths. Presently, such natural cosmic emission can be studied only from space with the coarse angular resolution and limited sensitivity that small orbiting telescopes provide. The MMA will image at 1 mm wavelength with the same 0"1 resolution achieved by the Hubble Space Telescope (HST) at visible wavelengths and will provide scientific insight at longer wavelengths that is complementary to that of the HST, and its successor instrument the Next Generation Space Telescope (NGST), and will do so with the same image detail and clarity. In addition, the reconfigurability of the MMA antennas gives the MMA a *zoom-lens* capability so that it can also make high-fidelity images of large regions of the sky. Uniquely, the MMA is a complete imaging instrument.

The Millimeter Array has been described in the MMA Proposal submitted to the NSF by AUI in July 1990 and augmented by the MMA Design and Development Plan submitted to the NSF in 1992 that was subsequently updated by the MMA Program Plan submitted to the NSF in 1998. Upon completion the MMA will become a user research facility of the NRAO and will be operated by the NRAO at that time in conjunction with the other NRAO telescope facilities, the GBT, the VLA, and the VLBA.

Objectives and Scope — Scientific

In specifying the scientific goals of the MMA, astronomers have called for the capability for precise astronomical imaging with an unprecedented combination of sensitivity and angular resolution at the shortest radio wavelengths for which the Earth's atmosphere is transparent. This unique combination of capabilities will make available for astronomical investigation a wealth of new opportunities and new science. Scientists using the MMA will:

- Image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as z=10;
- Determine through molecular and atomic spectroscopic observations the chemical composition of star-forming gas in the earliest forming galaxies;
- Map fluctuations in the microwave background that result from formation of the first mass structures in the universe;
- Reveal the kinematics of obscured galactic nuclei and QSOs on spatial scales smaller than 100 pc;
- Assess the influence that chemical and isotopic gradients in galactic disks have on star formation and spiral structure;

- Image heavily obscured regions containing protostars, and protostellar and pre-planetary disks in nearby molecular clouds with a spatial resolution less than 10 astronomical units and a kinematic resolution better than 1 km/s;
- Detect the photospheric emission from thousands of nearby stars in every part of the Hertzsprung-Russell (H-R) diagram;
- Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of stellar nuclear processing and envelope convection;
- Establish the relative distributions of the large number of complex molecular species in regions of star formation, relating them to shock fronts, grain disruption, and energetic outflows—information which is essential to the understanding of astrochemistry;
- Obtain unobscured sub-arcsecond images of cometary nuclei, hundreds of asteroids, *Centaurs*, Kuiper-belt objects, planets and satellites in the solar system—observations that can be done for astrometric or astronomical studies uniquely during daylight or nighttime hours;
- Image solar active regions and investigate the physics of particle acceleration on the surface of the sun.

The MMA is a long-lived user observatory. Its scientific impact at any time will be facilitated by the quality of its instruments and limited only by the creativity and industry of its astronomer users.

Objectives and Scope — Technical

The burden of designing a powerful and unique instrument is that it requires an extension of existing technology. This is as true for the MMA—with its densely packed mosaicing configuration, broadband sensitive receivers, total-power instrumentation, and precision antennas—as it was for the Keck Telescope with its segmented, optical-quality primary mirror, and as it will be for the NGST which attempts to combine the Keck segmented mirror technology with ultra light-weight materials and metrology suitable for the space environment. Application of significant technological advances is the *sine qua non* of the design of a forefront scientific instrument.

Precision astronomical imaging and the need for sensitivity sufficient for the study of faint objects with the MMA defines the three broad categories of technical requirements for the array: (1) development of broadband, quantum-limited receivers; (2) design of antennas of very low blockage so that the *warm spillover* is minimized; and (3) choice of a site for the array where the background emission and absorption from atmospheric water vapor is minimized. The first two points are the focus of the initial three-year Design and Development phase of the MMA; the latter point has its resolution in the superb, dry, site recommended for the MMA in the Chilean Altiplano. The technical objectives of the MMA project are summarized in Table VI.1.

The combination of requirements for a high-tech instrument such as the MMA to be located at a remote site means that great care must be taken in the design of the array. The MMA instrumentation, in addition to being technically superior to instrumentation in use for millimeter wavelength astronomy, will also need to be exceptionally reliable so as to minimize the failure rate, and it must be modular so that it can easily be removed when necessary for repair at a laboratory located at lower elevation than the array site and perhaps very distant from that site as well.

The final general technical requirement for the MMA, also to be addressed in the Design and Development phase, concerns ease of scientific access. Recognizing that the MMA will be extremely fast—images of small fields can be done in minutes—and suitable for an extremely wide range of scientific investigation, astronomers will need to see images as one of the principal, nearly real-time, data products from the array. This goal should not remove the ability of the sophisticated synthesis astronomer to refine his or her image through subsequent processing, but it should allow non-expert astronomers to use the MMA effectively. This requirement involves development of instrumentation and software that is not part of operating radio synthesis instruments.

Table VI.1. Summary of MMA Specifications

Array	
Number of Antennas	> 30
Total Collecting Area	> 2500 m^2
Angular Resolution	0".07 λ (mm)
Configuration	
Compact:	70 m
Intermediate (2)	250 m, 900 m
High Resolution	3000 m
Antennas	
Diameter	10 m
Precision	< 25 micrometers RSS
Pointing Precision	0".8 RSS
Fast Switching	Cycle < 10 seconds
Total Power	Instrumented
Transportable	By vehicle with rubber tires, on roads

Receivers

28 - 45 GHz HFET	T(Rx) < 20 K
67 - 95 GHz HFET	T(Rx) < 40 K
91 - 119 GHz HFET or SIS	T(Rx) < 50 K
125 - 163 GHz SIS	T(Rx) < 6 hν/k SSB
163 - 211 GHz SIS	T(Rx) < 6 hν/k SSB
211 - 275 GHz SIS	T(Rx) < 6 hν/k SSB
275 - 370 GHz SIS	T(Rx) < 6 hν/k SSB
385 - 500 GHz SIS	T(Rx) < 6 hν/k SSB
602 - 720 GHz SIS	T(Rx) < 8 hν/k SSB
Dual Polarization	All receivers

SIS Mixers

Image Separating	All SIS frequency bands
Balanced	All SIS frequency bands
Integrated with IF amplifier	All SIS frequency bands

Intermediate Frequency (IF)

Bandwidth	8 GHz, each polarization

Correlator

Baselines	> 600
Bandwidth	16 GHz per baseline
Spectral Channels	4,096 per IF

Objectives and Scope — Project

The project objective is to build the MMA and prepare it for use by visiting astronomers who will compete for time on the telescope via peer-reviewed proposals. A summary of the tasks to be carried out to reach the objective include the following:

- Design and prototype of representative modules of the technically demanding instrumentation;
- Decision on the local oscillator technology: either a multiplier chain or a photonic system;
- Decision on the IF signal transmission: either analog or digital;
- Development of an engineering test interferometer at the NRAO VLA site comprising the first two prototype antennas that will be used throughout the construction phase of the project to evaluate compatibility of pre-production instrumentation modules and to use to test prototype MMA software systems;

- Development of the MMA site including provision for all utilities and support infrastructure;
- Development of construction and operational support facilities in Chile;
- Recruitment and training of an operational staff for the MMA in Chile and in the U.S.;
- Development of wide bandwidth communications between the MMA and astronomer-users in the U.S. suitable for astronomers to make effective use of the MMA in nearly real-time;
- Planning for a minimum 30-year lifetime of the facilities, including facilities for research and development of successive technical generations of instrumentation.

Organization of the MMA Project

The organization of the MMA project during the initial three-year Design and Development phase is represented in Figure VI.1. This organization is based on the Work Breakdown Structure (WBS) for the tasks in the D&D phase. The numbers in the organizational boxes shown in Figure VI.1 refer to all the major tasks in the WBS. The D&D WBS is structured by MMA systems, not necessarily by location of the individuals doing the work; for this reason the same responsible project manager, or MMA Division Head, appears in more than one box. Should international partners join the MMA, the organizational structure will evolve in an orderly way to accommodate the requirements of those partners.

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

Role of the Millimeter Array Development Consortium

Millimeter wavelength synthesis astronomy was pioneered by the Radio Astronomy Laboratory (RAL) at the University of California and by the Caltech Owens Valley Radio Observatory (OVRO). The early RAL effort was subsequently broadened to include the University of Illinois and the University of Maryland under the aegis of a consortium called the Berkeley-Illinois-Maryland-Association (BIMA). Recognizing that the MMA will benefit from the experience of astronomers and staff at the operational OVRO and BIMA millimeter wavelength facilities, an agreement was forged among the NRAO, BIMA, and OVRO to form the Millimeter Array Development Consortium (MDC). As described in that agreement, the MDC provides overall direction for the development phase of the MMA. The MDC is managed by an Executive Committee of four members—two representatives from the NRAO and one each from OVRO and BIMA—appointed by the participating institutions and reporting to the Director of the NRAO. The MDC institutions participate in the D&D phase of the MMA by working as full partners in the development tasks specified in the MMA ProgramPlan. It is the expectation that the MDC will be an effective mechanism not only to recruit to the

