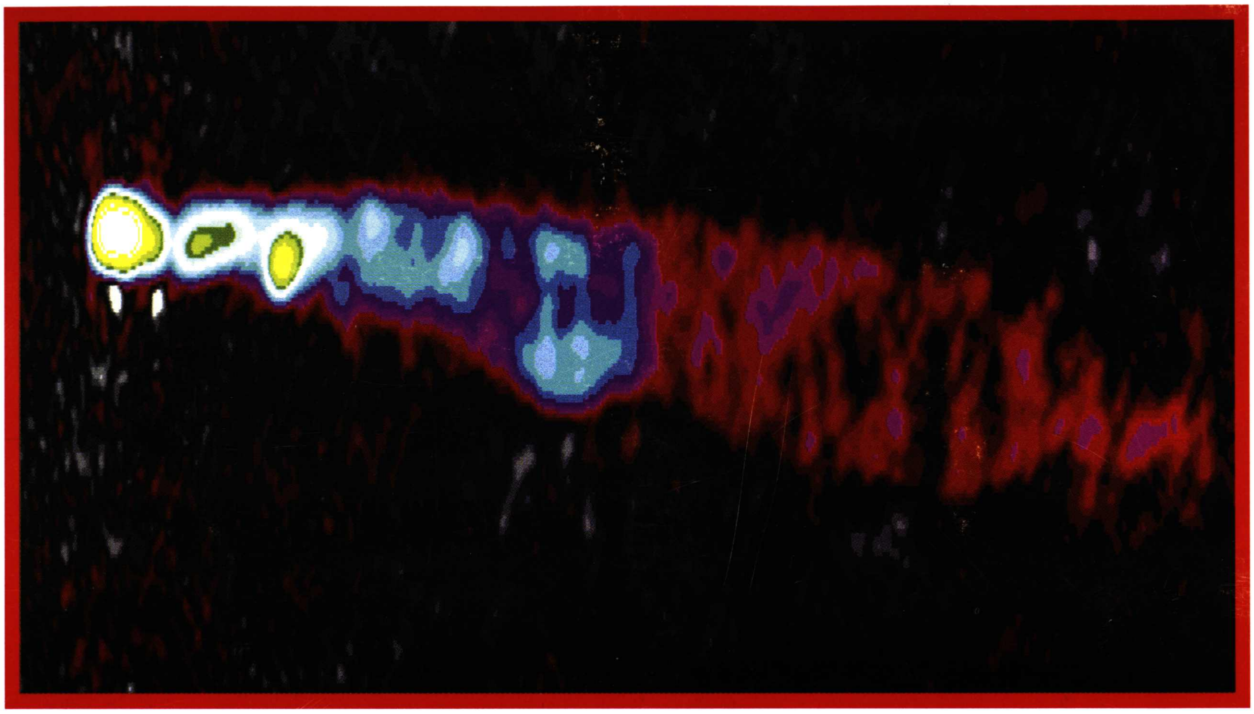

PROGRAM PLAN
1996

NRAO

NATIONAL RADIO ASTRONOMY OBSERVATORY

Front of card: VLBA image of the radio jet at the center of the galaxy 3C120. Even at the great distance of this galaxy, 400 million light years from the Earth, the great resolving power of the VLBA makes it possible to image details as small as 1.5 light-years in size within the jet structure which is itself 100 light-years long. "Time-lapse" images made over several years show the jet to be moving outward at an apparent speed faster than the speed of light. Observers: R.C. Walker and J.M. Benson

NATIONAL RADIO ASTRONOMY OBSERVATORY

CALENDAR YEAR 1996

PROVISIONAL PROGRAM PLAN

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I. INTRODUCTION

In 1996 astronomers using the NRAO telescopes will advance their research with observations achieving unprecedented angular resolution, recorded bandwidth, mapping speed, and spectral sensitivity. The high angular resolution will come from use of the VLBA together with the Japanese spacecraft, VSOP, a radio telescope that will observe while in orbit at several earth radii. The new level in recorded bandwidth will come from full implementation of the VLBA capability to record data at a sustained rate of 128 Mbits per second and with burst capacities of 256 and 512 Mbits per second. The latter rate is more than 100 times greater than that provided by a home VCR recorder using what is, in essence, the same tape recording technology. The mapping speed and spectral sensitivity both result from the powerful on-the-fly capability at the 12 Meter Telescope combined with a broader band IF that permits spectra of 1 GHz bandwidth to be analyzed in two polarizations simultaneously. With the new technical capabilities will come exciting new science as noted in the pages of this NRAO Preliminary Program Plan.

The image on the cover of this document illustrates the power of the new instruments to facilitate new discoveries. The image is a VLBA image of the radio galaxy 3C120. A jet of relativistic particles is ejected from a supermassive black hole in the central region of the galaxy and those particles generate radio emission as they proceed outward. With this VLBA image we can see enough spatial detail with enough clarity that the trajectory of the relativistic stream of particles can be reliably traced and that information used to infer the nature and physics of the black hole ejection process. High fidelity images such as this answer questions.

The overall plan of the NRAO in 1996 is to build on the capabilities of the instruments and provide an opportunity for the next discoveries to be made. In Section II a brief overview is given of the science we expect to see done on the NRAO instruments in 1996. The telescopes themselves are described in Section III. The section following describes the plans for new instrumentation and the scientific motivation for those plans. Sections V and VI are devoted to the future instruments: The former describes progress on the construction of the Green Bank Telescope (GBT) and the latter reviews the development work on-going for the Millimeter Array, work planned for the VLA, and work on the AIPS++ Project. Section VII describes the scope of research at the NRAO that is done in behalf of, and supported by, agencies other than the NSF. The next section is an overview of educational activities at the Observatory. Finally, the preliminary financial plan for the NRAO in 1996, designed to support all the NSF research activities, is given in Section IX.

II. 1996 SCIENTIFIC PROGRAM

1. The Very Large Array

As a mature and versatile instrument, the VLA continues to produce valuable data for an extremely broad range of studies. The user community innovatively builds upon success to expand the VLA's capability to contribute to new lines of investigation. Demand for VLA observing time remains double the time available. As astronomy becomes an increasingly multiwavelength enterprise, numerous VLA observations are coordinated with other ground and space-based observatories to maximize the scientific productivity of each.

In an early follow-on to the NVSS (NRAO VLA Sky Survey), a large radio galaxy discovered by the survey will be studied in detail by observations with different VLA configurations. This unusual galaxy shows evidence of misaligned outbursts, suggesting that the ejection axis varied between outbursts at different epochs. The FIRST (Faint Images of the Radio Sky at Twenty centimeters) survey was scheduled for its second major set of observations during the 1995 B-configuration. Image production will continue in 1996. Images from the FIRST survey also are being made available on the Internet as soon as they are completed. The FIRST project is designed to produce detailed maps of at least 5,000 square degrees of sky, to coincide with much of the area covered by the Sloan Digital Sky Survey at optical wavelengths. As both surveys produce more data and completed images through 1996, the value of this effort to the scientific community will grow.

The VLA will again serve as a resource for the planetary science community in 1996, following a year which saw the instrument used for such varied planetary work as radar investigations of Titan and observation of thermal emissions from the moon. Bistatic radar work in collaboration with the NASA Solar System Radar transmitter at Goldstone, California, will include observations of Titan and Mercury. The Titan observations will seek to provide more information about a previously detected radar-bright region, which also appears bright in reflected one micron emission detected by the Hubble Space Telescope. Radar observations of Mercury will continue to investigate the probable detection of water ice at the planet's north pole. The impacts of fragments of Comet Shoemaker-Levy 9 in 1994 caused a dramatic outburst in Jupiter's magnetospheric synchrotron radiation; VLA observations will continue to monitor the evolution of this phenomenon. Stellar research at the VLA begins with observations of the sun. Coordinated observations at several wavelengths have become a hallmark of recent solar research. The VLA will be used in a campaign including ground-based spectral instruments and orbiting X-ray observatories to study the processes that occur when emerging magnetic flux reconnects with pre-existing magnetic fields in the chromosphere and corona above evolving active regions.

A number of binary star systems will come under the scrutiny of the VLA. Millimeter-wave observations of circumstellar CO around a spectroscopic binary at the center of a region called the Red Rectangle have led to a model that the binary system has a gravitationally bound disk with some dust particles larger than 200 μm. VLA observations will seek to test this model. An active binary consisting of solar-type stars locked in tidal synchronism will be observed in conjunction with the Extreme Ultraviolet Explorer (EUVE) satellite to detect flares more visible in the radio, to establish relationships between the thermal component of the corona and the non-thermal component, and to relate the coronal emission to starspot activity. Another binary flare star will be observed in conjunction with EUVE to determine the quiescent and flaring coronal conditions as seen in the thermal EUV emission and the nonthermal radio emission. A recent model of flaring in active binaries that invokes episodic injection of non-thermal electrons into a coronal magnetic loop will be tested by multifrequency VLA observations to determine the evolution of the radio spectrum during flares. An unusual Wolf-Rayet (W-R) system will be observed simultaneously with the VLA and the Advanced Satellite for Cosmology and Astrophysics (ASCA) satellite to test a hypothesis that the system consists of a neutron star accreting in an equatorial W-R wind.

A high-resolution VLA 7 mm survey of T Tauri stars will be conducted along with surveys at the Owens Valley Radio Observatory (OVRO) millimeter array and the Hale 5 meter telescope to gain information on the radial temperature and density profiles of circumstellar disks. In addition, it is hoped the survey will yield data about the properties of the dust. T Tauri binaries in nearby star-forming regions will be studied, also at 7 mm, in an attempt to learn what effects the binary companions have on circumstellar-disk structures. The information on disk evolution in binary environments should shed light on how binary companions may influence the frequency of occurrence of planetary systems.

A recently discovered magnetic cataclysmic variable which has an extremely long period for an orbitally locked binary will be observed to search for radio emission, flares, and eclipses. Detection of flares would support a suggestion that, in this system, the white dwarf's companion has a magnetic field strong enough to maintain orbital synchronism. A group of rapidly rotating, X-ray luminous F to M dwarf stars in the Pleiades will be observed in an attempt to make a preliminary determination of the mass dependence of the radio luminosity of coeval solar-type stars.

A number of VLA observers will probe star-forming regions, young stellar objects, and protostellar and circumstellar disks. Protostellar disks in HII regions will be observed with the VLA, seeking to correlate the radio objects with objects observed by the Hubble Space Telescope (HST). The VLA 7 mm system will be used to resolve and hopefully image disks around a number of protostars and very young stars. Other VLA studies of star-forming regions will seek to gain new information about stellar winds, photo-evaporating disks, the nature of ionized gas in such regions, shocks, molecular outflows, velocity fields, and maser activity.

An unusual planetary nebula that exhibits an extended bipolar halo with opposite hot spots surrounding its core will be observed to test the hypothesis that a collimated jet could be responsible for its activity.

Pulsars have received much attention at the VLA in the past, and planned observing will continue this tradition. The Crab pulsar will again be the target of VLA studies, including observations of its high-frequency polarization properties to investigate the nature of as-yet unexplainable frequency dependent behavior above 1.4 GHz. The VLA also will be used in conjunction with the X-ray Timing Explorer spacecraft to search for X-ray fluctuations that correlate with the Crab's giant radio pulses. A long-term VLA program of timing fast pulsars not observable by the Arecibo telescope will continue, yielding information about orbital companions (including a pulsar in a triple system), binary-pulsar orbital decays, and accurate neutron star masses. The millisecond pulsar B1937+214 will be observed to search for pulses similar to the Crab's giant pulses. An unusual head-tail source in the galactic plane will be observed to determine if it is galactic or extragalactic. If galactic, it may be a young neutron star leaving the galactic plane at high velocity, creating a structure similar to that observed near several young pulsars.

Supernovae studies at the VLA have proved to be an extremely productive contributor to the understanding of supernova progenitors and the nature of their circumstellar environments. The VLA has been very successful in producing multi-frequency radio light curves of newly discovered supernovae over the past few years, and that target-of-opportunity program will continue. In addition, several known radio supernovae will continue to be observed to complete their light curves. The high-quality radio light curves will help lead to an understanding of the mass loss in the progenitor stars and the nature of those stars. Several peculiar supernovae that were previously not detected at radio wavelengths will be re-observed, since other peculiar supernovae with similar optical spectra were detected in the radio and investigators seek to determine the cause of the earlier non-detections. The VLA will be used in an attempt to detect intermediate age supernovae in nearby galaxies. Such objects, it is hoped, can yield information on the poorly understood evolution of supernovae into supernova remnants.

Supernova remnants will be both observed and sought in planned VLA programs. New observations of a clump of hot gas beyond the main shock front of the Vela SNR will seek to reveal more about the physical structure of the knot, about its magnetic field, and its radio spectrum. A follow-up to an earlier study of galactic SNR candidates will seek to determine if some of these may indeed be previously undiscovered galactic SNRs. The galaxy M31, which has more than 220 SNR candidates, will be observed at 90 cm to provide information on radio flux, spectral index, and morphology for this population, which has largely not been observed at wavelengths other than 20 cm.

The shocks of SNRs are thought to provide the energy required to accelerate particles to cosmic ray velocities. VLA observations at 74 MHz, corresponding to electron energies associated with the process of particle injection into shocked regions, will seek to probe the acceleration process in SNRs and test the models. In the Milky Way, a VLA study will focus on the threads at the galactic center in an effort aimed to learn their latitudinal extent, their intrinsic polarization angles, and details of any substructure that may be present.

The study of external galaxies has long been a major part of the research effort at the VLA. The VLA is able to serve investigators interested in a wide variety of phenomena associated with galaxies of many types. Coordinated observations with the VLA and ROSAT will monitor radio and X-ray emissions from the nucleus of M31. The nuclear radio source in M31 is variable, and anticorrelation of radio and X-ray fluxes could provide evidence of a massive black hole in the nucleus of M31. M31 also will be observed to measure Faraday rotation to test for the presence of a halo of ionized gas and to reveal the structure of the halo's magnetic field. A study of small, linear-scale star formation in nearby flocculent galaxies seeks to examine star formation in the absence of strong density-wave processing. Radio recombination line studies of galaxy nuclear regions will provide information on the nature of ionized gas in the nucleus, the expected Hα flux and optical extinction to the nucleus, and the nuclear velocity field of starburst galaxies. The nucleus of M82 will be studied to obtain high-resolution spectral-index maps aimed at resolving a number of outstanding questions. Following up on Hα detection of spectacular filaments of ionized gas connecting the disk and halo of NGC 2188 and earlier HI observations showing peculiar gas motions and supershell expansion in its halo, new VLA observations attempt to test models of disk-halo interactions.

Observations of HI continue to serve as a powerful tool for studying the structure and dynamics of galaxies. One study will involve mapping the HI velocity field of bulgeless, edge-on spirals which, along with Hα rotation curves, will allow a determination to be made of the fraction of mass in dark matter haloes that may be in the form of brown dwarfs. Other HI studies will include: determining the kinematics of galactic star forming regions; mapping a nearby W-R starburst galaxy and its peculiar polar orbiting HI disk or ring; HI mapping of a nearby, quiescent irregular galaxy; and a study of the distribution, kinematics, and velocity dispersions of small clouds in a dwarf irregular galaxy to try to learn about the relationship of the atomic ISM to star formation and how these interact to determine the evolution of dwarf galaxies.

Radio galaxies are, of course, prime targets for the VLA. Detailed mapping of the ends of the tails of Faranoff-Riley Type I (FRI) sources will help distinguish between alternative models for the flow in such objects. Observations of other FRI jets at high resolution and sensitivity will seek to provide direct observational information on variations in the radio spectrum and polarization and thus on the ranges and distributions of velocities in the jets. Other radio galaxy studies will address questions such as the location and nature of the medium causing depolarization across lobes; the relationship between optical and IR polarization morphologies and radio morphologies; and, in a joint VLA-HST study, the high-resolution correlation between radio and optical components for sources exhibiting the optical-radio alignment effect. A sample of radio galaxies showing characteristics of both FRI and FRII sources will be examined to further investigate the traditional division of radio sources.

A variety of interacting galaxies will be studied. A multifrequency continuum and HI line study of an interacting pair will seek to determine the past pattern of star formation in the pair and relate it to dynamical effects of the interaction and structure in the interstellar medium (ISM). A pair of interacting ring galaxies will be studied to determine the kinematics, constrain models of the interaction, and examine the relationship between the HI and CO in the system. Observations of a quasar (0959+6827) near the M81-M82-NGC 3077 group of galaxies has raised the possibility that HI absorption may be detectable due to gas associated with the galaxies. If so, this will provide a unique opportunity to probe the nature of highly extended gas in interacting galaxy systems.

Polarimetric observations of radio galaxies in an Abell cluster will seek to provide information on the intracluster magnetic fields, and thus of the poorly understood intracluster medium. Another set of observations will look at a pair of high redshift clusters which show the highest known fractions of blue galaxies (Butcher-Oemler effect). This study will seek to find out if, as seen in other clusters, there is an excess of radio galaxies in clusters of higher redshift and to determine if such an excess is a function of richness or cosmological epoch.

Active galaxies will be the objects of a number of VLA observational programs. A sub-parsec-scale molecular disk recently was discovered at the nucleus of the unusual galaxy NGC 4258 by VLBA observations of H_2O masers. Ongoing VLA observations will seek to characterize the magnetic field of this disk and to monitor the intensity and velocity drift of the maser features, to coordinate with VLBA observations aimed at detecting proper motions in the masers. A newly detected H_2O megamaser in IC 1481 will be studied to determine if it is arising from a similar structure to that in NGC 4258.

Starburst activity will be studied in several galaxies. VLA observations of M82 will be combined with MERLIN data to image extended supernova remnants and to determine spectral indices. Nuclear starburst clusters will be observed to identify supernova remnants and HII regions as part of a program aimed at gaining understanding of young stellar clusters and their role in the evolution of galactic nuclei. A sample of mildly active galaxies showing evidence of nuclear radio rings and spirals will be examined to help constrain models of star formation in the nuclear region. Both the VLA at its highest resolution and HST will be used to study the jet of 3C 273. This study seeks to compare radio and optical morphology and resolve major questions about the basic particle acceleration mechanism in jets. A study of a powerful, intermediate-redshift radio galaxy will examine the radio morphology and polarization characteristics to learn about the interactions between the radio plasma and the ISM.

The VLA remains a valuable tool for testing models of active galactic nucleu (AGN). A search for near-nuclear thermal radiation sources in AGNs will seek to test the hypothesis that some of their optical/UV sources are extended on ~100 pc scales. A search for remnant hotspots in a radio quiet quasar will help determine if radio quiet quasars with the most massive black holes were radio-loud in the past. The VLA will be used to make multi-configuration, multi-frequency maps of a sample of both high and low-luminosity quasars also selected for detailed imaging by the HST. The VLA observations in this survey will seek to test the scope of jet-IGM interactions and to gain spectral index maps of the sources. Other studies of AGNs include observations of a Seyfert galaxy to gain information on the fueling mechanism for the nucleus; deep, multi-spatial-scale observations of other Seyferts; and an HST-VLA study of a low-redshift quasar showing evidence of an ongoing tidal encounter with a nearby galaxy.

Survey follow-on observations will be a basic element of research in cosmology at the VLA in 1996. The NVSS already has revealed several categories of objects that will be the targets of additional observation. These observing programs include polarization observations of sources within and behind Abell clusters for a study of the clusters' magnetic fields; high resolution observations of discrete, highly polarized sources; and observations of a sample of large angular size sources selected from early NVSS maps.

Additional survey work will include target sources such as point source contaminants in the OVRO microwave background fields; a pair of HST-VLA surveys of 3CR radio galaxies; an evolutionary study of radio quasars and their environments in the redshift range $z = 0.5$-3; a detailed polarization study of radio galaxies and quasars; and very deep mapping of the areas of a ROSAT survey to determine if there is a correlation between the cosmic soft X-ray background and the presence of sub-millijansky radio sources.

Finally, a number of studies will investigate gravitational lenses. Some of these studies will look in detail at individual lenses, while others will seek to identify new lenses. Lens observations are aimed at probing the properties of the lensing objects, learning about the distribution of clumpy mass in the universe, and, hopefully, aiding in the determination of the Hubble constant.

2. The Very Long Baseline Array

In 1995, the impressive capabilities of the VLBA were widely demonstrated to the scientific community. The instrument consistently produced high-quality images with great resolution and dynamic range, and a steady stream of scientific results came from it. In 1996 we expect that the additional capabilities of the instrument will enable further discoveries to be made.

One well publicized highlight was the VLBA discovery of a warped disk of water masers at the center of NGC 4258 – a disk with a radius of only 0.25 pc, but showing rotational velocities up to 1,000 km/s. Measured rotational velocities in this disk showed Keplerian motion around a central object of nearly 4×10^7 solar masses, and the small volume in which this mass must reside provides compelling evidence that the object is an extragalactic black hole. This success has led to planned observations in which VLBA observers will seek to use H_2O masers to probe the inner regions of other galaxies, including an early-type galaxy containing the most distant known water masers and the only elliptical galaxy known to have water masers.

Target-of-opportunity observations during an outburst of the Galactic X-ray nova GRO J1655-40 revealed a pair of radio jets with apparent superluminal velocities. With the angular resolution and image fidelity of the VLBA, complex motions in these jets were detectable, leading to a model consistent with later optical spectroscopy that showed an eclipsing binary system with a 4.0-5.2 solar-mass black hole. This system, at a distance of only about 3 kpc, now becomes a prime target for multi-wavelength studies aimed at deciphering the physics of accretion disk-jet interactions.

Science with the VLBA also includes participation in the NASA Space Geodesy Program. Geodetic observations with the VLBA are aimed at three major goals: improvement of the techniques of geodetic VLBI, determination of the Terrestrial Reference Frame, and determinations of the positions and structures of radio sources to improve the celestial reference frame. VLBA geodetic experiments also seek to characterize the degree of stability and rigidity of the North American tectonic plate and to improve knowledge of the probabilities and mechanisms of intraplate seismic activity.

Other investigators will use the VLBA to make astrometric observations of compact extragalactic sources in a continuing program to establish an all-sky radio/optical reference frame. Astrometric observations of a quasar pair will seek to characterize their structures and establish how stationary one of the cores remains. Researchers who have made astrometric VLBI observations of a number of radio stars for a decade will use the VLBA to try to determine astrometrically if a Jupiter-sized planet is orbiting the nearest star in their program.

In order to serve both the VLBA and the wider VLBI community, a survey program will continue to produce a list of phase-reference calibrator sources. In producing this list, the survey also will directly impact research in areas such as gravitational lensing and cosmology.

The angular resolution and frequency coverage of the VLBA allow valuable work to be done on stars and stellar systems. Ongoing studies of SiO masers in circumstellar shells will continue, focusing on the changing structure of these emission shells and, through proper-motion measurements, allowing distance determinations. A set of circumstellar OH maser shells with peculiar spectra also will be studied.

Observations of a magnetic cataclysmic variable star known to be the source of radio flares will seek to constrain the morphology and evolution of the radio emission region. Monitoring of a set of RS CVn binary stars will examine the changes in their flux, morphology, and polarizations over a complete orbital period. Other studies will investigate R Aquarii, the nearest symbiotic star, which has a precessing jet; a mapping in all four Stokes parameters of a weak lined, possibly binary, T Tauri star; and a pilot study to investigate the most radio-bright of the nearby dMe stars in an attempt to measure the size and determine the shape of the radio coronae.

The VLBA will continue to make regular observations of supernova 1993J in M81, an effort that is expected to yield a wealth of information about this object whose distance, and hence luminosity, is well-known. Already, the VLBA maps show expanding, shell-like radio structures. Future work will be directed at tracing the dynamical evolution of the supernova, investigating deceleration due to the circumstellar ISM, obtaining the first spectral index maps of a young supernova, monitoring a variety of phenomena expected to be observed as the supernova shell expands, and making a time-lapse study, a movie, of the expanding debris of the exploded star. As a target of opportunity, the galactic superluminal source GRS 1915+105, should it undergo a suitable outburst, will be observed with the purpose of using its expanding bright ejecta as a probe of structure in the intervening galactic HI. By measuring the variation in HI opacity along the rapidly changing line of sight to the bright ejecta, the ISM structure on 10-100 AU scales may be mapped.

While radial velocities have been measured previously for OH/IR stars near the Galactic center, the VLBA will be used to observe some of these stars that have circumstellar SiO and H_2O masers. The resolving power of the VLBA is expected to allow measurement of transverse velocities in some of these high-velocity objects. If successful, such measurements will provide valuable information on the mass distribution and gravitational potential of the Galactic center. Observations of sources near the Galactic anticenter are designed to map the distribution and strength of interstellar scattering and thus test models for the distribution of ionized gas in the Galaxy. HI absorption measurements toward pulsars and extragalactic sources will yield information about variations at AU scales of the neutral ISM. Other Galactic observations will include a project directed at imaging a protostellar molecular outflow at unprecedented resolution and study of SiO masers believed to reside in a disk around a very young star in the Orion K-L star-forming region.