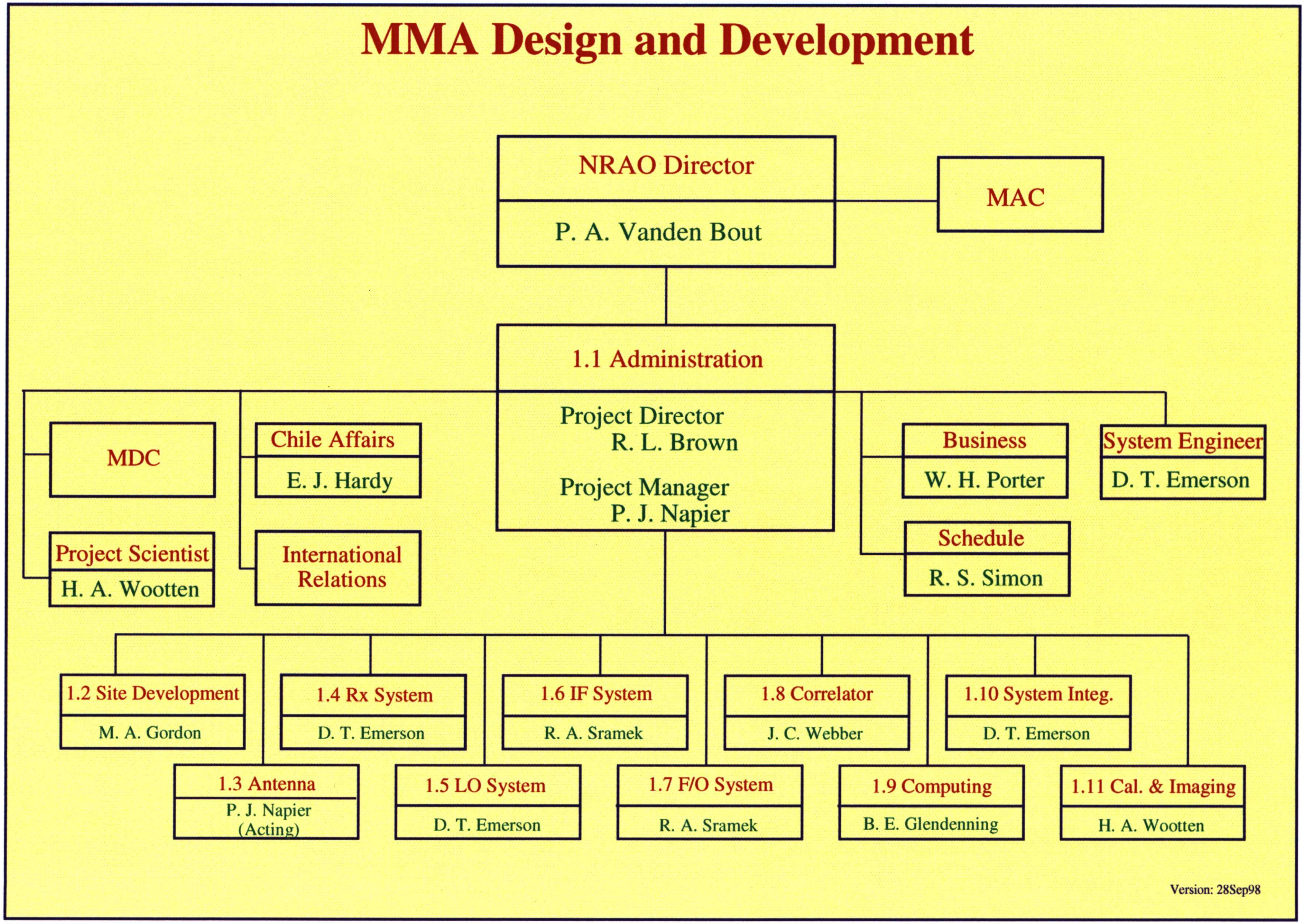

MMA Design and Development
NRAO Director
P. A. Vanden Bout
MAC
1.1 Administration
Project Director
R. L. Brown
Project Manager
P. J. Napier
MDC
Project Scientist
H. A. Wootten
Chile Affairs
E. J. Hardy
International Relations
Business
W. H. Porter
Schedule
R. S. Simon
System Engineer
D. T. Emerson
1.2 Site Development
M. A. Gordon
1.3 Antenna
P. J. Napier (Acting)
1.4 Rx System
D. T. Emerson
1.5 LO System
D. T. Emerson
1.6 IF System
R. A. Sramek
1.7 F/O System
R. A. Sramek
1.8 Correlator
J. C. Webber
1.9 Computing
B. E. Glendenning
1.10 System Integ.
D. T. Emerson
1.11 Cal. & Imaging
H. A. Wootten
Version: 28Sep98

Figure VI.1

MMA project the experience of university-based individuals but also to stimulate the long-term vitality of millimeter wavelength astronomical research and development at the universities.

Role of International MMA Partnerships

Among the *deliverables* of the MMA Design and Development initiative is an agreed partnership in the array by foreign countries or by U.S. agencies other than the NSF. Partners in the project will have their own ideas as to the structure of the project—they will need to be included in the intellectual and financial description of the MMA.

Two partnership possibilities may have a significant effect on the MMA planning. These are the possibility of joining the MMA with the Japanese project, the Large Millimeter and Submillimeter Array (LMSA), or with the European Large Southern Array (LSA). Both of these initiatives have considerable support among their respective scientific communities and the leaders of both have expressed interest in discussing how their projects could be joined with the MMA to the benefit of all. Either combination with the MMA, or better, a combination of all three, would provide such a truly powerful imaging instrument that the U.S. community has been supportive of efforts by the MMA staff to secure such a partnership. One barrier to a joint project is the dissimilar antenna diameters considered by the three. Recent discussions among the three groups have led to successive compromises on the diameter to the range 10 to12 meters. The MMA Design and Development antenna design efforts will therefore focus on antennas of 10 m diameter to facilitate a partnership with one or both of these groups. Should the partnership initiatives fail, the MMA construction budget estimates would allow an array of 30 or more antennas to be built. This subtle change in the baseline MMA planning is therefore an asset to be used to court partnership with the LMSA or LSA without compromising the MMA as a stand alone instrument. Progress in securing partnerships for the MMA, as indeed progress in realizing the technology to achieve the capabilities desired of the MMA itself, begins with the efforts outlined in the MMA Design and Development Plan.

Budget

The 1999 Design and Development phase of the MMA is funded from the NSF Major Research Equipment program at a planned level of $9M. The allocation of these funds and the carryover from 1998 is shown on the NRAO budget tables of Section IX of this Program Plan. The detailed budget for the entire Design and Development phase of the project is given in the MMA Management Plan.

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 these 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 or more 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 upgrade:

Phase 1: An Ultrasensitive Array

- New receivers: lower noise temperatures and much wider bandwidth performance (up to 8 GHz in each polarization channel) in existing bands; addition of 2.4 GHz and 33 GHz bands at the Cassegrain focus; completion of the outfitting for the 40–50 GHz band; extension of the 1.4 GHz band to lower frequencies. The goal is to provide continuous frequency coverage from ~ 1 GHz to 50 GHz.
- A fiber optic data transmission system to transmit the broadband signals and monitor data from the antennas to the control building, replacing the original waveguide.
- A new correlator, able to support 40 or more antennas, to process broadband 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.

Improvements to Existing Frequency Bands

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

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

Two components of these receiver improvements will begin in 1999: (a) completion of the 45 GHz system, using monies granted the NRAO by the NSF through the MRI program; (b) retrofitting the 23 GHz system with a modern receiver/polarizer. Both projects will take about 3 years to complete.

New Observing Bands at the Cassegrain Focus

Two new receiver systems will be added at the Cassegrain focus: 2.4 GHz and 33 GHz. The 2.4 GHz system is optimal for study of objects with a normal synchrotron spectrum, would provide an outstanding capability in studies using Faraday rotation, and will allow the VLA to participate in bistatic planetary radar observations with Arecibo Observatory. The 33 GHz is optimal for study of objects with a thermal spectrum, and will allow imaging of many interesting molecular lines, including redshifted CO and O_2. Table VI.2 summarizes the proposed new and upgraded VLA Cassegrain observing bands.

Table VI.2 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

A plan is being developed in which a rotating turret will be installed, permitting access to the VLA's prime focus. The turret would contain the current subreflector, plus three or four low-frequency feed/receiver packages, and would enable complete frequency coverage from ~200 MHz to ~1.2 GHz with good sensitivity.

Sensitivity Goals

Table VI.3 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.3. VLA Sensitivity

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

New LO/IF Transmission System

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

A New Correlator

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

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

High Surface-Brightness Sensitivity – The E Configuration

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

To fill this u-v gap, up to eight new antennas would be built in New Mexico and Arizona to make the density of u-v coverage in the 40-500 km baseline range similar to the VLBA now beyond 500 km.

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

Table VI.4. Illustrative Budget

	Cost ($M)	Subtotal (SM)
PHASE 1:		
Antenna LO/IF	5.8	
Antenna Mechanical	2.0	
LO/IF Transmission	2.4	
Central LO/IF	3.4	
Correlator	9.0	
Test Equipment and Hardware	0.9	
Cassegrain Feeds and Receivers	13.7	
PRIME FOCUS:		
200-1000 MHz	7.1	
SUB-TOTAL		44.3
E CONFIGURATION:		
27 Stations	5.0	5.0
COMPUTING	1.2	
MANAGEMENT	2.3	3.4
SUB-TOTAL PHASE 1		52.8
CONTINGENCY PHASE 1	10.6	
PHASE 1 TOTAL		**63.4**
PHASE 2:		
Eight new antennas	50	
Fiber to local antennas (700 miles)	10.5	
Lawyers and EIS	0.1	
10 Station Interconnect	2.0	
SUB-TOTAL PHASE 2		62.6
CONTINGENCY PHASE 2		12.5
PHASE 2 TOTAL		**75.1**

3. AIPS++ Project

The AIPS++ Project is a collaborative initiative to develop a new data reduction and analysis 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 Telescope National 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 now uses AIPS++ as the platform for data acquisition and monitoring for the VLBI correlator now under development. Additionally, AIPS++ has been selected as the platform for the NRAO MMA, and is being actively considered as a prime component of a number of different non-consortium telescopes.

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 and difficult to use. Our major remedy to this problem is to write graphical user interfaces for major applications, and to improve the command line interface. This approach will be tested in a number of subsequent beta releases planned for late 1998 before a first public release is made in early 1999. 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 late 1999.

We have also been involved in a collaboration with NCSA to investigate parallelization of AIPS++ applications. First results are very promising: for example, a parallelized Clark Clean algorithm showed essentially linear speed up for 1–32 processors on an SGI Origin 2000, reaching about 60–70 percent efficiency. This capability is now available in the development system and will be included in the first release.

VII. NON-NSF RESEARCH

1. United States Naval Observatory

The 20 meter telescope at Green Bank will continue to be used as part of the USNO geodetic VLBI array during 1999. The telescope is equipped with receivers at S- and X-band and operates as an interferometer with telescopes in Hawaii, Brazil, Alaska, and Germany. Data from the telescopes are correlated at the USNO in Washington, DC, and provide fundamental information on earth rotation and polar motion which is published in the International Earth Orientation Service Bulletin A each week. The 20 meter telescope is also used for occasional geodetic VLBI experiments organized by the NASA geodetic group in cooperation with the USNO.

In 1999 the control computers, telescope operators, recorders, and all other equipment associated with the 20 meter telescope will be moved from the old interferometer building to shielded rooms in the new wing of the Jansky Lab.

2. Green Bank Interferometer

The Green Bank Interferometer (GBI) is a radio source monitoring facility operated by a consortium which includes NRAO, the USNO, the Naval Research Lab, and the NASA High Energy Astrophysics Program. The GBI observes a group of radio sources at 2.7 and 8.3 GHz and provides the measured flux densities to the astronomical community via the NRAO web site. A steering committee with representation from all groups reviews requests for objects to be included in the source list. At present about two dozen objects are observed between one and eight times each day depending in their level of activity.