As expected, the astronomical community will use the VLBA to investigate other galaxies in a number of ways. By looking at galaxy/quasar pairs, observers will seek to use the quasar's radiation to probe ionized gas in the galaxy by measuring angular broadening. The sub-parsec radio source in Centaurus A will be observed by VLBI for the first time at 22 GHz, both for comparison to images at longer wavelengths and to plan for future space VLBI observations at that frequency. Polarimetric observations of Virgo A strive to clarify the nature of structures in the jet, test unification schemes for FRI radio galaxies and BL Lac objects, constrain jet production models, and yield information about the nuclear accretion disk. A pair of FRI radio galaxies will be observed to detect proper motion in their nuclear regions, and a polarization study of another FRI will seek to aid in comparison of jets at parsec scales with those of FRIIs. A radio galaxy suspected of ejecting radio components about every four years will be observed in an attempt to confirm the suspicion; if true it would suggest the presence of a binary system as the source of the ejecta.

A large number of VLBA studies will probe the nature of cosmic jets from radio galaxies and quasars. These studies will provide information on structures, the magnetic field, spectral energy, and evolution of jets, and serve to test models of jets and of unification schemes for radio galaxies and quasars. The phenomenon of helical jets will be studied with the resolution provided by the VLBA. Several of these investigations include observations by other radio observatories as well as by the ROSAT and ASCA satellites. Observations should provide considerable new information on a variety of jets at parsec scales.

Quasars and AGNs will account for a large amount of VLBA observing time. Investigations of these objects fall into two general categories: those that will observe and compare multiple sources and those that will concentrate on single sources.

Surveys and studies of multiple sources will seek to answer a number of important questions, such as, why do lobes of radio emission extend far outside the optical galaxy in some active galaxies and not in others; how do jets form and evolve in active nuclei; do active nuclei lie at the heart of ultraluminous IR galaxies; are there structural differences in the cores of BL Lac objects and flat-spectrum radio galaxies that might be accounted for by different viewing angles; and are X-ray BL Lacs a possible transition population intermediate in viewing angle between highly beamed radio BL Lacs and unbeamed FRI radio galaxies? A comparison of 3C 273 and BL Lac will search for similarities and differences in the physical processes in their parsec-scale jets. An extended study of a sample of very active BL Lac objects will provide detailed information about their cores as they give birth to new components and about the evolution of shock components as they propagate outward. Hotspots in FRII galaxies will be mapped to test models of jet flow, obtain jet and IGM parameters, and to select sources for further study. A number of sources will be observed to map the 7 mm linearly polarized emission and to search for intra-day polarization variability. Observations of a sample of weak and strong-lined blazers will seek to clarify questions about the division between BL Lacs and quasars. A multi-epoch survey of superluminal sources will investigate the kinematics of quasars and AGNs on small linear scales and explore their use as a measure of cosmological models.

The compact extragalactic source 3C 84 served as the target for the VLBA's "first science" continuum image. That 1994 effort revealed the unexpected presence of a counterjet. The counterjet has been found to be hidden at low frequencies by free-free absorbing gas in a disk or torus. Planned additional VLBA studies on this object, with the counterjet providing back-lighting, thus will offer unique insight into the physics of an accretion region in an AGN on sub-parsec scales. Other AGNs to come under investigation by VLBA observers include: an optically violent variable source with both stationary and superluminal jet components, apparent superluminal motion in the core and a bent jet; a lobe-dominated quasar that is the first of its type to display acceleration and non-radial motion of parsec-scale jet components; a strong, compact, radio-loud quasar that has properties characteristic of both quasars and BL Lac objects; a flat-spectrum quasar that has undergone a dramatic radio flare; and the unusual radio morphology of the well-known quasar 3C 48.

Cosmological researchers will use the VLBA in attempts to refine the Hubble Constant through gravitational-lens studies. The VLBA will be used to search candidate lens systems identified by other instruments to distinguish the true lenses. In addition, known lens systems will be monitored for the variability that is required to obtain a distance estimate. In a particular system, if the mass model for the lensing object is accurate, measurement of time delay in variability among components of the lens can yield a distance estimate independent of other parameters, and thus help calibrate the Hubble Constant. The VLBA's resolution, fixed configuration, and full-time availability make it an ideal instrument for this work.

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 year with the advent of the new on-the-fly (OTF) observing mode. This is a highly efficient observing technique that can be used in either spectral line or continuum modes. This technique is made possible by a marriage of the powerful and flexible on-line computer systems and the high-sensitivity receivers at the 12 Meter. OTF observing can be used with any of the single-beam, dual-polarization receivers and will be available for use with the 8-feed, 230 GHz receiver in the autumn of 1995. 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. In the present observing term about 20 percent of all observing programs specifically request the technique and we expect the demand to grow even more. OTF mapping targets include a variety of Galactic and extragalactic sources. For example, one group will study CO (1-0) emission in the nearby barred spiral NGC 253 with the aim of determining how the structure and kinematics of the molecular gas relates to the bar of the galaxy. Since the OTF technique can be used with any of the receiver systems, another group will image CO (2-1) emission in the large, nearby galaxy IC 342. The intent of this study is to determine why there is little star formation in the bar of the galaxy despite large concentrations of molecular material there. Other OTF mapping programs will focus on regions of our own Galaxy. For example, one program will image the ring nebulae around Wolf-Rayet stars to study the nature of mass loss from these rapidly evolving objects.

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. About 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 an aluminum isotope in the envelope of an evolved star. This study will constrain some specific predictions of theories of nucleosynthesis. By studying interstellar sulfur isotopes, another program will address specific predictions of nucleosynthesis theories. Further programs will study the details of interstellar chemistry such as grain surface reactions and the chemistry of translucent clouds. Translucent clouds are the simplest category of interstellar cloud to support complex chemistry; hence, they are good astrophysical laboratories.

Research on external galaxies continues to be 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 search for CO emission in a complete sample of low-z powerful radio galaxies detected by IRAS. This program will test the theory that the radio sources are triggered by gas-rich galaxy mergers. Another group will seek to complete a comprehensive survey of spiral galaxies with the intent of defining the molecular content of normal spirals as has been previously done for HI in these objects. Other upcoming programs focus on the properties of specific prototypes for general classes of galaxies such as early-type galaxies or barred spirals. The power of the on-the-fly imaging technique will be particularly useful for these studies.

A number of programs will use the new polarimeter at the 12 Meter. This instrument is available for use with the 3 mm receiver and can measure both linear and circular polarization. Astronomers are using this device to search for Zeeman splitting in selected molecular lines. The results will be used to measure the strength of the magnetic fields in these clouds, a critical parameter of the star formation process. Other projects will use the polarimeter to measure linear polarization in SiO maser emission and to measure the polarized component of dust emission in protostellar dust cores.

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 a essential baseline for most experiments and the sensitivity of the 12 Meter makes it critical to the success of many VLBI experiments. The 12 Meter is now linked to the Kitt Peak VLBA station by fiber optics and makes use of the VLBA maser time and frequency standard and the VLBA data recorders. With a global network, millimeter-wave VLBI can achieve resolutions of 50 micro-arcseconds. In the coming year the 12 Meter will participate in several VLBI sessions that will seek to image the cores of distant quasars and active galactic nuclei, study the structure of 86 GHz SiO maser emission about evolved stars, and measure details of the millimeter-wave emission from our own Galactic Center.

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

4. The 140 Foot Telescope

In 1995 the 140 Foot Telescope celebrated its 30th anniversary of astronomical observations. In 1996 visiting astronomers will use the telescope for a variety of projects in the frequency range 327 MHz to 35 GHz, for single-dish spectroscopy, pulsar studies, measurements of source continuum fluxes, and as an element of various VLBI arrays.

Pulsar observations continue to be a mainstay of the 140 Foot. With the good sensitivity of the latest generation of HFET receivers and the upgraded spectral processor, pulsar observations will be made at frequencies up to 3 GHz. Observations at such relatively high frequencies may reveal a class of flat-spectrum pulsars. Regular timing of selected pulsars will be done by several groups in search of variations in pulsar periods that might signify the presence of pulsar companions, and also to measure relativistic effects in binary systems. Observations of a large group of pulsars distributed around the sky are establishing a timing array that can be used for many fundamental studies, from measuring the masses of the outer planets to detecting gravitational radiation. Studies of individual pulsars will yield information on the still enigmatic pulsar emission mechanism. Temporal and spectral fluctuations in pulse intensities probe the structure of the interstellar medium on extremely small angular scales.

Several large projects to measure the HI redshift and properties of galaxies will be done in 1996. One survey targets a specific galaxy type, dwarf irregulars, with the intent of deriving a sample with highly accurate redshifts. Another survey will measure galaxies that have very extended HI envelopes to determine total HI fluxes for comparison with the fluxes derived from VLA maps. Still another survey will examine a set of elliptical galaxies that have shell-like structures in their optical images to see if there is any associated HI. Several large galaxies will be mapped in HI to provide zero-spacing data that complement VLA maps. Studies of redshifted HI will also be made, taking advantage of the near-continuous frequency coverage of the 140 Foot below 1.4 GHz. There will be a search for HI in absorption against bright radio sources in an attempt to understand how the presence of neutral gas affects the evolution of radio jets.

At the upper end of the 140 Foot's frequency range there will be several searches for extremely redshifted emission from molecules like CO and O2. This is a very active field of study that takes advantage of the telescope's state-of-the-art receivers and its broad-band spectrometer. The early findings indicate that some galaxies have substantial amounts of molecular gas at redshifts >3. The telescope will also be used for searches for H_2O masers in the nuclei of nearby galaxies. By monitoring the H_2O spectra and their change with time, the evolution of gas in nuclear disks can be studied, and objects can be identified that look particularly promising for observations with the VLBA.

Interstellar chemistry in our own Galaxy will be the topic of several observing programs in 1996. A number of interesting molecular species have transitions in the 8 - 22 GHz range, within the capabilities of the new GBT receivers on the 140 Foot. Projects will include a search for several new species and studies of abundances of molecules and their correlation with other tracers of interstellar gas. High latitude, translucent molecular clouds continue to be of special interest because recent studies have suggested that the CH lines at 3.3 GHz may be more suited than the traditional CO lines at tracing the lowest density molecular clouds. The 18 cm OH main lines have proved to be an interesting tracer of cool interstellar clouds that are not predominantly molecular. Further experiments to determine the extent of the OH molecule in atomic clouds will be made in 1996. The H_2O masers in the Rho Oph star-forming region will be monitored to study this phase in the evolution of young stellar objects.

There is a continuing demand for observation of the Galactic 21 cm line of HI. Some studies will use the line as a probe of the interstellar magnetic field through measurement of the Zeeman effect. These challenging experiments provides unique information about the poorly-understood galactic magnetic field. Other HI observations will be made in an attempt to understand the origin of the soft X-ray emission by mapping HI clouds that appear in absorption against the X-ray background. Several HI clouds will be mapped to provide zero-spacing data and total fluxes to VLA maps.

The effects of the impact of comet Schoemaker-Levy on the planet Jupiter will continue to be monitored at 1.4 GHz on the 140 Foot Telescope. A search for the radio counterparts to gamma-ray bursters will also continue. About 20 percent of the time will be spent on VLBI observations. With the newly installed VLBA back end, the 140 Foot can now be operated for VLBI as if it were a part of the VLBA. This allows observations to be made more easily and uniformly while taking advantage of the added sensitivity of the telescope as part of the array.

III. USER FACILITIES

1. Very Large Array

Present Status

More than 600 scientists used the VLA for their research work in 1995, and a similar or larger number will do so in 1996. Demand for the VLA arises both from the multi-wavelength nature of contemporary astronomical research and from the flexibility of the telescope. With regard to the former, it is now widely recognized that radio observations provide unique insight into a variety of astronomical objects that may be used to complement the information gained with telescopes operating at visible, infrared, gamma-ray, or x-ray wavelengths. Radio observations also may be the focus of research with complementary data provided from observations at other wavelengths. For either case, the fact that the angular resolution and field of view of the VLA is nearly identical or better than that achievable with modern detectors at other wavelengths means that all the data can be merged with no ambiguity. This is the capability astronomers need for their research.

Present Instrumentation

The VLA consists of twenty-seven, 25 meter antennas arranged in a wye configuration, with nine antennas on each 13 mile arm of the wye. The antennas are transportable along double rail track and may be positioned at any of 72 possible stations. In practice, the antennas are rotated among four standard configurations which provide a maximum baseline along each arm of 0.59, 1.95, 6.39, and 21.0 km. 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] Eight antennas equipped; T_{sys} includes galactic background
[2] Thirteen antennas equipped by end of 1995.

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 Preliminary 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 wide band 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. Three more 45 GHz receivers are under construction and will be installed before the winter observing season of 1995. A retrofit will also be started in 1996 to replace the first stage amplifiers in the older 45 GHz receivers with amplifiers being developed at the CDL using the new HFET InP devices. The zenith system temperature at 7 mm should be reduced from 95 K to 70 K with this change.

Design and prototyping has begun for the next generation of wide bandwidth VLA receivers. The most challenging task is the design of a circular polarizer with a bandwidth ratio of 1.5:1. This will be needed if a single receiver is to operate from 18 to 26.5 GHz or 12 to 18 GHz as proposed for the VLA upgrade. Design of this polarizer is currently underway at NRAO. The goal is to install a prototype wideband receiver on the VLA in 1996 for testing.

Modifications are being made to the 21 cm local oscillator system to reduce radio frequency interference introduced as intermodulation products. This retrofit should be completed by the end of 1996.

VLA — Repair and Maintenance

The maintenance of the VLA infrastructure continues at a high level but with a slowly changing emphasis. The long-term projects of rail maintenance and manhole replacement continue, and a new major program of antenna painting is gaining momentum.

Rail system maintenance continues as a routine but highly important task. In 1996 at least 24 spur lines will be realigned and six intersections will be rebuilt. The rail system will also be surveyed with new markers installed. Also in 1996 a large mainline leveling program and more extensive tie replacement is planned.

The aging of the VLA is clearly seen in the rust and staining on a large number of the VLA antennas. A program for painting the VLA antennas was initiated in 1993 to attack these problems before mechanical deterioration set in. In 1994 four antennas were completely repainted and four more had their quadrupods recoated. A similar amount of work should be done in 1995 and subsequent years. This work is performed by a four-man NRAO summer crew. It will take at least five years to address the current problem, and after that, antenna painting will become a regular maintenance item.

In 1991, the azimuth bearing in VLA antenna 21 failed, putting the antenna out of service for almost a year. Monitoring of the metal content of the bearing grease and the vertical play of the azimuth bearings shows 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. There are five other antennas that will need bearing replacements in the near future. The next bearing change will be done in 1996.

The program to replace the VLA waveguide manholes with steel culverts is progressing. The existing concrete manholes are deteriorating and collapsing. By the end of 1994, 35 manholes had been rebuilt out of a total of 122. Fourteen more culverts will be installed in 1995. A similar number should be installed in 1996. This replacement program is keeping ahead of the deterioration, and will run to completion in several more years.

Much of the VLA outdoor maintenance is done during the summer months with 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. Ten temporary summer employees were hired in 1995 which allowed us to augment the regular rail, manhole, and paint crews. A larger number of temporary workers will be needed in 1996.

2. Very Long Baseline Array

Status

The VLBA is now in routine operation and is performing astronomical observing approximately 50 percent of the time. The ramp up to this level of operation has been steady and we expect it to continue at a fairly even pace. The correlator is now operating robustly and producing prodigious amounts of high quality data. Most modes of observing are now being used, some of the more advanced (such as high density recording and pulsar observations) will become available in the future.

Present Instrumentation

The VLBA is a dedicated instrument for very long baseline interferometry. The ten antennas are distributed about the United States in a configuration designed to optimize the distribution of baseline lengths and orientations (uv coverage). Baselines between 200 and 8000 km are covered, which provides resolutions up to 0.2 milliarcseconds at 43 GHz. The shorter baselines, and hence the highest concentration of antennas, are near the VLA for optimal joint observations and to allow for a future project to fill the gap in the range of baselines covered by the two instruments. The antennas are 25 meters in diameter and of an advanced design that allows good performance at 43 GHz and useful performance at 86 GHz. The antennas are designed for remote operation from the AOC. Local intervention is only required for changing tapes, for maintenance, and for fixing problems.

The VLBA is outfitted for observations in nine frequency bands as shown in Table III. All receivers are dual polarization. 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 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

‡System equivalent flux density
* with 13/4cm dichroic

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

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

The correlator is now in routine operation for most types of data. It can handle the full complement of 20 stations for the majority of types of continuum and spectral line observations, including full polarization data. The core of the correlator real-time code was re-written in late 1994/early 1995 in order to improve its reliability. The improved robustness has been evident in the smoothness of correlator operations since the software upgrade.

VLBA postprocessing is done in the astronomical image processing system (AIPS). Software development for VLBI in AIPS is essentially complete apart from support for some advanced capabilities of the array such as phase referencing. Much work has been done to make the AIPS VLBI sub-system more robust and user-friendly. Astrometric/geodetic processing will be done primarily in the system developed by the Crustal Dynamics Project, now Dynamics of Solid Earth (DOSE), at NASA. The in-house computing for the VLBA is done mainly on workstations of the SUN IPX and IBM RS/6000-560 and RS/6000-580 classes.

Future Plans

There are several major milestones to be achieved in the near future.

(a) The major task facing the VLBA is developing the ability to handle Space VLBI data once the Japanese VSOP satellite is launched (late 1996). NRAO has committed up to 30 percent of the science time of the VLBA to co-observing with VSOP and other ground antennas and has also committed to correlating this data on the VLBA correlator. Our major goal is to ensure that the VLBA correlator is capable of processing such data. We should have full Space VLBI capability early in 1996.

(b) The VLBA correlator already handles much greater quantities of data than previous VLBI correlators. In order to achieve maximum efficiency we must ensure that the handling of VLBI data is as automated as possible at all stages of the process, from the schedule generation, the tracking of the data tapes, the generation of correlator control scripts, to the correlation, generation of distribution data and quality control over the final data product. Our plan envisages a coherent software suite to govern all stages of this procedure. Some pieces are currently in place and others will be developed over the next few years.

(c) The VLBA data recording system was designed to run at a sustained rate of 128 Mbps. This nominal rate was to include spectral line observations which typically run at rates much lower than that as well as continuum observations made at even greater rates. In particular, we should be supporting 256 Mbps routinely and offering the ability to run two recorders simultaneously and record 512 Mbps for those observations that need it (e.g., 7 mm continuum projects). Unfortunately high density recording (i.e., 256 Mbps) is not yet available on the VLBA. We have recently conducted a successful test and our goal is to provide this ability to our users in the near future.

(d) As shown in Table III, the VLBA is equipped at nine frequency bands. Work is in progress to add a tenth, at 86 GHz. The VLBA antennas are designed to work at such high frequencies and the scientific benefits from observing at 86 GHz will be tremendous. We shall be able to extend the highly successful 43 GHz SiO maser observations to another transition of SiO and be able to investigate the physics of these interesting objects. The resolution available at 86 GHz will be ~90 microarcseconds. This will be of great benefit to astronomers studying the nuclei of AGNs. We hope to fully equip the VLBA at this frequency over the next few years.

Scheduling and Observing

Astronomical observing on the VLBA consists of Global Network projects during the Network sessions and VLBA projects at other times. Global Network observing amounts to about three weeks every three months and is expected to continue into the future. Projects that need more baselines than the VLBA can provide, or that need to use large antennas for sensitivity, will continue to use the Network. Most Network projects use the VLBA, the 140 Foot Telescope, the VLA, and antennas of the European VLBI Network (EVN). Arecibo, NASA's Deep Space Network, and antennas in places such as South Africa, Brazil, Japan, Australia, and China are occasionally used. NRAO, along with the EVN, administers the proposal submission and, along with the Europeans, assesses the Network projects, thus allowing a uniformity with VLA and VLBA projects.

3. 12 Meter Telescope

The NRAO 12 Meter Telescope began as the 36 Foot Telescope, the telescope responsible for the birth of millimeter-wavelength molecular astronomy. Following a period of explosive growth in this new area of astronomical research, during which most of the dozens of molecular species known to exist in the interstellar medium were first detected at the 36 Foot, the telescope's reflecting surface and surface support structure were replaced and the 36 Foot was re-christened in 1984 as the 12 Meter. Subsequently, the scientific program has evolved from one dominated by observing programs in astrochemistry to one with a broader mix of studies of molecular clouds and galactic star formation, evolved stars, astrochemistry, and external galaxies. The 12 Meter is the only millimeter-wavelength telescope in the U.S. operated full-time as a national facility. More than 150 visitors make use of the telescope annually. It offers users flexibility and the opportunity to respond quickly to new scientific developments. Low-noise receiving systems at a wide range of frequencies, currently covering all atmospheric windows from 68 GHz to 300 GHz, are maintained. Operational reliability throughout is emphasized. Flexible spectral line and continuum backends allow the observer to match the instrument to the scientific goals. The development of multi-beam receivers and the new 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
	48% at 115 GHz
	32% at 230 GHz
	23% 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 minutes. The receivers are configured remotely from the control room with a computer-aided tuning system.

Receivers

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

Table III.3. 12 Meter Receiver List

Frequency Range (GHz)	Mixer	SSB Receiver Temperature (K) Per Polarization Channel	Notes
68 - 116	SIS	60 - 90	
130 - 170	SIS	120	
200 - 260	SIS	200 - 400	1
260 - 300	SIS	400 - 500	
Eight-beam Receiver:			
220 - 250	8-SIS	200	2

Notes:

1. Receiver noise is around 200 K single sideband for most of the band, increasing somewhat at the high frequency limit.
2. The 8-feed Schottky system has been upgraded to an SIS system. The system will be released to observers in late 1995.

Note: All single-beam receivers have two orthogonal polarization channels. Receiver temperatures include all receiver optics.

Spectrometers

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

Table III.4. 12 Meter Filter Bank List

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

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

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

- 8 independent, tunable IF sections;
- 1536 spectral channels (can be split into 8 sections);
- maximum total bandwidth options:

  1 x 2400 MHz

  2 x 1200 MHz

  4 x 600 MHz

  8 x 300 MHz
- frequency resolution (per channel): variable in steps of two continuously between 1.56 MHz and 24 kHz for each of two IF channels.

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

Future Instrumentation Plans

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

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

One-Millimeter Imaging SIS System

Millimeter-wave telescopes inevitably have small beams, and hence, with the usual single-beam system, true imaging of large fields is particularly difficult and time-consuming. For large-scale imaging, the smaller diameter of the 12 Meter Telescope compared, e.g., with the IRAM 30 meter telescope in Spain, is no disadvantage. We plan to provide a powerful imaging system at our optimum wavelength of 1.3 mm.

To this end, the 8-feed Schottky mixer system was made available during the 1989-1990 season. The system was a great success, in spite of compromises in the implementation. (The hybrid spectrometer was not yet operating with the full versatility of its original design, and the telescope control system at that time severely restricted the convenience and efficiency of the system.) The 12 Meter Telescope now operates under a completely new control system using modern hardware, and we will finish the planned implementation of the hybrid spectrometer by the end of 1994.

The 8-feed Schottky system has been upgraded to use SIS mixers, thereby giving state of the art sensitivity in all feeds. This upgraded system should become available to observers late in 1995. The key to future development is the backend electronics. We are cooperating with the Green Bank Telescope correlator group to make use of the same printed circuit cards and chips as are being developed for that project for a multi-feed digital auto-correlator spectrometer for the 12 Meter Telescope. As a prototype development for a spectrometer to support multiple beams, we plan first to build a new 8-i.f. spectrometer. This will immediately give the 12 Meter 8-feed, 230 GHz extra capability. The current hybrid spectrometer is limited to 300 MHz instantaneous bandwidth per beam, when supporting the 8-feed system. For extragalactic work this total bandwidth is inadequate. The new prototype system will support 1.2 GHz instantaneous bandwidth simultaneously on 8 i.f. channels, a substantial improvement on our existing capability. All multi-feed systems put severe demands on the computer hardware and software. The telescope real-time control system has been completely replaced with a modern design which offers great flexibility for future developments. Already, remote observing, controlling the 12 Meter telescope over a wide-area network has been demonstrated, and is expected to become a more common mode of operation in the next few years. Recently we have concentrated on improving the observing efficiency of the telescope and on developing and implementing new observing techniques. The data acquisition rate will have increased by between 1 and 2 orders of magnitude. The postprocessing environment is becoming a network of modern workstations. We have begun to build this network with existing funds, but a great deal of new computer hardware and software development will be required in the next three to four years.

A New 8-Feed SIS System for 3 mm

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

Future Single-Beam Systems

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

Antenna Improvements

With the improved surface accuracy, operation of the 12 Meter Telescope at the highest frequencies (~300 GHz) is becoming more productive. This puts a more critical demand on the pointing characteristics of the telescope. In order to improve the pointing, we have implemented several upgrades in the past year. We are also installing an improved real-time monitoring system for movements of the prime focus, utilizing a laser and x-y translation detector. We have reevaluated feedleg insulation and are installing blowers to circulate air through the interior of the feed legs. 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.

Polarimeter

We have constructed a polarimeter for the 12 Meter Telescope, which will be used to study linearly and circularly polarized emission in both the broad-band continuum and the spectral-line mode. This device became available in mid-1994. The design uses an adjustable grid and plane reflector combination, is quite compact, and will become a prototype design able to give similar capability to the MMA. A future project is to construct a version for a wavelength of 1 mm.