3. NASA – Green Bank Orbiting VLBI Earth Station

The Green Bank Earth Station supports Space VLBI satellite experiments, particularly HALCA, launched in 1997, and RadioAstron, which is still in development. This effort is funded by NASA. The Earth Station sends timing information to the Japanese orbiting VLBI satellite, HALCA, records the downlink data on VLBA or S2 tape, and processes the downlink data to produce a 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 Earth Station will continue to perform tracking passes on this satellite for the duration of its mission.

In addition to normal satellite operations, the earth station staff will continue to improve the operational software and the station hardware in 1999. An upgrade to the control system will me made to improve the telescope reliability.

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 from many foreign countries. 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 (WVU). These programs began in 1987 with support from the Education Division of the National Science Foundation. The training targets elementary, 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 700 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 interact with the many professional astronomers who are visiting the Observatory at the same time. After participation in 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 1,500 students have been able to gain first-hand research experience using the NRAO education facilities.

In 1999 the program will begin the first full year under a new grant from the NSF Education Division. This grant will run through 2003, and will allow us to provide our program, which its strong research component, to teachers as part of a systematic State wide effort to enhance the teaching of science in West Virginia. Teachers who participate in the combined programs will receive extra support for teaching astronomy in their home classrooms, and receive training which helps them integrate appropriate technology into their teaching.

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 NSF. In 1998, 50 college teachers participated in a Chautauqua held at NRAO-Green Bank. Two Chautauquas are planned for 1999.

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 1999.

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 who guides their work. In 1997/98 Green Bank staff mentored six high school students, and the effort will be expanded in 1999 in conjunction with West Virginia's School-to-Work educational reforms.

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 1997/98 approximately 21,000 people visited the Observatory. About 20 percent of the visitors came with school groups.

Plans are underway to overhaul the tour program. A three-year grant has just been received from the Education Division of the NSF that will provide funds to construct a series of interactive science exhibits which will allow the public to experience the ongoing research at NRAO more directly. The grant will allow for the development and construction of new exhibits, and for development of educational programs that can present science to groups of visiting school children.

There is now a tour coordinator who works year-round to expand the tour offerings. We received a small advertising grant from the West Virginia State Division of Tourism to promote an evening event series at the Observatory this season consisting of star parties, "insiders'" tours, and hands-on activities. These were well attended and we plan to expand them in 1999.

Socorro Educational Program

Through widespread exposure in movies, news media, magazines and science textbooks for all grade levels, the VLA has become perhaps the most famous radio telescope in the world. This exposure has generated steadily increasing interest in the VLA and radio astronomy in general between both the public and educators. This interest, in turn, has brought more participation in NRAO's Socorro-based educational programs and allowed us to expand those programs.

The Socorro educational programs, while centered around the VLA Visitor Center, also include a growing range of cooperative efforts involving local and regional schools and colleges, other observatories and amateur organizations, in addition to providing public lectures and educational support to public events.

VLA Visitor Center: The VLA Visitor Center is becoming an ever more popular destination for tourists. Recorded attendance for 1997 was more than 50 percent higher than that for 1994, and 1998 attendance through the summer tourist season showed nearly a 25 percent rise over 1997 figures. More than 20,000 visitors signed an unattended guest book in 1997, and tourism experts contend that in such a situation the actual number of visitors is as much as three times higher. The VLA Visitor Center thus may be serving as many as 60,000 tourists annually. In a typical year, these tourists come from all 50 states and some 40 foreign countries.

The visitor center features an automated video presentation, displays on the history of radio astronomy, the operation of the VLA and VLBA, and information on scientific results from both instruments. It is the starting point for a self-guided walking tour that provides visitors a close-up look at a VLA antenna and, from an outdoor balcony on the control building, views of the electronic equipment and the control room. A free brochure guides visitors around the walking tour and informational signs at strategic points on the tour explain the workings of the instrument.

We plan to completely redesign the educational displays at the VLA Visitor Center to provide an updated treatment of astronomy and NRAO's role, and to incorporate more modern and effective techniques for stimulating learning. We have applied to the NSF Informal Science Education directorate for a planning grant to develop inquiry-based exhibits and programs that will more effectively convey the basic concepts of astronomy and radio observations to our diverse visitor population. If approved, this grant will support a one-year planning project that, utilizing the expertise of professional educators and museum specialists, will include prototyping, testing and evaluation of new exhibits and produce detailed plans for a new suite of displays and expanded educational outreach efforts. These detailed plans then will form the basis of an implementation program to build and install the new suite of displays and to establish additional outreach partnerships.

We designed and produced a display panel about radio astronomy and the VLBA for the visitor center at Mauna Kea, and are currently working with personnel of the joint National Solar Observatory/Apache Point Observatory visitor center to produce a radio-astronomy exhibit for that facility.

Guided Tours: Though the VLA Visitor Center is designed to provide a self-guided educational experience for tourists, NRAO also provides a number of guided tours. In the summer months, we offer regularly scheduled weekend tours, using our summer REU students as guides. Throughout the year, by appointment, we conduct guided tours for educational and scientific groups. These include school and university classes, amateur astronomy clubs, engineering societies and others. There are usually about 50 of these special tours per year, serving more than 1,000 people.

In the past year, we have provided guided tours to elementary and secondary school groups from New Mexico, Arizona, Texas, and as far away as Virginia, in addition to participants of national meetings of the Institute of Electrical and Electronic Engineers (IEEE), Astronomical Society of the Pacific, and the International Conference on Technology and Education. The University of New Mexico, New Mexico Tech, and Los Alamos National Laboratory regularly schedule VLA tours for classes and summer-student programs.

We distribute a booklet entitled "Bringing Your Class to the VLA," that provides teachers with background information and tips on maximizing the educational value of a class visit through prior preparation and follow-up activities.

Lectures and Public Events: 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. We provide speakers to service clubs and other organizations throughout New Mexico.

NRAO provides a display and staffing for career days at area schools, a particularly important function in a region where there are large numbers of minority and disadvantaged children who need to be made aware of the possibility of scientific or technical careers.

In cooperation with the National Solar Observatory and Apache Point Observatory, we provide and staff a display at the New Mexico State Fair, an event that in a typical year draws about 200,000 attendees.

We provide a display and staffing for the Albuquerque Astronomical Society's annual Astronomy Day event at New Mexico's largest shopping mall. In 1998, more than 43,000 people visited that mall during the Astronomy Day exhibition.

Science Fairs and Science Olympiad: NRAO provides financial support and prizes for science fairs in Socorro County, the state science fair and the New Mexico Science Olympiad. We also provide numerous staff members as judges and officials for these events. Both the New Mexico State Science Fair and the state Science Olympiad are held every year in Socorro, and we schedule a special, guided VLA tour for participants of both.

Southwest Consortium of Observatories for Public Education (SCOPE): NRAO-Socorro is a member of this consortium, which also includes Kitt Peak National Observatory, Lowell Observatory, Whipple Observatory, McDonald Observatory, Apache Point Observatory and the National Solar Observatory. SCOPE is an effective vehicle for cooperation and information exchange about public-education programs among the participating observatories. In addition, this organization has raised funds from both public and private sources to produce educational materials about astronomy. These materials have been distributed at no charge to tourists at the VLA Visitor Center, to visitors at other regional tourist attractions, and to area schools.

Project ASTRO: NRAO is a member of the Southern New Mexico Project ASTRO coalition, which serves schools in the southern half of the state. Project ASTRO is an educational program of the Astronomical Society of the Pacific, and is funded by the National Science Foundation. This program links professional and amateur astronomers with elementary and middle-school teachers to bring astronomy into the classroom. NRAO staff members serve as team members with local school teachers, and we also support Project ASTRO by providing educational materials, information and class tours for teachers in this program. In 1998, we hosted the regional Project ASTRO meeting at the AOC.

Chautauqua Short Course for College Teachers: In cooperation with the University of Dayton, we conducted the first Socorro short course for college teachers in 1998. Thirty teachers from 19 states attended the short course, which included lectures on the history, theory and practice of interferometry and aperture synthesis, as well as several areas of astronomical research at the VLA and VLBA. The course also included detailed technical tours of the Array Operations Center and the VLA. Based on the success of this course and the enthusiasm of the participants, we anticipate conducting another in 1999.

Amateur Astronomers: Amateur astronomers are a proven resource for public education, many of them showing great enthusiasm for bringing astronomical information to the public and to schools. NRAO has forged close ties with New Mexico's extensive amateur astronomy community. We regularly provide lectures and tours for amateur groups. In addition, NRAO provides staff assistance, VLA tours and lecturers for the annual Enchanted Skies Star Party, an event that draws amateur astronomers to Socorro from across the 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 highlights of their visit.

Amateur Radio Operators: NRAO is ideally positioned to use the amateur radio community, with more than 600,000 licensed operators in the U.S., as a force multiplier for public education efforts. As expected, many of our staff members are licensed radio amateurs and are involved in local and national radio organizations. Staff members present lectures to amateur radio organizations and NRAO provides displays and information about radio astronomy at amateur radio events. We also have frequent contact with national amateur radio publications, resulting in articles on NRAO scientific results and technical developments.

The World Wide Web: At least 200,000 non-NRAO people access our World Wide Web site annually, and this number is growing rapidly. In 1998, we greatly expanded the amount of Web information aimed at the general public. This had a demonstrable effect in that certain types of inquiries that were increasing by email and telephone dropped dramatically after relevant information was placed on the Web.

Currently, we have basic information about radio astronomy, the VLA and VLBA, and the VLA Visitor Center on the Web, in addition to NRAO press releases about recent research results. The amount of information aimed at the general public will be increased steadily. The plans for outreach associated with the VLA Visitor Center exhibit upgrades include a significant component of Web-based information dissemination and educational activities.

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 reinitiate 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 fully participate 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.

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 eight 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 residing 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 Research Associates 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 Research Associates are available not only to those in radio astronomy but they are also available to recent Ph.D. recipients in engineering and computer science.

Research Associates at the NRAO are encouraged to define their own research program; they are not asked to serve as apprentices to NRAO staff scientists. The purpose of the program is to provide an opportunity for young scientists to establish their research credentials so that they may more effectively compete for permanent positions and become themselves better teachers of, and researchers in, radio astronomy. Approximately ten Jansky Research Associates are in residence at the NRAO at any time.