Telescope Control, Data Acquisition, and Data Analysis Improvements

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

On-the-Fly Observing

The new on-the-fly observing mode has now become the preferred mapping mode. With this technique, the observer makes several rapid passes over the field of interest, recording data continuously.

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

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

Longer Term Future Plans

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

4. 140 Foot Telescope

The 140 Foot Telescope will be maintained as a user facility until the GBT comes into operation in 1997, but major changes in its instrumentation will be made only if they aid in the development of the GBT. The telescope is in good shape mechanically, and both short-term and long-term maintenance procedures are being followed.

The GBT receivers now mounted at the Cassegrain focus will remain on the 140 Foot during 1996. They have greater bandwidth, stability, and sensitivity than the previous receivers, and also need less maintenance. Critical parameters are monitored using the GBT monitor and control software and are logged to disk. These receivers have proved quite popular with users.

A VLBA back end was installed in May of 1995 and has been used for all subsequent VLBI network observations. This system is fully compatible with the VLBA, making the 140 Foot capable of operating as an element in the VLBA array. This system will eventually be moved to the GBT for its VLBI observations. By 1996 the spectral processor will be running solely under GBT software, and observers at the 140 Foot will point the telescope and acquire pulsar data using code that is identical to that which will be used on the GBT. The upgrade of the spectral processor was completed with the recent purchase of a more powerful control workstation. The new computer makes the spectral processor more efficient for pulsar searches.

A timing center has been constructed for distribution of precise time and frequency around the Observatory. The primary frequency standard is a Sigma-Tau hydrogen maser located in a clock room in the Interferometer building. The signals are distributed on optical fiber cables installed in buried conduit. A one Hertz tick is now available at the 140 Foot and is used primarily for back-end hardware synchronization and clocking of data. By early 1996 the 5 MHz distribution system will be complete to the telescope and a round-trip measurement system will be installed to calibrate propagation delays. The timing center serves all the telescopes at Green Bank as well as equipment in the Jansky Lab.

The 140 Foot will continue to be used as a test bed for GBT development during 1996. We have run successful experiments with GBT software controlling the receivers, the antenna servo system, and the GBT's new digital continuum backend. In 1996 we will be developing and installing further GBT hardware including the GBT IF distribution system, and all three local oscillator stages. Data from the timing center and the GBT weather station will be integrated with astronomical data. These devices will run under GBT monitor and control software allowing an end-to-end test of the GBT systems in the environment of a working telescope. AIPS++ will be used as the data reduction package for these tests. Selected users will be asked to make their 140 Foot observations in a complete GBT environment, from telescope control to data processing. This should give 140 Foot users a few new capabilities, but the purpose is primarily to develop and debug the GBT components and to gain operational experience with them.

IV. TECHNOLOGY DEVELOPMENT

1. Electronics Development Equipment

Cooled HFET Amplifier Development

Centimeter-wave radio astronomy receivers (< 50 GHz) now almost universally use cooled HFET (heterostructure field-effect transistor) amplifiers as the low-noise input amplifier. NRAO has worked on the development of these amplifiers for many years and is largely responsible for their wide acceptance by the radio astronomy community. HFET amplifiers are reliable, stable and can be made up to an octave in bandwidth without significant penalty in noise.

A recent program has been started to develop HFET amplifiers in the 60-115 GHz frequency range. We have demonstrated them to be able to approach performance comparable with the noise performance of SIS mixers. Their comparatively low cost, high reliability and ability to operate at a temperature of 15 K instead of the necessary 4 K for SIS mixers may make them the preferred receiver for arrays up to 115 GHz (VLBA and Millimeter Array).

Since HFET's are not commercially available, NRAO contracted with Hughes Research Laboratory to manufacture two wafers of indium phosphide (InP) HFET's similar in performance to devices that were evaluated by NRAO during 1993-1994. These devices were delivered at the end of 1994 and have been successfully used in amplifiers between 18 and 50 GHz. Significantly improved performance has been obtained from these amplifiers. A development program to use these devices to 115 GHz is under way, the first objective being to produce amplifiers covering 60-90 GHz for a prototype 3 mm receiver for the VLBA.

Millimeter-Wave Receiver Development

The design and fabrication of Superconductor-Insulator-Superconductor (SIS) mixers covering the frequency range 68-300 GHz are done by the CDL in collaboration with the Semiconductor Device Laboratory at the University of Virginia. These mixers are used on the 12 Meter Telescope, and several have been supplied to other observatories.

In addition to supporting receivers on the 12 Meter Telescope, the CDL is working on two new designs: (a) A fixed-tuned mixer of a completely new design, initially for 200-300 GHz with very low IF output capacitance, enabling it to operate with a multi-octave IF bandwidth. (b) A fully integrated image separation mixer on a chip, also for 200-300 GHz initially. This will prevent atmospheric noise in the image band from degrading the system noise temperature during spectral line observations, and is expected to improve the sensitivity of spectral line observations by at least 30 percent. Both these projects are of direct relevance to the planned Millimeter Array.

Other Development Projects

The CDL is also responsible for developing and supplying specialized millimeter-wave components which are not commercially available, such as electro-formed scalar feed horns, LO couplers and vacuum windows. The CDL's high precision machine shop and plating/electroforming laboratory primarily support the millimeter-wave work, but also provide a service to the whole of NRAO.

Other millimeter-wave projects include several frequency multiplier projects in conjunction with the University of Virginia and the University of Michigan.

During 1996, the construction of the GBT spectrometer will be completed at the CDL. This instrument will analyze as many as eight bands, each of which may have a bandwidth of 800 MHz or it may analyze separately each of the thirty-two 50 MHz baseband amplifiers of the GBT. A total of 262,144 correlator lag channels will be provided.

Other projects include the development of broadband low-frequency receiving systems for array use.

2. Computing

The revolution occurring in computing hardware provides an unprecedented opportunity to leverage the current state of the art for computing into major scientific advances and new capabilities. Comparatively small investments in new hardware should significantly improve NRAO's ability to support current facilities as well as new facilities coming on line over the next few years.

There have been major advances in imaging algorithms over the past year. Significant new scientific results using advances such as robust weighting and various improvements in AIPS will appear this year. For example, ultrahigh dynamic range observations using advanced algorithms are now possible with the VLBA, and should start to have a scientific impact during the coming year.

The Japanese VLBI satellite mission, VSOP (scheduled for launch in September 1996), will be completely dependent on NRAO software for key steps in data reduction, especially for fringe finding and calibration.

The new NRAO scheduling program will provide a major advance in the planning of VLBI experiments. Initially developed for the complex scheduling situation faced by the VLBA, it will have an impact on the way Space VLBI observations are scheduled, and on the scheduling of VLA observations, and it may also influence other current and future arrays around the world (e.g., the MMA).

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

In 1996, with the rapidly advancing observational capabilities of the VLBA (including the start of orbiting VLBI), and with the promise of GBT operations starting in 1997, it will be a prudent time to enhance certain critical areas of the NRAO's computing facilities and infrastructure. The rapid improvements in computing technology over the past few years give the NRAO an opportunity to upgrade current facilities to meet pressing needs and meet the demands of new scientific opportunities, at comparatively modest costs.

Maintaining observational and scientific capability remains the fundamental goal of computing at NRAO. Implicit in this goal is the necessity of constant striving to keep ahead of computing demands at NRAO. Computing systems and software should not be the limiting factor in the science which users are able to accomplish with NRAO facilities. As observational requirements on computing increase, driven by improved observational methods, new technological capabilities, and deepening scientific understanding and knowledge, the Observatory must respond.

For 1996, the following areas are priorities for computing facilities, equipment and support.

System Upgrades

During 1996, approximately one-third of the workstations at NRAO should be upgraded to more capable systems. These machines were purchased in 1991 and earlier, and are now showing their limitations. Their upgrading or replacement is required by the increasing demands on computational capability at NRAO from both increased demands from NRAO users and increased observational capabilities brought about by technological advances and improved observational techniques. These upgrades will allow most workstations at NRAO to be replaced or upgraded by the end of their useful lives (typically 3-4 years for scientific workstations). These upgrades are now especially urgent, in view of the

VLBA's operational status, and the newly developed mapping capabilities at the 12 Meter Telescope. The upgrades will accomplish three goals:

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

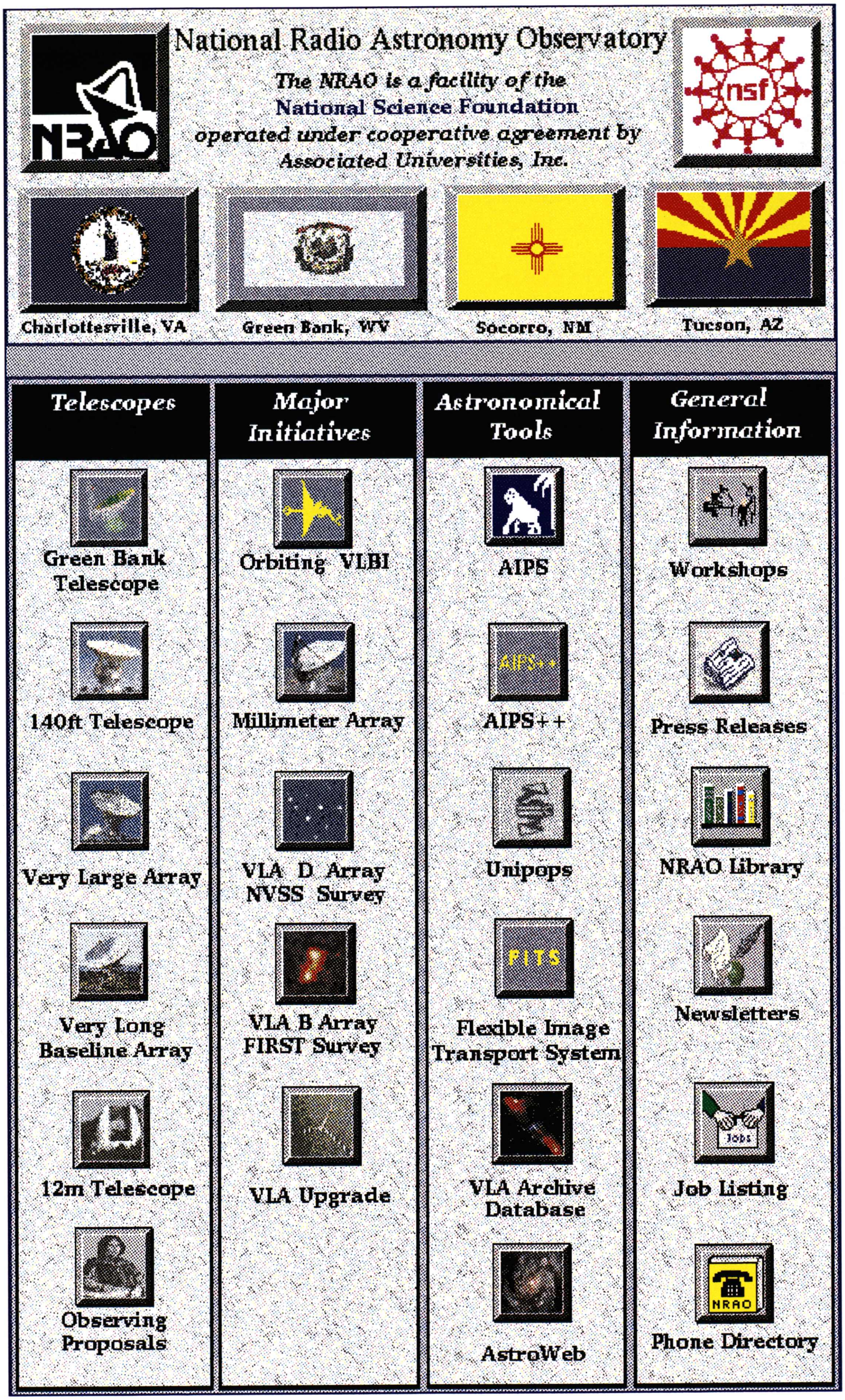
With the resources expected during 1996, the focus will remain on the first goal above. Resolving the infrastructure and high-end computing problems can be deferred, but the overall return on the investment in NRAO facilities and instruments will be reduced.

Networking and Networking Upgrades

At each of its major sites, NRAO operates a complex networked computing environment. This offers numerous advantages for efficiency and flexibility in meeting the needs of computer users at NRAO, and allows a small support staff to support a large number of workstations. The tightly networked computing systems at NRAO are an ideal environment that enables the Observatory to provide significant support to its 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 World Wide Web is http://www.nrao.edu/). Users can access online documentation, download software, peruse recent NRAO preprints, newsletters, and technical memos, or download available images from the ongoing VLA sky survey projects, the NRAO VLA Sky Survey (NVSS), and the Faint Images of the Radio Sky at Twenty-centimeters survey (FIRST). The figure on the following page is from NRAO's home page on the World Wide Web, and introduces many of the on-line facilities available.

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.

The specific goal for 1996, funding permitting, is to begin upgrading the networks at the sites to provide improved bandwidth to critical workstations and groups of workstations. This process should be accomplished in time for major new observational capabilities and opportunities at NRAO associated with



This figure has been extracted from the NRAO's home page on the World Wide Web, **http://www.nrao.edu/**.

the GBT and OVLBI, as well as the VLBA and the 12 Meter. A related goal is to provide high speed links between NRAO sites, and between NRAO and external institutions. Current network connections only allow limited access for remote observers; the pioneering efforts at the 12 Meter to provide support for remote observers should be enhanced and expanded to provide such capabilities for remote observer access for NRAO's other instruments.

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 (GBT) project, the proposed Millimeter Array (MMA), and the proposed VLA upgrade. These projects are heavily dependent on the use of advanced engineering workstations to carry out various aspects of their design and fabrication, even at an early stage. Presently, many engineers at NRAO are faced with carrying out design efforts using obsolete or inadequate workstations and PC's. Rectifying this situation will increase the productivity of NRAO's engineers, and the effectiveness of NRAO's operations over the long term. Although efforts in this area have been planned in past years, the budget situation forced these plans to be deferred. Estimated cost of this effort during 1996 will be approximately $160,000. This will allow both the acquisition of appropriate workstations and required software.

VLA On-line System Upgrade

The current VLA On-line Control System is nearing the end of its useful lifetime. The computers and disks used in the system are nearly ten years old, and represent a growing maintenance problem. Some of the disk systems are completely obsolete, and can be maintained only by having a large number such ancient disks for spares (support and repair from the manufacturer is no longer available). This situation can be rectified before any disastrous failures occur by continuing the effort begun in 1995 to upgrade and replace the aging systems with modern systems. The effort will yield several benefits, including a large reduction in risk of major system failures, a modest reduction in downtime for the VLA, and lay the preliminary ground work for any upgrades to the VLA which may occur later in the 1990's. The effort will cost approximately $150,000 during 1996.

Mass Data Storage

A hallmark of radio astronomy is the large volume of data which must be managed, stored and reduced. Three efforts will stretch the capabilities of NRAO's computer facilities for dealing with extreme data volumes. First, results are beginning to appear from two large-scale surveys being conducted with the VLA. To provide broad access by the astronomical community to these results, NRAO will make them available on-line, via the Internet. Although NRAO may not be the only such source for these data, NRAO is certainly the only institution with a long-term interest in maintaining access to these surveys. Depending on how rapidly results from the surveys become available, several ten's of gigabytes will be needed during 1996. Eventually, as these surveys are completed, versions will be made available through other distribution media (such as CD-ROM).

Second, new techniques and capabilities at existing NRAO instruments (such as mosaicking with the VLA, on-the-fly imaging at the 12 Meter, or the GBT spectrometer) are increasing the amount of data which must be handled by off-line data reduction systems. 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.

Finally, and most importantly, the VLBA has become operational during 1995. Previous estimates were that the VLBA would place approximately the same load on data reduction facilities at NRAO as the VLA; experience shows that this was an underestimate by perhaps an order of magnitude. A VLBA-only observation of a single source in continuum may be greater than 1 gigabyte in size, for example. Substantial improvements in data storage and tape facilities at the AOC will be needed during 1996 to meet the expected demand.

3. Operating Equipment

Funding for Operating Equipment provides for the replacement, upgrading, and acquisition of equipment, including maintenance and shop equipment, office and library equipment, vehicles, living quarters furnishings, and building equipment. Funding for personal computers and items of other major office equipment has been substantially reduced.

As in previous years, the NRAO has supplemented its funds for Operating Equipment by acquiring property under the Government surplus program. During 1995, we obtained approximately $350,000 in surplus equipment, including multi-fuel engines, truck tire changer and mounter, and shelter buildings.

Although this program has been a tremendous benefit to NRAO, we cannot depend on this source for equipment when planning future needs. The equipment is only available on a first-come, first serve basis.

The 1996 funding requirements are estimated at $500,000, which includes replacement telephone systems, two high-rail pickups and a bobcat for the VLA, machinery and office equipment, and additional memory for the administrative computing system. However, based on the presidential budget, we expect to be able to commit only $100,000 to this area in 1996.

V. THE GREEN BANK TELESCOPE

Antenna Construction

Since the submission of the 1995 Program Plan, significant progress has occurred in the growth of the Green Bank Telescope antenna structure. As may be seen by a comparison of the photograph included in last year's Program Plan with the photo included here, much headway has been made surrounding the elevation bearing and shaft installation.

During April 1995, all welding was completed on the elevation shaft on the ground. The bearing housings were set in place atop the alidade towers, some 165 feet above ground level. The housings were accurately leveled and positioned to receive the two segments of the 150 foot long shaft. Axle support cradles were placed midway between the alidade towers on the temporary support tower which had been erected earlier. The elevation shaft was raised in two lifts during the first week of May. Each segment weighed slightly over 100 tons. When the shaft was placed, the two sections were pulled together and precisely aligned using a complex jacking arrangement, thus preparing for the final weld. The inward movement of the alidade support towers provided an excellent check of the design calculations which predicted both the tower deflections and stress in the shaft accurately. The final weld joining the sections was made and erection of the box girder truss surrounding the elevation shaft began.

As may be seen in the photograph, the framework for attachment of the backup structure, feed arm and elevation wheel, directly above and below the elevation shaft is now complete. This acts as a truss and allows the shaft to be self-supporting, so the temporary support tower has been removed, allowing installation of the elevation wheel to commence. When complete, the 140x163x40 foot deep box structure will act as the support for the reflector, feed arm and elevation wheel.

The forward half of the elevation box structure has been completely trial erected on the ground and will soon be installed on the antenna. The rear half of the box structure is now in trial erection. The box will be lifted in large fully welded modules to facilitate erection. The first sectors of the elevation wheel keel plate are in place, including several of the 100 foot long spokes, the elevation drive bogies and the stow pin assembly.

A jig for assembling the reflector backup structure trusses has been built on the site. The jig is approximately 175 feet long and 40 feet wide. It is used for assembling the large trusses *on the flat* while maintaining the critical surface curvature. At the time of writing, the center truss was nearing completion on the jig. As the trusses are completed, they will be lifted off the jig and placed on the large concrete erection pad adjacent to the telescope site where the entire reflector backup structure will be constructed.

Other recent progress includes the completion of the actuator equipment room, including electrical installation and air conditioning. NRAO personnel have been able to outfit the room with equipment used for controlling the actuators. Construction of the feed/receiver room including installation of the interior walls, insulation, and the feed turret is also underway.

During 1996, the elevation structure will take shape and the overall structure will begin to take on the aspect of a radio telescope. The elevation wheel and box structure will be erected around the elevation shaft. The segments of the box structure above the elevation shaft will be installed alternately to maintain balance in the tipping structure. The bull gear segments will be attached to the wheel, along with the counterweight boxes which will be filled with concrete in a pre-determined order to keep the structure balanced and *tail heavy*. If the weather allows construction to proceed during the winter months, this part of the erection will be complete in March.

The assembly and trial erection of the reflector back-up structure (BUS) will continue throughout the remainder of 1995 and into the first half of 1996. The horizontal feed arm is scheduled to be installed on the antenna by the end of the first quarter, as well. Once the horizontal feed arm and portions of the lower vertical feed arm are successfully installed, erection of the BUS on the antenna may begin. The BUS modules will be disassembled from the trial erection pad and lifted into place on the antenna. This trial disassembly and installation on the structure will occur from February through November 1996.

Preparations have been made for the trial erection of the upper 60 feet of the vertical feed arm at Green Bank. During 1996, this assembly will be used for final setting of the subreflector surface and testing and calibrating all mechanical elements on the feed arm including the prime focus boom, the prime focus feed rotation mount (FRM), the subreflector adjustment mechanism, the turret in the feed receiver room, and the entire feed arm servo. If possible, the entire assembly will be installed as a unit on the telescope following this extensive testing.

The main reflector panel installation will begin in November 1996 and carry through until completion in June 1997. The final alignment and test of the antenna will occur during June and July 1997 with antenna delivery scheduled for early August of that year.

Current construction progress of the Green Bank Telescope (GBT).

Servo

NRAO's initial responsibility with respect to the GBT servo involves monitoring the progress of the servo contractor. This entails reviewing schedules, test procedures, and other documents. It also involves witnessing tests of various subsystems and evaluating the results. Finally, it requires the clarification of requirements and specifications as the design process evolves. The Contractor is providing two servo systems for the GBT, one to control the AZ/EL motion (AZ/EL servo) and a second to control motion of various components near the tip of the feed arm (Feed Arm Servo). NRAO assumes the responsibility of assuring that the servo system will be suitable for high frequency (>50 GHz) operation of the GBT; the contract with the Contractor specifies a 15 GHz instrument.

Several major accomplishments were achieved during the past year.

- The factory testing of the AZ/EL servo was completed. This involved a thorough test of both the hardware and software, and included everything but the antenna itself (the antenna position was simulated by integrating the tach feedback from the drive motors).
- The design of the Feed Arm Servo was completed.
- A plan for calibrating the subreflector mechanism, as part of the plan to enhance the tracking capability of the GBT, was designed. A contractor, a consultant, and internal staff who would implement the plan were identified.
- The pointing of the as-delivered GBT was studied by consultants and NRAO staff. The behavior of the RF beam on the sky in response to various pointing commands was studied using a detailed model of the telescope. This has been referred to as the dynamic analysis. Using this model, software enhancements will be implemented in 1996 which assure pointing stability sufficient for the high frequency performance of the telescope.

Plans for 1996 will include completion of the design and the factory testing of the Feed Arm Servo. NRAO will review and critique the test procedure and witness the testing. In addition, field testing of the Feed Arm Servo will be conducted in Green Bank. For this test, the servo and associated mechanisms will be mounted on the tip of the feed arm before the arm is lifted onto the structure. Measurement and fine setting of the subreflector surface also will take place during 1996. Calibration of the subreflector positioning mechanism will also be performed. Photogrammetry will be used to measure the position of the subreflector at various command orientations. These positions will be analyzed by software supplied by a consultant to arrive at refined equations of motion. Remaining portions of the AZ/EL servo will be delivered to Green Bank, and final installation will begin.

Schedule

The NRAO Program Plan for 1995 reported the Contractor's delivery date for the GBT as the end of 1996. Over the ensuing year, complications in fabrication and erection of the complex tipping structure have led to an additional delay. Fortunately, however, as also reported in the Program Plan for 1995, NRAO has developed a plan to absorb the cost of this delay through a program of personnel transfers and technical program review. The additional project delay, from late 1996 until mid-1997, will be covered with the same measures.

A carefully planned transition of NRAO employees has begun in order to move personnel from the construction project budget to operations budgets. This transition allows the necessary build-up and training of operations staff at the Green Bank site in anticipation of completion and commissioning of the GBT. In addition, following a rigorous review of the in-house technical programs, the decision was made to halt development of the active surface autocollimator and floodlight systems and to postpone the development of the 40-52 GHz receiver. Also, in early 1995, a review of the entire cost structure of the GBT was carried out to provide an accurate, precise budget for the remainder of the project. These actions yielded a collective project contingency of $600k after the cost of the additional schedule delay was built into the budget.

It is anticipated that through careful interface with the contractor and use of the 140 Foot Telescope as a test bed, the GBT commissioning phase will begin sooner and possibly be shortened relatively to the one year estimated earlier.

System Integration

During 1995, the scope of integration of GBT systems at the 140 Foot Telescope was expanded and organized to include major subsystems of monitor/control, data analysis, and electronics in order to evaluate the performance of these systems working together. The Electronics systems put in place at the 140 Foot Telescope now include three GBT front-ends, the GBT continuum backend, and the upgraded spectral processor, and additional subsystems are being phased into use. The AIPS++ project has provided significant resources to support this integration effort, providing the data analysis tools used to manipulate and display continuum and engineering data acquired by the monitor/control system. The integration effort is organized to first emphasize the performance of astronomical observations of the types which will be needed during the commissioning and early use of the GBT, moving from basic continuum observations toward spectroscopy, holography, pulsar observations, and VLBI. This effort allows GBT developers to evaluate their designs working in conjunction with the systems of other groups, in the real world environment of a working telescope, and while being used by observers and telescope operators. This effort will extend into 1996 with the addition of other subsystems and observing capabilities. Additional integrated tests will be utilized as deemed necessary.