IX. 1999 PRELIMINARY FINANCIAL PLAN

by Budget Category

(NSF Funds, $ in thousands)

	New Funds	Uncommitted Carryover of 1998 Funds	Total Available for Commitment	Commitments Carried Over from 1998 Funds	Available for Expenditure
Operations					
Personnel Compensation	$19,380		$19,380		$19,380
Personnel Benefits	5,814		5,814		5,814
Travel	750		750		750
Material & Service	5,956	400	6,356	700	7,056
Management Fee	640		640		640
Common Cost Recovery	(800)		(800)		(800)
CDL Device Revenue	(100)		(100)		(100)
Total Operations	$31,640	$400	$32,040	$700	$32,740
Research & Operating Equipment	500	0	500	100	600
Total NSF Operations	$32,140	$400	$32,540	$800	$33,340
MMA Design & Development	9,000	5,010	14,010	350	14,360
MRI (2)	0	750	750	100	850
GBT	0	500	500	100	600
TOTAL NSF PLAN	$41,140	$6,660	$47,800	$1,350	$49,150

IX. 1999 PRELIMINARY FINANCIAL PLAN

NRAO Non-NSF Funding

($ in 000's)

Organization/Project	1999 Funds
USNO:	
Operations & Maintenance	$435
GB/HA Repairs	200
NASA:	
Science OVLBI	983
Earth Station OVLBI	827
Miscellaneous:	150
TOTAL	$2,595

IX. 1999 PRELIMINARY FINANCIAL PLAN

by Function/Site

(NSF Funds, $ in 000's)

	Personnel	Salaries, Wages, & Benefits	Materials, Supplies, & Services	Travel	Total
Operations					
General and Administrative	26	$1,741	$870	$125	$2,736
Research Support	48	4,728	465	285	5,478
Central Development Lab	16	1,274	110	30	1,414
Green Bank Operations	87	5,006	582	40	5,628
Tucson Operations	23	1,612	321	40	1,973
Socorro Operations	187	10,833	3,608	230	14,671
Management Fee			640		640
Common Cost Recovery/ CDL Device Revenue			(900)		(900)
Research and Operating Equipment			500		500
Total NSF Operations	387	$25,194	$6,196	$750	$32,140

APPENDIX A – NRAO SCIENTIFIC STAFF ACTIVITIES

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

The planned 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

The VLA remains a premier instrument for solar radio observations with high spatial and time resolution. Solar research on the VLA is directed primarily toward understanding flares on the Sun and stars, and scattering of radio waves in the solar wind. The new 74 MHz receivers on the VLA will be exploited to search for coronal mass ejections from the Sun. Given the geomagnetic impact of this energetic phenomenon, interest in coronal mass ejections and related phenomena is keen in the solar and "space weather" communities. The 74 MHz system will also offer the exciting possibility of detecting coherent radio emission from extra solar planets. It is known that all magnetized planets in our own solar system emit coherent cyclotron maser emission. If any of the extra solar planets reported so far have magnetic fields of one to a few times the magnetic field of Jupiter, they may emit cyclotron maser emission that would be detectable by the VLA. Such a detection would be the first direct detection of an extra solar planet.

VLA observations of both angular broadening and scintillation phenomena of a sample of compact background sources were obtained in 1992 (during an active phase) and in 1996 (near solar minimum). The properties of the angular broadening of the background sources are used to deduce the strength, degree of anisotropy, and the spectral index of the spatial spectrum of electron density inhomogeneities on scales of a few kilometers to tens of kilometers and to exploit the phenomenon of "refractive scintillation" to deduce the properties of the spatial spectrum of electron inhomogeneities on scales of several hundreds to thousands of kilometers. The solar minimum observations will be compared with those obtained near maximum levels of solar activity.

The relative timing between the thick target hard x-ray emission observed by the Yohkoh Soft- and Hard-X-ray Telescopes, the Compton Gamma Ray Observatory observations, and Nobeyama Radioheliograph at 17 GHz observations of the spatially and temporally resolved microwave source, is being studied to clarify the role of electron injection and trapping in flaring coronal magnetic loops. New dual frequency radio observations planned in the coming year will clarify the role of electron trapping effects and possible "second step" acceleration.

With the recent visit of comets Hyakutake and Hale-Bopp, interest in the molecular spectral line emission from comets has increased dramatically. New observations will explore the relationships between mutated parent/daughter variation of molecular species in comets to better understand the chemical processes occurring around and on cometary nuclei. High resolution spectroscopy will examine the temporal variability in comets and the relevance to cometary structure. A number of studies of Comet Hale-Bopp utilize the efficient 12 Meter Telescope. The 12 Meter Telescope data will be used to image the HCN, CO, H^2CO, HCO+, and CH^3OH emission from this remarkable visitor and to evaluate the kinetic temperature evolution.

OH emission has been observed from Comets SOHO, Linear K5, and 21P/Gizcobini-Zinner. Ammonia was also detected in C/1995 O1 (Hale-Bopp) in May 1997 at an abundance similar to that measured in Hyakutake, and methanol and formaldehyde emission was monitored in Hale-Bopp. Further study of these observations along with OH occultation observations and observations of thermal emission observations of Hale-Bopp will lead to a better understanding of the variation of molecular production rates with heliocentric distance, and the thermal development of the coma.

Other planned solar system studies include the analysis of Venus continuum emission, new VLA and OVRO observations of the Pluto/Charon system, along with new VLA observations of Jupiter at 74 MHz. The Martian atmosphere will be studied using H_2O data. Radar observations will be used to study the surface of Mars and Mercury.

2. Stellar Evolution

VLA observations will concentrate on the earliest and latest stages of stellar evolution to 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 known cases of multiple objects within a single core. Planned observations may lead to a better understanding of why some cloud cores give birth to more than a single star at nearly the same epoch. In these maps, differences among the objects become quite apparent. In objects so young that no bipolar flow has commenced (thus, strictly speaking, even younger than Class 0) such as IRAS16293B or NGC 1333 IRAS4C, ammonia structures are readily discerned. In another group of objects, including L483, IRAS16293A, NGC 1333 IRAS4B, and VLA1623-2418, very cold ammonia exists, but shows only subtle correlation with cold dust structures enveloping the star.

VLA ammonia maps reveal a rotating disk in HH212 whose surfaces are concave upward, suggesting its role in directing the bipolar flow. In turn, the flow apparently excavates the surface of the disk, resulting in its concave appearance. The molecular core of Ophiuchus 'A', in which four dense clumps have formed a single star, will be of special interest. But, but other clumps, may be in the earliest formative stages of star production. The protostar VLA1623 will be shown to be an example of star formation induced in the core by expansion centered on

HD147889, a nearby O star. In a final group of objects, such as L1448C, L1448IRS3, NGC 1333IRAS4A, S68N, and S106FIR, warm ammonia correlates well with the dust emission, and may show up in outflowing gas as well. It appears that ammonia becomes severely depleted, perhaps through freezing onto grains, in the final stages before stellar ignition.

CS data taken with the BIMA and Haystack radio telescopes have been combined to provide a picture of the outflow from the S68N protostar over a complete set of spatial scales. The OVRO millimeter array will be used to examine the innermost region of this extremely young protostar. Interestingly, a density profile derived from SCUBA maps succeeds very well in reproducing the H_2CO spectrum observed toward the envelope of this protostar. The OVRO maps will extend our investigation into the inner region where the star is actually formed.

Previous studies of the ionization fraction in the dense cores of the S68N, L483, and other clouds have determined that the low ionization fraction in their envelopes does not impede collapse. New observations will concentrate on higher excitation transitions to investigate the ionization fraction within the denser portions of the cores.

A program to investigate the 650 GHz lines of H_2CO is being pursued in order to determine the extent to which these very highly excited lines emit in star-forming molecular clouds. Lines at 631 GHz were detected and modeled. These models demonstrate that very warm molecular gas exists in a number of massive star forming regions which are not well probed by lower energy lines. It is hoped to develop a study of this emission into a tool for high resolution studies of matter in protoplanetary or protostellar systems, appropriate to the MMA. The initial observations show that clumps of gas associated with young stars in NGC 2024 were much hotter than had been supposed, and that the apparent depletion of molecules in the dusty clumps was not so great as had been thought.

Infall appears to be a characteristic phenomenon among the youngest Class 0 objects. The parameters of infalling gas have been studied in HCO+ lines and in an assortment of other lines. A comprehensive set of formaldehyde data has been assembled to test whether these models of infall are sensitive to the choice of molecular data used to derive them, as may be the case if complex chemistries operate in near-protostellar regions. Many objects have been modeled successfully, revealing the detailed structure of young stellar envelopes.

Observations of the Serpens Molecular Cloud will investigate the chemical evolution of nearby young stellar objects through multispecies, multitransitional microwave spectroscopy combined with millimeter continuum observations of the thermal dust with the aim of characterizing the molecular cloud core chemistry on the scale of the condensation and in the associated embedded objects. Planetary nebulae are luminous, short-lived remnants of dying stars with masses from 0.8 to 8 solar masses and, as such, are potentially valuable as statistical indicators of the galactic star-formation history. Most of the known planetary nebulae were detected by the NVSS. Unfortunately, dust extinction strongly discriminates against the optical discovery of low-latitude planetary nebulae. Selection from a flux-density and color-limited sample of far-infrared sources avoids dust extinction. Far-infrared samples are heavily contaminated by radio-quiet AGB stars, while planetary nebulae emit free-free radio emission. About 400 of these 1,300 far-infrared sources were detected by the NVSS, of which nearly 300 are known planetary nebulae. The remaining 120 candidates are probably low-latitude planetary nebulae. Some have already been confirmed spectroscopically. New spectroscopic observations at Palomar will check the remaining candidates. If they are successful, it will be possible to construct a flux-limited sample of planetary nebulae suitable for statistical studies of galactic star-formation history. Measurements of the CO isotope ratios in a broader sample of planetary nebulae will constrain mixing theories in stellar evolution models and provide a connection between similar measurements in red giant branch stars and the interstellar medium

3. Novae, Supernovae, X-ray Binaries, Pulsars, and other Radio Stars

The analysis of radio light curves and images of classical novae will be extended to determine their structure and kinematics. Coordinated observation campaigns for new novae, beginning with VLBA imaging and continuing with Merlin and VLA images will also be carried out.

The powerful supernova remnant Cas A appears to show significant changes in the meter wavelength flux density on time scales of a year or so. Flux density measurements of this archetypical supernova remnant will continue in Green Bank at wavelengths between 2.5 and 10 meters in order to better characterize these unusual variations.

Studies of molecular shocks in supernovae remnants will draw upon the findings of an earlier program which studied the OH maser line at 1720 MHz. This maser line has proven to be an exceptional tracer of molecular shocks. Millimeter and submillimeter observations will be made of various molecules toward the OH 1720 MHz maser spots in a program designed to measure the physical parameters of the shock. In addition, the observed Zeeman splitting in the masers themselves yield a unique measure of postshock magnetic field.