During 1996, significant effort will go into planning the outfitting and the commissioning of the antenna. The on-the-ground outfitting of the actuator control room has already been completed, and similar outfitting of the receiver room is expected to begin in January. We will coordinate the purchasing of cabling, the installation of equipment on the antenna, and the schedules of the various NRAO groups in order to ensure that the GBT is ready for use as soon as possible after the antenna delivery.

Electronics

Over the last 12 months many of the GBT subsystems have been designed and/or integrated and tested at various locations around the site. In particular, the 8-10 GHz, 12-15 GHz, and 18-26.5 GHz receivers have been installed on the 140 Foot Telescope and their critical parameters are being monitored and logged continuously. An X21 multiplier and LO distribution module has been designed, built, and tested and will serve as the third LO in the oscillator chain. A phase-monitored fiber optic LO reference distribution system has been designed and fabrication is 80 percent complete. The weather station was installed. Temperature, dew point, barometric pressure, wind speed, and wind direction are being continuously recorded. A Site Timing Center is operational and includes subsystems for precise time such as a maser, GPS receiver, IRIG-B time distribution system, 1PPS distribution and phase measurement system. Each of these subsystems are being monitored and logged continuously. The digital continuum receiver was integrated with the monitor and control system on the 140 Foot Telescope and is presently under going tests. The design of the spectrometer was completed and construction begun. Enhanced performance for the system in supporting pulsar observations was proposed and incorporated into the system specification. Prototypes for the 1024-lag correlator chip to be used in the system were successfully completed.

During 1996 the following actions are planned:

- The 1.7-2.6 GHz receiver, 40-52 GHz receiver, and the GBT tertiary mirror will be designed in 1996 and construction will begin.
- The prime focus receiver and the design/construction of the feeds of the three lowest frequency bands will be completed.

  The design of prime focus receiver #2, including the 910-1230 MHz band will begin.

- The GBT holography receiver will be further tested to investigate its performance and that of the entire system.
- A second IF converter rack and most of the analog rack will be constructed. Further tests of the IF system will be done in the lab and at the 140 Foot Telescope.
- Design of the GBT control room wiring and cabling will be completed and construction will be started. Design of the wiring and cabling on the GBT will be completed.
- Outfitting of the receiver room will take place, on the ground.
- The weather station will be made fully operational with all instruments calibrated to the specified requirements.
- Construction and preliminary testing of the spectrometer system will be completed. The remaining correlator chips required should be completed. Software support, both for the embedded microprocessors and for the system VME computer, have a high priority in 1996. Shipment to Green Bank after completion of stand alone testing in Charlottesville should take place in the second quarter. On-site testing and integration into the GBT system will start upon its arrival in Green Bank.

Monitor and Control

The past year has witnessed the completion of operational software systems for the site timing center, weather station, spectral processor, 140 Foot Telescope, and Cassegrain receivers; of coordinated control of the DCR, spectral processor, antenna, and registries (producers of data associated parameters); of production of FITS files for backend data, logs, and data associated parameters; of a console GUI rewrite to give it an improved "look and feel"; of the message system; of the Solaris port; of the control of monitor and control systems from Glish; and of the development of the basic analysis and algorithms for controlling the active surface (best fitting parabaloid) and Gregorian optics.

Besides applying the basic monitor and control software to further devices, e.g., holography and LO, the following tasks are scheduled to be worked on in 1996:

- Panel Gateway – design and implement a system for the M&C LAN/site LAN gateway machine which: (1) allows the operator to control all network access to the GBT, (2) buffers I/O to GBT managers so clients' performance (e.g.,consoles and Glish) cannot affect the managers, and (c) minimize Internet traffic by passing the minimum information needed by remote clients.
- Observing Frequency Formula – design and implement a system to define or verify the IF's observing frequency formula by equation, matrix, or component settings.

- Setup DAP – save defining setup parameters for each scan into a FITS file as data associated parameters.
- Simulator – define and design an approach to simulation of the telescope control system to allow observer verification of observing runs and instruction of telescope operation.
- IF Emulation – design and implement enhancements to the console to emulate and display IF signal characteristics.
- On Demand Logging – implement the selection and control of monitoring points for temporary logging.
- Error Logging – implement the logging of specified monitor points dependent on error states.
- Task Independence – enhance libraries so that programs on the Suns or single-board computers may be restarted or initialized independently. This includes shutting down gracefully upon receiving a termination signal.
- Watchdog System – design and implement a system to detect failure of any task in the GBT system.
- Glish Accessor – implement a Glish client for interfacing to the accessor to allow users to read any monitor point and to generate streams of monitor values as Glish events.

The central theme to the 1996 monitor and control development is not the ability to write a system that can control a telescope but rather to build a foundation on which features may be added that provide all the information and control the observer needs to do science. Some of these features will be tested during 1996.

Open Loop Active Surface

During the last 12 months, several tasks have been accomplished in the Open Loop Active Surface project. The actuator control room has been outfitted with everything that can be installed while the room is on the ground. This includes mainly mechanical and electrical furnishings.

A cable tester for evaluating all the actuator cables has been selected and purchased. Work is about 50 percent complete towards integrating it into a cable/actuator testing system. A total of 52 control panels, which contain the actuator control modules required to control all 2209 actuators, were built and tested. A test was set up and run to evaluate the effect of one million start/stop cycles on the actuator motors. The number one million was selected based on operational requirements of the actuator. It was shown that the bulk of the wear on the motor brushes is due to the number of mechanical rotations of the motor; only a small amount is due to the number of start/stop cycles. During the above test, it was found that grease migrated from the actuator gear box into the motor. Causes of and solutions to this problem were investigated. The solution taken was for NRAO to remove excess grease from all actuators manufactured to date (approx. 1800) and to replace bearings in motors that appeared to have been affected by grease migration. The vendor has modified the procedure for greasing the gear box on the final 600 actuators. This provided a good opportunity for NRAO to test each of the actuators received.

Detailed system and software requirements were written in order to organize the design of the control software. Rudimentary software is now in place to control and monitor all actuators.

The order of 2400 actuators was completed. Actuator power supply turn-on transients were found to be larger than expected and were suspected of causing damage to several motor drivers. Circuits to keep the transients in an acceptable range have been designed.

During 1996, the power supply transient monitoring circuits will be built and tested. In addition, NRAO will complete the cable test system for the actuator cables and all software which controls and monitors the 2209 actuators, will be completed and tested. Additional software will be used to monitor various devices related to actuator control.

Circuitry required to monitor specific parameters related to actuator control will be designed, built and tested. All cables and actuators will be tested after installation on the structure. The software interface to the 3D Surface Designation System (the higher level system that controls the active surface) will be tested.

Closed Loop Active Surface and Laser Pointing

Progress on the electronic distance measurement hardware and software has continued during 1995. The Green Bank machine shop production of the first six mirror units was on schedule, and the remaining seventeen units will be complete by the end of the year. All control panels have been completed, tested, and crated awaiting installation on the GBT. All laser modulators are complete and the laser detectors will be finished by the end of the year. The panel retroreflectors and mounts are in Green Bank awaiting assembly and calibration, which will start fourth quarter 1995 and extend into 1996. The University of Arizona Optical Sciences Center delivered two prototype wide angle spherical retro-reflectors and complete design drawings. The embedded laser control computer system architecture has been extensively tested with excellent results. With the successful demonstration of moving retroreflector tracking, and a revision of the documentation manual, the embedded control portion of the system will be essentially complete. The NRAO has applied for a patent on the system. The patent office has allowed the claims on an application filed in 1994 and the patent number should be issued in 1995.

The GBT system architecture will be finished by the end of 1995. The ground based laser locations have been surveyed, and the arm mounted laser locations will be on the drawings by the end of the year. In 1996, the finite element analysis model of the laser and retroreflector locations and instrument pointing corrections, as a function of elevation, will be complete. Work is underway on the prototype panel setting tool, and the complete unit will be delivered to the Contractor by the end of the year. After approval by the Contractor, the remaining units will be built in 1996.

The 140 Foot Telescope demonstration is well underway. This will test GBT laser hardware, software, monument construction, and calibration procedures and techniques. While the first two quarters of 1995 have concentrated on construction and installation of equipment, the remainder of the year will concentrate on calibration and software testing – including tracking moving retroreflectors for the first time.

In 1996, attention will move from instrument hardware production and the embedded control system software to the GBT system architecture and calibration methods. Software design will begin interfacing with the monitor and control active surface and precision pointing groups. The 140 Foot Telescope demonstration will continue to operate and serve as a prototype for all GBT hardware, software, and calibration procedures. Actual hardware location and cable detail drawings will be generated in preparation for the contractor granting access to the structure and surrounding site. Instrument enclosures will be designed and built. Spherical retroreflectors will be located on the structure drawings and mountings will be designed. The spherical optics will be purchased and mounted in the calibration lab. The calibration lab workload will increase in support of the panel retroreflector mounting and instrument system final assembly. A number of calibration jigs and fixtures will be built. Extensive documentation of the system hardware, software, calibration, and operations will be generated.

GBT Data Analysis

The 140 Foot Telescope GBT integration tests in July 1995 successfully demonstrated control of the 140 Foot Telescope and the DCR digital continuum receiver using the Glish command line interpreter. Standard pointing observations were taken and analyzed using AIPS++ routines from Glish. During 1996, it is planned to extend the functionality and ease of use of both AIPS++ and Glish for GBT telescope control and data analysis. All data analysis software needed for the acceptance of the GBT should be available by the end of 1996. This will include standard telescope pointing analysis as well as holography.

Other major areas of development will include data archiving of both observational data and telescope monitor data. The use of FITS binary tables for all archive data insures compatibility with the astronomical data standard. Having data in a standard format makes it possible to process GBT data using several data analysis systems in addition to the AIPS++ system. The operational aspects of GBT data taking and archiving will be fully developed during 1996, using the 140 Foot Telescope as a testbed.

Pointing

Several areas will be addressed by the Precision Pointing group during 1996. Of particular interest are the focus-tracking module, the interface with the active surface, the calibration of the subreflector motion, and the review of the astronomical algorithms used in the monitor and control system.

The heart of the GBT positioning problem is in two stages. First, the principal axis of the primary must be directed toward the source of interest. Second, the optics, either the prime focus feed or the combination of Gregorian mirror and secondary feed, must be positioned to achieve optimum gain and purity of polarization. The first stage will be accomplished in Phase I using an algorithm which models the various components of the systematic, repeatable pointing errors. This algorithm which has already been installed in the monitor and control will be augmented in later phases by measurements from components of the precision pointing system such as the laser rangers and the quadrant detector. The effort in the second stage during the next year will be directed toward the development of the focus tracking module which commands the location of the prime focus feed and the Gregorian subreflector. Development of the programs which describe the structure of the telescope and which calculate by ray-tracing the optical path has proceeded well. These programs will be used to estimate the motion required as a function of telescope attitude in order that the GBT remain focussed.

In Phase II the figure of the surface will be determined by the positioning of the actuators. The commanded position will be deduced from the structural model of the telescope. Since the optimal position for the telescope optics requires knowledge of the figure of the primary mirror, the Precision Pointing group will work with the Active Surface group during 1996 to develop programs which command the actuators to drive the requisite distance so that the desired surface figure can be achieved. A program which computes the positions the actuators should be set at as a function of telescope attitude, in order that the desired surface be achieved, will be completed.

One of the uncertainties in the design of the Gregorian focus-tracking module is the actual displacement of the mirror corresponding to the motion of one or more of the six actuators on which the mirror is mounted. The complicated problem of the calibration of the mirror mounting is similar to the calibration of so-called Stuart Platforms, a problem which has been discussed in the literature of mechanical engineering and robotics. The calibration of the GBT system will begin with an extensive study when the mirror has been received in Green Bank in early 1996. The planning for this measurement has already begun. It is expected that these calibrations will be sufficient to provide the capability to position the subreflector in Phases I and II. In the later phases it will be necessary to update the initial ground-based calibration with a series of measurements using the GBT itself. The design of the system for calibration in the later years will begin in 1996, following the completion of the ground calibration program.

In a related study, an effort will be made to model the effects of observational errors on the calibration of the position of the subreflector, in order to better understand the precision with which in situ calibration can be performed, and to explore which observational techniques will be most useful. The study will be based on Monte Carlo simulations.

Finally the monitor and control system will use the precise algorithms to calculate the customary corrections to be applied to the astronomical coordinates. The accuracy of the codes for precession, aberration, and nutation will be verified. The calculation of atmospheric refraction will need to be made to a higher accuracy than has been generally true in the past, and efforts are in progress to specify a suitable algorithm. Routines for tracking objects moving at other than sidereal rates, and for the generation of ephemerides for planets, planetary satellites, and comets, also will be developed during 1996.

VI. MAJOR INITIATIVES

1. The Millimeter Array

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

In 1996 we anticipate committing $1M to the further development of the MMA. The activities to be given emphasis this year include site studies, the antenna design, and development of a phase calibration technique suitable for the atmospheric conditions of the sites under study.