VLA observations of a newly discovered completed sample of the radio stars from NVSS are now complete. In collaboration with optical astronomers from Beijing Astronomical Observatory, high-resolution optical spectroscopy will be used to follow these stars. The NVSS and follow-up VLA observations were also used to find and confirm a sample of the 50 brightest radio stars (primarily Tycho stars with $S > 5$ mJy at 1.4 GHz) in the sky visible from the northern hemisphere. Collaborators at Beijing Observatory are obtaining optical spectra.

VLA multiwavelength studies of outburst events in x-ray binaries and x-ray transients will search for the radio counterparts of new x-ray transients. Follow-up images of the relativistic jets produced by these systems with the VLA will be obtained as well as VLBA imaging of new outburst in old transients and x-ray binaries such as Cyg X-3. One of the recent major discoveries is that some x-ray transients leave behind a slowly-expanding, synchrotron-radiation emitting remnant or afterglow with structure and evolution that can be observed with the VLBA. The study of the evolution of these remnants with the VLBA is therefore important.

In the case of classical flare stars, new observations will concentrate on the problem of induced scattering processes. The extremely high brightness temperatures of the radio bursts produced on these objects, coupled with the high Thompson depths of their coronae, should drive induced scattering processes such as induced Compton scattering, stimulated Raman scattering, or other nonlinear scattering mechanisms. The upgraded facility at Arecibo offers a powerful new opportunity to study the role of these phenomena. In the case of active binaries, new observations will be used to explore the nature of flares on RS CVns at a level of detail that has been impossible previously. High quality multiband VLBA observations of the RS CVn binary UX Ari in both quiescent and flaring states will be used to model the flaring source using a magnetized model of the binary.

A relatively new area of research in radio astronomy is connected with the soft gamma ray repeaters which are a galactic population of neutron stars with dipole magnetic fields more than 100 times greater than normal pulsars. These so called "magnetars" undergo outbursts due to starquakes. This results both in hard x-ray emission and synchrotron bubble events as accelerated electrons escape from the star. Research in this area will focus on the study of the nebulae created from this burst activity.

Combined VLA, UKIRT, and RXTE of the microquasar GRS1915+105 show: (a) the disappearance of thermal x-rays from the accretion disk, due either to a disk instability, or possibly the loss of the disk by advection onto the black hole; and (b) simultaneous ejection of relativistic electrons, as traced by the hardening of the power-law spectrum, and synchrotron emission in the radio and IR bands.

VLBA images during such activity indicate a synchrotron jet of size 1–10 AU, whose flux is pulsed with a 30 minute period, in response to the injection of plasma from the disk instability. VLBA astrometry gives a motion of about 5.5 mas per year, primarily in the galactic plane due to secular parallax, in agreement with the HI distance of 12 kpc. The goal for 1998-99 is to refine the astrometry and clarify the connections between the accretion disk, the genesis of the jets, and their co-evolution on AU scales.

4. Interstellar Chemistry, Molecular Clouds Star Formation, and Cosmic Masers

The investigation of the kinetic temperature and spatial density structure within young stellar and protostellar environments will continue using centimeter- and millimeter-wavelength interferometers and single dishes with emphasis on molecular and dust emission properties. VLBA observations of OH, water vapor, SiO, and methanol maser emission offer a unique opportunity to study the life cycle of stars from the formation to the late stages of evolution.

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 the gas phase (after H_2 on grains). The Polaris Flare Cloud is a well-mapped object in HI, CO, and IRAS 100 um. Extensive and commensurate maps of OH show stronger intensities than expected and, as predicted, in regions where CO is undetectable. New observations of the Polaris Flare molecular cloud in 12CO and 13CO (J 2≥1) transitions will be used to determine the effects of opacity and the transition from supersonic to supersonic turbulence on the observations of molecular cloud turbulence.

The study of physical and chemical conditions in small translucent molecular clouds will continue. These involve self-consistent models in which the physical conditions (radial dependence of density, temperature, ionization; external radiation field) have all been derived in terms of hydrostatic equilibrium polytropic models. An extensive study of ion-molecule chemistry with detailed modeling of some 27 species, including a recent study of ten complex molecules containing more than four atoms has been completed. This study appears to mark the transition between gas-phase and grain chemistries, with the more complex species requiring the latter. A similar study of 11 hydrocarbon species, which constitute the backbone of gas-phase chemistry, shows excellent agreement between chemical models and observed abundances.

The 12 Meter Telescope large spectral band scan at 2 mm (130 to 170 GHz) of eight sources is nearly complete. Calculations of molecular spectra are being used to extend the Lavs and JPL catalogs of spectra. The new catalog will be key to the identification of the myriad of lines detected in the spectral survey. After all possible identifications have been made, the task of analyzing abundances of the many molecular species detected will begin. This will include a merging of the 2 mm survey with an earlier 3 mm survey.

Dedicated searches for two new molecular species, HCS, and the cumulene species $H_2C=C=C=C=C$ will be initiated. The former is identified as key to understanding one of three "branches" of the sulfur chemistry which we have set out in the translucent cloud studies. The latter has been predicted by our hydrocarbon chemical models to occur in detectable quantities.

Water masers trace out very dense gas regions. Toward these low-luminosity sources, they almost always occur in sources with high-velocity molecular outflows. In some scenarios, the masers arise as a flow that impacts quasi-stationary objects, such as planets. The 140 Foot Telescope is being used to monitor several dozen young stellar objects. VLA data have measured the positions of the masers to compare with other tracers of the outflow and the young star. This monitoring project will continue as long as the 140 Foot remains in operation. The VLBA will be used to determine proper motions in these objects.

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 (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? One possibility is that it arises at the working surface of the bipolar jet on the ambient molecular cloud; another holds that it occurs where material entrained in or along the jet interacts with the surface of a protoplanetary disk. High time resolution VLBA observations map the proper motions of the masers, and therefore explore the kinematics of outflow gas. In HH212, for example, outflows with velocities of 50–100 km/s explore the evolution of the postshock material. This work will be continued with emphasis on IRAS16293, which shows expansion of masers in the flow at velocities of about 65 km/s. Interestingly, a static ringlike maser structure lying coincident with the star suggests that some masers may form at an accretion shock boundary within 1 AU of the young star. VLA studies of the massive young star S106FIR demonstrate expansion which is being explored in more detail with the VLBA.

VLBA observations of the water masers in the nucleus of the elliptical galaxy NGC 1052 will determine the proper motion of the water masers and help us resolve the question of whether the masers are entrained in the jet. The masers do not appear to be in a Keplerian disk around a massive central object, as those in NGC 4258 appear to be.

High resolution VLBA and MERLIN polarization observations of the 1720 OH MHz masers in the supernova remnants W 44 and W 28 are being analyzed with regard to measuring the magnetic field at high angular resolution and also to characterize the sizes of the masers and to infer conclusions about the scattering along the line of sight to the masers. This may allow limits on the scattering screen(s), and for W 28, may answer the question of whether or not the pulsar thought to be associated with the remnant is truly at the same distance.

A major emphasis during the next year will remain the intensive monitoring campaign of the 43 GHz SiO maser emission toward the late-type star TX Cam using the VLBA. This involves full-polarization imaging of the v=1, J=1-0 SiO maser emission in the near circumstellar environment of this object every two weeks. The monitoring will extend over a full pulsation period for the Mira variable and offers unprecedented insight, into the kinematics, dynamics and magnetic field distribution in the extended atmosphere of this object. This has significant implications for mass-loss models. Already, more than twenty epochs have been imaged to produce a dramatic movie of the mass-loss in the near environment of this star. This is the largest VLBA project ever undertaken, and a major effort has been expended on automating the data reduction process as far as possible. Further work in this area is expected, but with a renewed emphasis on proper motion determination and modeling.

The reduction of related polarization VLBA observations of other maser species toward late-type stars will continue, particularly the OH maser emission from candidate post-AGB objects with the aim of determining the onset of asymmetry as found in many planetary nebulae.

5. The Interstellar Medium

Research on the interstellar medium will include both the galactic and extragalactic interstellar medium, with emphasis on the structure, kinematics, evolution, distribution, and properties of molecular clouds; along with the relationship of atomic and ionized gases to molecular material.

A survey of approximately 60 HII regions has just been completed with the 140 Foot Telescope to search for carbon radio recombination line emission in classical HII regions. Over half of these objects have detections. When combined with atomic (CI), molecular (CO), and 158 micron (CII) data, this survey will provide an important, complementary diagnostic probe of the structure, kinematics, and physical properties of photodissociation regions. The observed hydrogen recombination line and continuum emission, also obtained with the 140 Foot Telescope, will yield an accurate determination of the electron temperature gradient in the galaxy.

High resolution, deep images of H and ^{4}He in W43 and NGC 6334A have been made 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+ (^{4}He+/H+) due to mass loss from evolved stellar objects are examples of the possible properties that can be determined. These images are also being used to determine if the nonthermal component of the line is turbulent and if so, whether this energy is being generated within the HII region.

Planned observations will address the question of whether diffuse HII regions create the enhanced turbulence observed for pulsars toward the galactic center. Fine scale structure in the interstellar medium will be studied using absorption of pulsar radiation and interferometry. Space VLBI observations of the pulsar B0329+54 are planned to compare properties of interstellar turbulence using simultaneous single-dish dynamic spectra, VLBA and Space VLBI dynamic spectra, and angular broadening.

6. Normal Galaxies

Asymmetry in galaxies is evident in optical images, in their HI distribution and even in their kinematic properties. Such asymmetry is not surprising when found in interacting systems. However, at least 50 percent of "isolated" galaxies display asymmetric features. A central theme of current research concerns these asymmetries. The principal goals are to quantitatively describe asymmetry, to evaluate its persistence in the presence of differential rotation and to seek the origin of such asymmetries. Both HI single-dish and synthesis data are being used for these tasks.

High-velocity gas has been known to exist in the Milky Way for some time yet has only recently been observed in other galaxies. Since the number of known galaxies with high velocity gas is small, it is difficult to compare the properties of galaxies with and without high velocity gas and, therefore, difficult to determine what causes the phenomenon. As shown by preliminary observations with the 140 Foot Telescope, high signal-to-noise observations of a large sample of face-on galaxies should significantly increase the number of known galaxies with high velocity gas. Galaxies detected to have high velocity gas can then be statistically compared and studied at high resolution with interferometers in order to help solve the riddle of high velocity gas.

The cosmic evolution of gas in galaxies will be studied through observation of redshifted radio emission and absorption lines, including high frequency observations of transitions from various molecules using the VLA and the VLBA. During the next year the results of a pilot VLBI observation of redshifted 21 cm HI absorption using Effelsberg, Westerbork, Jodrell Bank, and the 140 Foot Telescope will be analyzed, and new observations initiated to search for molecular absorption toward optically obscured quasars using the IRAM interferometer and the VLA.

HI synthesis observations give unique insight into the dynamics of spiral galaxies. Near infrared (NIR) observations indicate a likely bimodality of the distribution of the central surface brightness of stellar disks in spiral galaxies. Analyzing the HI rotation curves of these galaxies, it was found that this bimodality in stellar surface density relates to a dichotomy in the kinematics of High and Low Surface Brightness galaxies. The kinematics of high surface brightness systems are dominated by the luminous matter in the inner regions while the kinematics of low surface brightness systems are dominated by the dark matter halo at all radii. Spiral galaxies seem to avoid a situation in which the stellar disk and the dark matter halo contribute equally to the potential: stellar disks do not like to be barely self-gravitating.

To improve the statistics and to investigate whether these phenomena are characteristic of just the Ursa Major sample, a blind survey of a contiguous volume in the Perseus-Pisces ridge was performed with the VLA. The aim is to obtain an HI selected sample of galaxies, avoiding possible optical selection effects against low surface brightness galaxies. Once detected in HI, NIR surface brightness photometry of these galaxies will be obtained. The NIR and HI data will then allow further study of this bimodality.

The evolution of the HI content of galaxies will be studied as a function of redshift and environment. This study comprises several large projects involving the following extensive HI surveys: a) Westerbork HI observations of Ursa Major Cluster spirals (z=0.003)—about 60 spirals in this cluster were mapped in HI and analyzed; b) a volume limited VLA HI survey in the Perseus-Pisces ridge (z=0.017); c) VLA HI imaging of galaxies in Abell 85 (z=0.055); and d) the HI content of galaxies in the B-O cluster A1689 (z=0.182). This is the most challenging project, given that the distance to this cluster is the highest redshift at which HI can be detected in emission with current synthesis arrays, within a realistic amount of integration time.

HI observations will also be used to: determine of the column density distribution function at z=0; obtain a detailed comparison of the kinematics of the HSB-LSB galaxy pair N 2403–U 128; map HI in the extreme low surface brightness (proto?) galaxy U12695; search for new 21 cm quasar absorption line systems; and determine the faint end of the luminosity function in the Ursa Major cluster through HI identifications.

Several projects during the coming year will focus on understanding the relationship between the neutral gas distribution and kinematics and the star formation process in galaxies. One project involves an investigation of the evolution of Blue Compact Dwarf galaxies. In order to explain their compact, low-luminosity, low-metallicity nature, it has been hypothesized that these systems undergo episodic bursts of star formation, with the corresponding conclusion that they spend a fraction of their lifetime in a quiescent state. In fact, several of the popular evolutionary scenarios predict that these Blue Compact Galaxies will fade into dwarf ellipticals. However, high resolution HI kinematic studies of Blue Compact Dwarfs indicate that these are rotation dominated systems. In contrast, stellar kinematic observations of dwarf ellipticals find little to no evidence of rotational support suggesting that Blue Compact Dwarfs cannot evolve into dwarf ellipticals. To further test this result, additional studies of the gas kinematics of a small sample of Blue Compact Dwarfs which appear to be hosted by dwarf ellipticals are being initiated. These are the systems mostly likely to evolve into dwarf ellipticals after the starburst. If the gas in these Blue Compact Dwarfs and dwarf ellipticals show rotation, then it is unlikely that the starburst will ultimately result in blow-away and cessation of rotation; thus, the Blue Compact Dwarf to dwarf elliptical evolutionary scenario may be ruled out.

In a related project, UVB and Hα images of galaxies are being obtained to address the question of which physical processes induce/inhibit star formation in low mass galaxies. Previous work on low surface brightness dwarf galaxies suggests that the local gas density plays a critical role in regulating star formation since the gas density rarely crosses the gravitational instability threshold in these star formation inhibited systems. However, it is also possible that star formation is inefficient in these objects simply because massive star formation has never been induced via an interaction. To distinguish between these mechanisms, it is necessary to investigate the star formation histories and gas distributions of apparently isolated dwarf galaxies which do have efficient star formation. In conjunction with complementary HI imaging, the optical observations will be used to look for correlations between local gas density and sites of active star formation as well as to constrain the average past star formation rate history.

Studies of individual galaxies from ongoing mergers to evolved ellipticals will continue, with the aim of understanding the evolution of the gas content of systems which undergo violent encounters. In particular, we wish to understand what the expected properties of such violent encounters are, in terms of the morphological properties of the remnants, and in terms of the distribution of the gas among the various phases in the remnants (cold atomic, cold molecular, and hot x-ray).

The first question is addressed via detailed numerical models of merging galaxies, which are constrained by high-quality VLA spectral line observations of the neutral atomic hydrogen. This coming year will be used to simulate three well-known mergers: NGC 4038/9 (*The Antennae*), NGC 4676 (*The Mice*); and Arp 299. N-body simulations indicate that heavy halos cannot raise tidal tails. Model matching provides an independent test of this conclusion, since the mass of the input galaxies is not set but rather is determined by the velocity and distance scale needed to match the data. Various progenitor mass distributions (i.e., velocity curves) can be used, and the resulting best-fit scale factors will determine the resulting properties of the halos (in particular, its mass). To aid in this work, software tools to help intercompare N-body simulations and spectral line data cubes are being developed.

The latter question is addressed from various angles: VLA spectral line observations of the neutral atomic hydrogen, OVRO spectral line observations of molecular gas, HST observations of the ionized gas, and ROSAT observations of the x-ray gas. In the coming year these data will be analyzed for various types of objects, from optically and IR selected mergers, to various early-type galaxies (low-luminosity ellipticals, shell galaxies, IRAS selected early types, x-ray selected ellipticals) and covering a range of environments (isolated, in compact groups, in loose groups, in clusters). The main question we wish to address is, "Could the presence of cold gas in early types be connected with a past merging event, as has been suggested?" A related question is, "Why do some early type galaxies have cold gas, while others do not?" By observing systems that span all evolutionary stages of merging (ongoing to very evolved) and using knowledge of the dynamical evolution gained from running numerical simulations, we hope to shed considerable light on these questions.

A number of new 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.

Other research activities will include, the study of hot (x-ray) and cold (HI and CO) gaseous components of early-type galaxies, the ultraviolet (λ 1500-2500 Å), properties of galaxies and star clusters, a study of molecular gas in Local Group dwarfs, the dynamics of the Large Magellanic Cloud from a study based on observations of ~ 600 carbon stars over the central 3 kpc of the LMC, ages and abundances of ellipticals, bulges, and Baade's window, the stellar populations of the Fornax dwarf spheroidal galaxy, and the stellar component of spiral disks and the dynamical effects of bars

7. Clusters

Work will continue on the properties of radio sources in rich clusters and the evolution of radio sources with redshift inside and outside of clusters using VLA radio and optical data. Very deep radio images of six rich clusters with redshifts between 0.25 and 0.41 are being analyzed. The radio data reach galaxies with luminosities of 10^{22} W Hz^{-1} and thus sample both the FRI AGN population and the starburst driven radio galaxies. The study reaches projected radii of 2.5 Mpc and thus covers a range of galaxy densities. Optical imaging and spectroscopy for this sample will be completed during the coming year. These results are being compared with similar data for lower redshift clusters in order to determine the evolution of the radio emission and its origin. A second, similar program has just begun to study nearby clusters ($z < 0.03$) to an order of magnitude lower radio luminosity, using the NVSS to identify weak radio galaxies.

A program to analyze the relation of radio galaxies in clusters to their x-ray properties as well as to study the environments of radio galaxies not cataloged in rich clusters will be continued. Further work is planned on the Faraday rotation (and thus the magnetic environments) of several nearby clusters. Centimeter VLA observations of SCUBA submillimeter sources found behind rich clusters will be used to optically identify the origin of the submillimeter emission.

The search for proto-clusters of galaxies through the observation of their (redshifted) 21 cm emission at a frequency in the range of 305–335 MHz will continue. A dozen fields at redshifts between 3.1 and 3.7 have already been surveyed by pushing the VLA to a sensitivity of better than 0.8 mJy/synthesized-beam with spectral channels of width 100 kHz. A number of tests located sources of systematic errors (interference, pointing) and ways have been found to correct them or eliminate their effects. The achieved sensitivity corresponds to a 1σ value of about 4×10^{12} $M_{\odot}$, somewhat dependent on the values of key cosmological parameters.

New algorithms to correct for the bandpass response in the presence of intermittent strong RFI have proven necessary to properly reduce the data. These procedures have been tested with observations of the 92α-recombination line in the HII region W3 with overlapping IFs, achieving a seamless high spectral dynamic range observation. These new procedures appear to correct the systematics in the 327 MHz band. Indeed, signal-free images are free of artifacts and achieve the theoretical sensitivity across the band.

A deep study of the cluster of galaxies A2029 in HI will continue. This is one of the densest clusters in the Abell catalog and, at a redshift of 0.08, one of the most-distant ones that can be studied with the VLA. The cluster requires seven different overlapping observational settings. One-half of the data have been obtained in the summer of 1997 and have been fully reduced. The sensitivity corresponds to 10^8 $M_{\odot}$ ($1\ \sigma$). More observations will be done in this winter's C-configuration. The goal is to learn about ongoing evolution in this most-evolved cluster 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.

Optical observations of nearby (z=0.02 to 0.25) dense clusters of galaxies will continue using data obtained at the Kitt Peak National Observatory. A tessellating technique has been developed in order to produce wide-field pictures from mosaics of CCD frames with good control of the systematic errors which are kept below 5×10^{-5} of the night-sky level. The goal is to detect diffuse optical light in order to determine the evolutionary history of the clusters through the debris that their formation has left behind. Diffuse light has been detected in dense cD clusters while similarly dense non-cD clusters do not show such a diffuse component. The diffuse component appears to be stellar in nature with essentially the same broadband colors as that of the galaxies in the clusters. More clusters will be observed in order to increase the statistics. The new clusters all have good mass models derived from weak lensing events. This program is being supplemented with Hα observations of some of these clusters using the Palomar 200-inch telescope.

8. Radio Galaxies, Quasars, Active Galaxies, and Gamma Ray Bursts

VLA and VLBA observations of radio galaxies, quasars, and AGN continue to make new discoveries. Radio observations of gamma ray bursts yield estimates of the size and expansion of the relativistic blast wave or "afterglow." Monitoring of the spectra and light curves of gamma ray bursts allows one to follow the evolution of the synchrotron spectrum and thus infer the physical properties of the blast wave, including total energy and ambient density. Recent observations with the VLBA have detected the second radio afterglow from the burst of July 7, 1998, (G980703). Observations of the unusual supernova associated with G980425 are being analyzed. Upper limits on the angular size and proper motion place limits that can already be used to eliminate some theoretical models. We anticipate a continued discovery rate of about four gamma ray bursts per year in the radio. The VLBA will follow up each such event. Based on the five radio loud GRBs so far observed and the most popular fireball models, a gamma ray burst occurring at z=0.2 will be just resolvable with the VLBA, and if sufficiently bright could be a target for space VLBI using the Japanese VSOP space VLBI satellite. Work on powerful radio galaxies, includes: (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, VLA, and ROSAT, and (iv) ISO and HST observations of select sources.

Other research is taking place in a variety of fields of extragalactic astronomy. Of particular interest is spectral structure of lobes in radio galaxies and quasars, using multifrequency VLA scaled-array imaging and the "spectral tomography" technique to explore the relationships between spectral structure and features within the lobes such as hot spots, jets and filaments. The standard models of particle injection at hot spots and subsequent diffusion and aging do not account fully for the spectral index distributions seen across some of the better-observed FR II sources. It is unclear how relativistic beaming of emission in (and around) the hot spots, and the presence of filaments and of large-scale "cocoons" around radio jets influence the observed spectral characteristics. Multifrequency spectral imaging of several bright, well-resolved FRII sources will be used to study these issues. Work will also continue on (apparently) jet-related asymmetries in lobe-dominated (FRII) quasars from the 3CR Catalog and on matching the kinematics of decelerating relativistic jets to high-resolution imaging and polarimetry of FRI radio galaxies, particularly 3C31 and NGC 315. This work explores whether the observed brightness and polarization distributions are consistent in detail with simple assumptions about field and particle conservation in decelerating jets, and seeks credible constraints on the internal velocity fields of kiloparsec-scale AGN jets from high-resolution VLA continuum imaging.

A long term study of the change in radio morphology from FRII to FRI with radio and optical luminosity will be completed during the coming year along with an optical photometry program. Deep x-ray observations of extreme rotation measure radio galaxies are being used to search for large scale structures (massive cluster atmospheres) at high redshift. An extensive VLA study of will focus on the properties of the radio halo using new data at 75, 330, and 1400 MHz. Because of its proximity, VLBA observations of M87 are able to concentrate on the flow of material from the central region on unusually small linear scales. VLA and VLBA studies of the giant radio galaxies 2146+82 and NGC 315 will continue.

More than 25 compact radio sources recently have been found in NGC 253 outside the central starburst disk and will be used to estimate the supernova rate in the galaxy. NGC 253 also has been observed with the VLBA at 18 cm to estimate the sizes of its compact radio sources. Most of the sources appear to be resolved, but the analysis is not complete. The merging starburst galaxy NGC 4038/4039 (the "Antennae") has been imaged with the VLA, and a large number of compact radio sources have been detected. Several EGRET blazars are being imaged with HALCA, for comparison with their gamma ray properties and constraints set on the various models for the gamma ray emission.

VLBA and VLA observations are leading to a better understanding of the Seyfert galaxy phenomena. VLBA investigations of the gas in Seyfert nuclei through its free-free absorption show the central tori directly. New observations will attempt the first direct measurements (or limits) to the speeds of parsec-scale jets in classical Seyfert galaxies. An unbiased Seyfert sample is being imaged with the VLA to derive the distribution of radio axes with respect to host galaxy axes in Seyfert 1 and 2 galaxies. The galaxies from this sample will also be imaged at high resolution with the Hubble Space Telescope. One or more Seyfert samples will be observed with the VLBA to look for systematic differences between type 1 and type 2 Seyferts on the smallest scales. A small sample has already been observed, but that sample does not contain enough objects to make significant statistical tests.

About 100 compact sources with extremely steep spectra ($\alpha > 1.5$) were found by a comparison of the 365 MHz Texas survey catalog with the 1.4 GHz NVSS. Some of these are known pulsars, but most are not. High-resolution VLA images at 1.4 and 5 GHz show that many are compact doubles, presumably high-redshift radio galaxies. There remain about ten unresolved (< 0.15 arcsec) steep-spectrum sources of unknown type. They have no visible counterparts on the POSS, so deep near-infrared images centered on their positions will be obtained at Palomar. Those visible from Arecibo are being searched for pulsed emission.

The brightest (> 0.1 counts/sec) x-ray sources from the ROSAT All-Sky Survey, the NVSS sources and their optical counterparts will be cross-identified. Such "triple identifications" yield reliable optical identifications of x-ray sources, despite the large x-ray position uncertainties. Optical spectra for many of the galaxies and quasars brighter than B = 18 are being obtained with the Kitt Peak National Observatory 2.1 m telescope, and will be used to derive luminosity functions characterizing the local ($z < 0.2$) population of extragalactic x-ray sources and to investigate the population of distant (z ~ 1) blazars since it has a strongly bimodal radio flux-density distribution which may be inconsistent with simple beaming models.

The unique resolution of the VLBA is being used in a wide variety of studies intended to explore the nature of the central engine in quasars and AGN. VLBA observations show highly collimated beams of relativistic plasma flowing from the central engine with apparent superluminal velocities. New observations will probe the morphology of the parsec scale jets with the goal of better understanding how energy is converted into relativistic plasma and how this plasma is focused into narrow beams or jets. Particular attention will be paid to polarization monitoring in sources such as 3C 138. In M87, VLBA observations are being used to look for Faraday rotation/depolarization effect in the radio jet due to the optical emission line filaments. VLBA observations of the rotation measure structure of both typical quasars and known high rotation measure sources will help to understand the origin of the Faraday screen. So far the major contributor to the high Faraday rotation appears to come from the optical narrow-line region close to the nucleus although in one source (3C216) there is an indication of enhanced Rotation Measure in a bowshock-like feature where the jet is bent through 90 degrees.

The resolution of the VLBA is enhanced with the use of the Japanese Space VLBI satellite, HALCA, and a number of investigations are planned which exploits this opportunity. This will include detailed observations of the quasar, 1413+135 to determine proper motions of jet components. A large sample of flat-spectrum radio sources selected from the FIRST survey has been imaged with the VLBA, and long-baseline information on a subset will be acquired with HALCA over the next year.

Special attention will be paid to observations of Compact Symmetric Objects (CSOs) discovered in the Caltech-Jodrell Bank VLBI surveys. By observing them over a wide range in frequencies we can pinpoint the center of activity and study the evolution of radio galaxies. The VLBA calibrator survey is expected to double the number of known CSOs. The bidirectional motions of the jet components in NGC 1052, 1946+708 and in NGC 3894 and other sources give powerful constraints on the Hubble constant. The high incidence of redshifted HI absorption toward CSOs is intriguing and will be pursued at the VLA, VLBA, and Westerbork telescopes. Other compact sources of special interest include the nearby radio galaxy 3C 111 where there has recently been a strong outburst, and 3C 390.3 which has an interesting combination of stationary and moving components.

The VLBA is also being used study weak radio galaxies. Studies of the radio luminosity function of UGC galaxies will continue into the next year. VLA and VLBA studies of nonthermal nuclei, especially in UGC galaxies is continuing. During the coming year it is hoped to examine the radio continuum evidence for outflow and absorption in UGC08058=Mrk231, a Seyfert 1 galaxy and the brightest infrared galaxy in the local universe; survey for radio continuum sources in the inner regions of 374 UGC galaxies; and test the starburst model for the nonthermal nucleus in the Seyfert 1 galaxy UGC09249=NGC5548.

The radio galaxy NGC 1275 (3C 84) remains an important target for the VLBA. Multi wavelength imaging will continue to follow the complex motions in this unique object over a wide range of scales. VLBA images of the inner parts of 3C 84 on scales of 0.05–5 pc, show, with great clarity, a complex central core, feeding plasma southward to an expanding bubble; and an inverted spectrum northern counter-jet, obscured at longer wavelengths by free-free absorption from a putative accretion disk. Images of the core at 200 micro arcsecond resolution show knots of emission moving at 0.05 c, 0.08 c, and 0.2 c at increasing distances along the jet, indicative of acceleration within the first parsec. Moreover, progressive flux changes in these slow-moving knots indicate a wave of brightening, moving out at a phase velocity close to the velocity of light. These complex changes will be monitored in the coming year to better constrain the inclination to the line of sight, and address such questions as: Is the motion ballistic or along a helical channel? Do plasma blobs survive the sharp bends? What is the physical nature of the transition region where the jet accelerates to 0.5c? Is there a counter-jet within the core?

9. Radio Surveys, Gravitational Lensing, and Cosmology

Historically, radio surveys of the sky have detected whole new classes of previously unknown objects. Because extragalactic radio sources are so powerful they are easily observed at very high redshift, so radio observations of galaxies and quasars have made many important contributions to cosmology.

Although designed for target observations, the VLA has proven to be a remarkably powerful and flexible survey instrument, both for all sky surveys, down to moderate sensitivities as well as for deep integrations on selected fields. The NRAO VLA Sky Survey (NVSS) is now essentially complete, and only a few short observations are planned to fix noisy images. A comparison with the Chinese MI-YUN 232 MHz survey will be the basis for a new study of the turnover frequency of free-free radio emission in several hundred galaxies. A 20 cm VLA survey of a 1x3 degree area of the sky is being used to identify candidates for very high redshift radio galaxies using the radio structural properties, spectral properties from lower frequency surveys and existing deep I-band images.

Very deep VLA surveys of the Hubble Deep Field and surrounding region are now complete and are giving new insight into star formation in the early Universe, free from the effects of obscuration which plague optical and infrared studies. A new deep VLA survey which will be initiated in the coming year, will cover the AXAF Ultra Deep X-Ray Survey field as well as WIRE survey fields. The VLA images will help distinguish normal and starburst galaxies found at 12 and 25 microns from radio-loud AGN, and they will also provide accurate positions for unambiguous optical identifications. The goal of this work is to measure cosmological evolution in the star-formation rate.

Accurate radio positions are needed for a multitude of radio source studies. New observations planned for the next year will extend the Jodrell Bank VLA Astrometric Survey to negative declinations.

Many of the traditional tests of cosmological models have not been definitive due to uncertainties in evolution of the population with a cosmic epoch. Compact radio source structure may offer evolution free standards as they are located deep within individual galaxies or quasars and are not affected by the large scale environment. Measurements of the angular size-redshift dependence for compact radio sources show, for the first time the effect of space curvature, but there are uncertainties in defining the size of individual sources. A more promising test is to use the angular velocity-redshift relation for superluminal sources. Observations of a sample of 132 compact quasars and AGN begun in 1994 will continue with the aim of determining accurate motions for each source.

Further VLBI observations of the gravitational lens 0218+357, as well as other gravitational lens systems, are scheduled to continue the investigation of polarization invariance under gravitational lensing, and the high-resolution Faraday rotation distribution in the lens galaxy.

10. Instrumentation, Geodesy, and Observing Techniques

Members of the NRAO staff are pursuing a variety of new initiatives including research leading to the design of the MMA, the upgraded VLA, as well as a solar-dedicated instrument designed to perform broadband imaging spectroscopy on the Sun. The optimization of array configurations is important both for the MMA and for the design of the expanded VLA. Work in this area will receive particular attention during the next year.

The solar dedicated array is designed to fulfill a broad science program, including studies of energetic phenomena on the Sun, the structure and evolution of solar active regions, and the structure of the quiet solar atmosphere. It will also provide much needed data products to the solar forecasting and space weather communities.

Research into imaging techniques continues to occupy many of the scientific staff as there are important applications to VLA, VLBA, and MMA performance. Work during the next year will concentrate on implementation in AIPS++, especially of parallelized algorithm for wide-field imaging and mosaicing. When both array and source are in the near-field of each other, there are special problems. This is important for earth imaging from an interferometric array in space and is being investigated. Other fields of research in synthesis imaging will include low frequency observing, interference, spectral dynamic range, mosaicing dynamic range, and wide-field polarization imaging.

Good receiver sensitivity at submillimeter wavelengths will be crucial to the performance of the MMA. Research leading to the design of high frequency SIS mixers will be an important new initiative. Work will begin by first designing a broadband fix-tuned mixer design for the 600–720 GHz band which will later be used as a building block to design the more complicated balanced, sideband-separating, submillimeter SIS mixers for the MMA. In a high current density $Nb/Al_2O_3/Nb$ SIS junction, a significant part of the leakage current is carried via barrier defects (pinholes). Since the charge transport mechanism in these pinholes is multiple Andreev reflection, the current follows in multiple-charged quanta (Andreev clusters). The shot noise associated with junction leakage current is therefore much larger than for the single-electron tunneling as assumed in Tucker's Quantum mixing theory. This may explain the discrepancy between the high noise often observed in SIS mixers and the low theoretical noise calculated from theory. Following a thorough analysis of this problem, the mixer noise temperature of a 210–270 GHz fix-tuned SIS mixer will be measured at several frequencies and compared with the results obtained from mixer simulations based on theory with the modification including the multiple Andreev reflection. This study should improve our understanding on the SIS mixer noise mechanism; interest in SIS mixers for submillimeter wavelengths; advanced applications of photonics; and very wide band signal transmission on optical fiber.

Work will also continue on the development of frequency multipliers for the MMA. Various designs for doublers and triplers to 700 GHz will be developed, fabricated, and tested. Design work will also begin on the development of tunable phase-locked sources for the MMA LO. Studies of very wideband signal transmission on optical fibers will have application to both the VLA and the upgraded VLA.

Full operation of the VLBA at millimeter wavelengths will further enhance the resolution as well as allow important investigations of millimeter maser activity. Further studies to improve the efficiency, pointing, and calibration of the antennas will be a major initiative during the next year. Particular attention will be paid to methods of phase calibration techniques for the VLBA, the VLA, and the MMA. A real-time site testing interferometer at the VLA and K-band radiometry are used for monitoring of phase stability with a goal of making decisions on observing strategies for high frequency observing at the VLA.

A novel focal plane array is being developed which will greatly increase the operating efficiency of the GBT. Further development is planned for the theory of full-sampling array feeds including application to the third generation prototype receiver and possible use of the technique to correct astigmatism on the Mark I Jodrell Bank telescope. An array feed design tool and analysis tasks are being written for the AIPS++ system. In order to decrease the noise temperature of the focal-plane array to below 50 K, a special low-noise element will be designed that will integrate the antenna and the low-noise amplifier into one unit. The existing array will be retrofitted with 19 such elements and then evaluated on the 140 Foot Telescope in early 1999.

Increasing levels of man-made interference threaten the future of radio astronomy. Work will continue on an adaptive interference canceling receiver. The current single reference channel prototype will be upgraded to four reference channels so that the spatial polarization of interference signals can be used in the cancellation process. A series of field tests will commence later this year with a goal of testing on the 140 Foot Telescope in early 1999.

Research will begin on developing an octave-bandwidth balanced amplifier using InP HFETs for use in an experiment to search for axions. This amplifier will also be important for the VLA Upgrade project.

APPENDIX B - SCIENTIFIC STAFF

(Does not include visiting appointments)

D. S. Balser — Galactic structure and abundances; HII regions; planetary nebulae.

P. J. Barnes — ISM; chemistry; star formation; molecular clouds; radiative transfer; galactic structure and dynamics; planets and asteroids.

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 of extragalactic radio sources; planetary nebulae; supernovae remnants.

G. Black — Planetary radar; VLBI radar; Saturn's rings; icy outer solar system moons.

J. Braatz — Galaxies; interacting galaxies.

R. Bradley — Millimeter electronics; low-noise amplifiers; array receivers; adaptive RFI excision.

A. H. Bridle — Extragalactic radio sources.

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

B. J. Butler — Planetary astronomy at radio wavelengths.

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

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 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; mm VLBI observations; mm instrumentation; history of mm research.

C. Fassnacht — Gravitational lensing; active galactic nuclei; groups of galaxies.

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.

J. Gallimore — Active galactic nuclei; accretion disks.

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.

E. J. Hardy — Cosmology; galaxies; stellar populations.

T. Helfer — Extragalactic and galactic molecular astronomy; star formation; millimeter interferometry.

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.

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.

L. D. Matthews — Structure and evolution of galaxies; extreme late-type spirals.

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 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.

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

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

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

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

M. Thornley — Starburst galaxies, galactic structure; flocculent galaxies.

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 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. Williams — Galactic star formation; mm interferometry; molecular clouds.

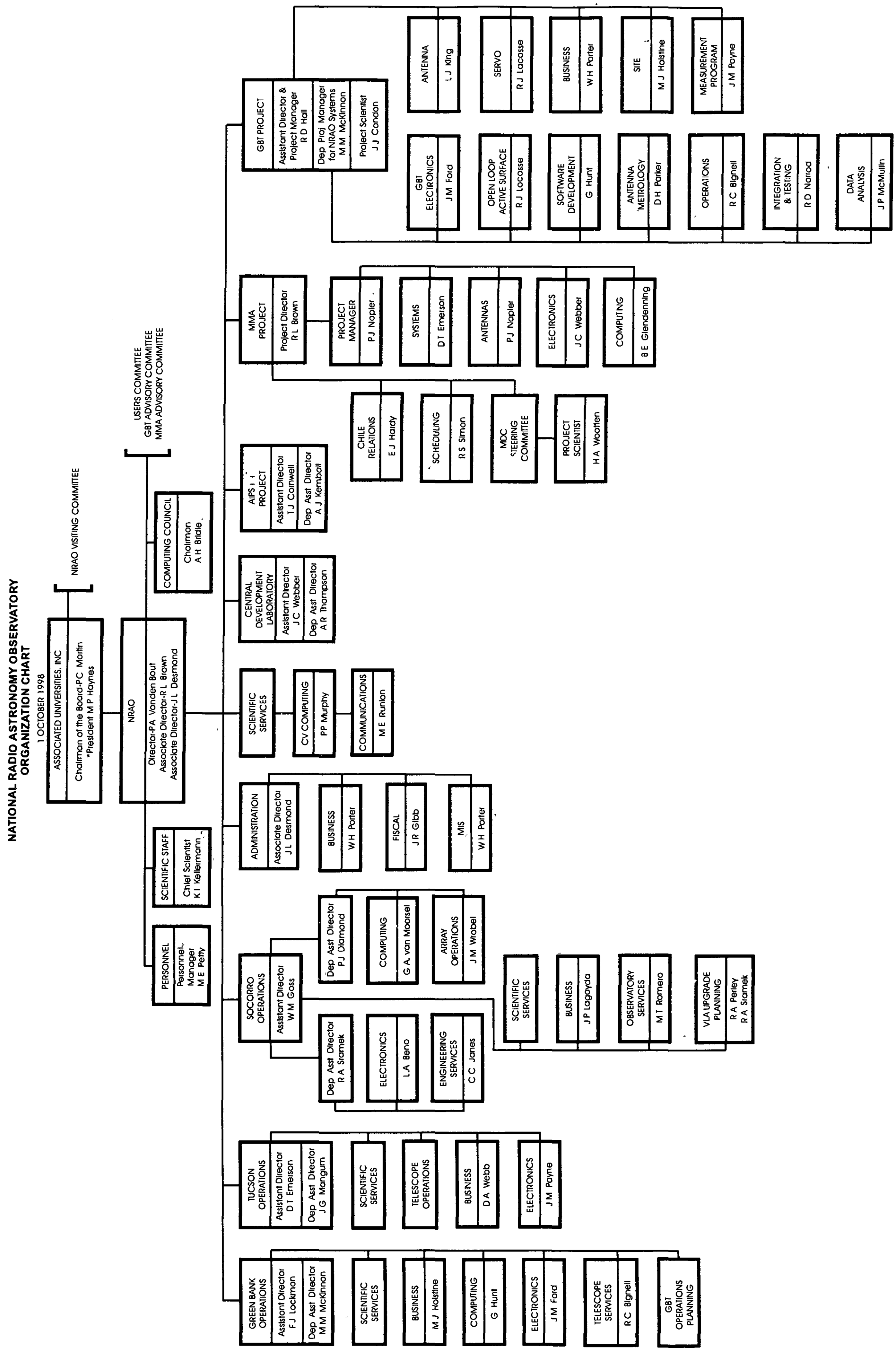
A. H. Wootten — Star formation; structure and chemistry of the ISM in galaxies; circumstellar material.

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

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

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

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
D. B. Campbell	Cornell University	Term Expires 1999
J. E. Carlstrom	University of Chicago	Term Expires 2000
R. Hanisch	Space Telescope Science Institute	Term Expires 1999
R. B. Partridge	Haverford College	Term Expires 2002
M. J. Reid	Center for Astrophysics	Term Expires 1998
L. F. Rodriguez	Instituto de Astronomia UNAM	Term Expires 1998
J. Turner	University of California, Los Angeles	Term Expires 2002

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
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. J. Greenhill	Center for Astrophysics
C. E. Heiles	University of California, Berkeley
L. A. Higgs	Dominion Radio Astrophysical Observatory

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

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

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
P. Goldsmith	Cornell University, NAIC
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

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