Site Evaluation

Site studies for the MMA have been narrowed to just two possibilities, one in the northern hemisphere, on Mauna Kea in Hawaii, and one in the southern hemisphere, in the foothills of the Andes in northern Chile. The Mauna Kea site is within a developed observatory complex managed by The Institute for Astronomy of the University of Hawaii. Atmospheric studies important for operation of the MMA have been in progress there for several years and from this work together with the experiences of other observatories on the site, it is possible to characterize Mauna Kea accurately vis-á-vis the MMA needs. Such precise knowledge is incomplete for the possible Chilean site.

In Chile MMA atmospheric monitoring equipment is now operating on the site at 5000 meters elevation as shown on figure on the following page. The equipment consists of a 225 GHz tipping radiometer and a phase monitoring interferometer. The tipping radiometer measures the opacity of the atmosphere above the site at the principal wavelength to be used by the MMA. Opacity measurements are made every ten minutes 24-hours a day. The interferometer operates at 11 GHz and observes a beacon from a geostationary satellite. The interferometer baseline is 300 meters. Between these two instruments, which have been running since April 1995, it will be possible to characterize the operational aspects of the MMA should it be placed on this site.

Antenna Design

The antenna design is an activity being conducted under the auspices of the MDC. The MMA antenna must meet the performance specifications given in the table below.

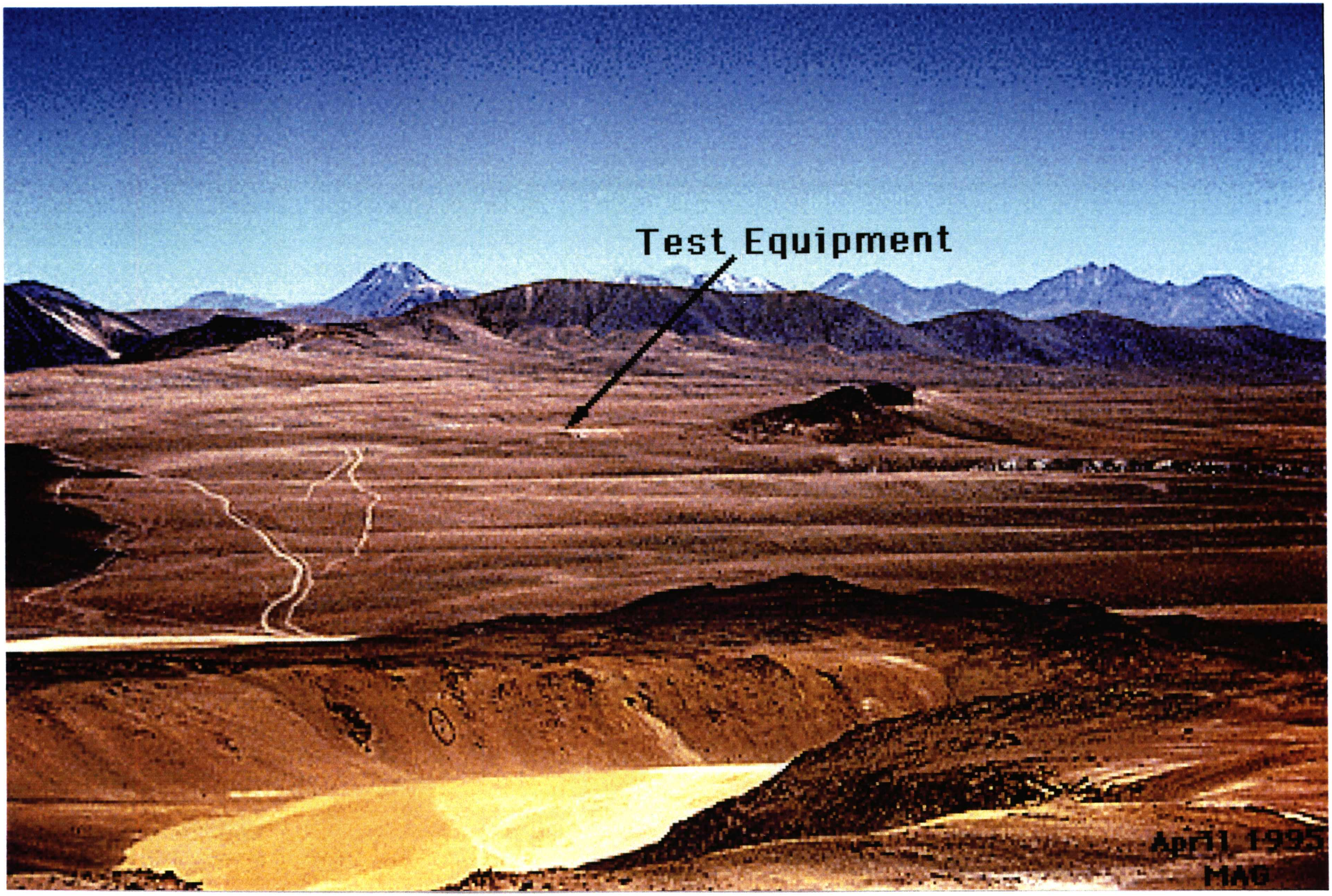
Table IV.1. MMA Antenna Specifications

Description	Specification
Antenna Diameter	8 m
Frequency Range	30-365 GHz
Surface Accuracy	≤ 25 μm RMS
Pointing Accuracy	≤ 1" 50% of the time ≤ 2" 75% of the time
Phase Stability	≤ 10 μm RMS 25% of the time ≤ 22 μm RMS 50% of the time ≤ 56 μm RMS 75% of the time
Dynamic Performance	Move $1\overset{\circ}{.}5$ in 1^{s} to 3" accuracy
Subreflector Nutation	3 beamwidths at 30 GHz
Close Packing	< 10.4 m
Physical Design	Simple and durable

The MDC antenna group has an engineering design for two different antennas that appear capable of meeting most of the MMA specifications. One is a conventional symmetric reflector on an alt-azimuth mount and the other design is an offset reflector on a slant-axis mount. In 1996 both designs will be carried forward in an increasing level of detail; at the end of the year we hope to be in a position to choose between the two approaches, perhaps combining the best features of each into a design that may be considered optimum for the MMA.

Phase Calibration

In order to maintain phase coherence of the MMA on the longer baselines and at the higher frequencies it will be important to employ a form of "adaptive optics" to correct the phase of the incoming ray for distortions occurring in the earth's atmosphere. There are two classes of techniques that may be applied successfully for the needs of the MMA, both of which need to be refined and demonstrated.



The potential MMA site in northern Chile. The elevation of the site (16,400 feet) assures the very dry atmosphere needed for optimum performance of the MMA.

The first technique is a straightforward adaptation of the traditional phase calibration used in centimeter-wave radio astronomy. It relies on a switching cycle between source and calibrator where the absolute position of the calibrator is assumed to be known. At millimeter wavelengths the issues are: (1) the density of suitable calibrators on the sky; (2) the speed of the switching cycle required; and (3) the sensitivity of the array needed to detect the calibration source. These issues will be addressed by the MDC in 1996.

The second class of techniques involves monitoring a quantity proportional to the atmospheric phase distortions and then applying a correction from the monitor data. Two ideas along these lines will be pursued in 1996: monitoring the total power of the radiometers, the fluctuations in which are ascribable to changes in the atmospheric opacity, and monitoring the fluctuating equivalent width of one of the atmospheric water lines, for example the 183 GHz line.

Receivers

The goal of the MDC receiver working group in 1996 is to establish clear criteria for the technology to be used in each of the MMA bands. This decision will set the specification for the number of cryogenic dewars needed at each antenna, and it will allow the optical layout of the antenna to proceed.

Tests will be made in 1996 of prototype MMA SIS junctions of a novel design incorporating balanced mixers incorporated on a single chip that will permit the sidebands to be separated. If successful these devices offer the prospect of reducing the system noise (i.e., increasing the array sensitivity) by eliminating the atmospheric emission in the unwanted sideband.

System Design

The goal of the MDC system working group is to provide a technical framework for the entire array into which all the pieces of the instrument clearly interface. This means, for example, that the IF bandwidth of the receivers should match that of the signal transmission system and the signal should arrive at the correlator with sufficient signal to noise, frequency stability, bandwidth and dynamic range to allow the astronomical objectives to be accomplished. The systems group has the responsibility for melding the scientific concerns with the technical outline of the MMA.

In 1996 the systems working group will build simple prototypes of MMA hardware and measure such quantities as the frequency response and phase variation in a long section of optical fiber when one is transmitting a wideband signal. The effect of temperature variations on the IF and LO stability as a function of frequency is another class of tests to be done in 1996 that requires both simple prototypes and the attention of knowledgeable engineers and scientists.

Community Interaction

All the MMA activities will continue to be documented in writing with those documents placed on the WWW for inspection by interested individuals. Monthly teleconferences will be held that provide a forum for questions to be asked and suggestions given. The annual review by the MMA Advisory Committee is very effective in enforcing a measure of community discipline on the entire enterprise.

2. VLA Development Plan

It has been clear for some time that the VLA's impact on astrophysics can be dramatically increased by upgrading or replacing the 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 antennas between the VLA and the VLBA.

The VLA development plan addresses the demands of a wide variety of scientific programs for greatly increased sensitivity, much broader frequency coverage, enhanced spectral line capabilities, and better angular resolution. 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 requirements also pose 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 near the millennium will be profound. Many hard limitations now constraining VLA observations will be removed or greatly relaxed. The continuum sensitivity will increase ten-fold in several bands. New frequency bands and increased bandwidth ratios will increase frequency coverage almost three-fold. The bandwidth which can be processed by the spectrometer, and its spectral resolution, will simultaneously increase by about ten-fold. The resolving power will improve fifty-fold. Finally, the new instrument, when cross-linked with the VLBA, will result in a VLBI instrument with greatly increased dynamic range, field of view and frequency-scalability compared to the present VLBA. The following technical capabilities are therefore key ingredients in a VLA development plan:

Phase 1: An Ultrasensitive Array

- New receivers: lower noise temperatures and much wider bandwidth performance (1 GHz in each polarization channel) in existing bands; addition of 2.4 GHz and 33 GHz bands at the Cassegrain focus; complete outfitting for the 40-50 GHz band; extension of the 1.4 GHz band to lower frequencies.
- 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 33 or more antennas, to process both broadband continuum signals and to provide improved resolution and flexibility for spectral line work.
- Improved low frequency (<1 GHz) capability, using prime focus feeds and new receivers.

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.
- New antenna stations for a super-compact E configuration to enable fast mosaicing of large fields.

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 seven. The sensitivity increases will allow the increase in angular resolution to be exploited fully when observing a wide (and in many cases for the first time, representative) variety of thermal and nonthermal objects, both galactic and extragalactic. Each of these project elements is now discussed in more detail.

Antenna and Receiver Improvements

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

Improved Low Noise Receivers

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

The VLBA-style receivers are now used in the 1.4, 8.4, and 45 GHz bands. These receivers will remain with perhaps only minor modifications. The greatest improvement in system temperature can be made in the 5, 15, and 22 GHz bands using the VLBA-style receivers and modern HFET amplifiers. Completely new receivers will be built for these bands, and should reduce the system temperatures by up to a factor of three. The new receivers will also provide 1 GHz bandwidth per polarization channel (needed for continuum sensitivity) and will tune over a wider frequency range (to include spectral lines, e.g., methanol, whose astrophysical significance was unknown when the VLA was built). Current plans call for bandwidth ratios of order 1.4-1.5:1 in many bands.

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

New Observing Bands at the Cassegrain Focus

Two new receiver systems will be added at the Cassegrain focus: 2.4 GHz and 33 GHz. A stand-alone 2.4 GHz feed will fit on the feed ring at the Cassegrain focus and will give higher performance than the alternative approach, a 1.4 GHz/2.4 GHz dual-band feed such as that used on the Australia Telescope. The 2.4 GHz system will let the VLA participate in bistatic planetary radar observations with Arecibo Observatory. The 33 GHz band can also support bistatic radar experiments, with the Goldstone 70 meter antenna, and it will allow imaging of many interesting molecular lines, including redshifted CO and 0_2. Table 1.1 summarizes the proposed new and upgraded VLA Cassegrain observing bands.

New Prime Focus Systems

Plans for new prime focus receiver systems are less well defined. A 330 MHz system is currently located at the prime focus, as is a low-performance, dismountable 74 MHz system on eight antennas. The presence of the 74 MHz dipole feed degrades performance of the 1.4 GHz band by about 10 percent. Hence, if 74 MHz feeds are deployed on all antennas, it must be possible to dismount them (or otherwise move them from the prime focus position by mechanical means), so that the L-band sensitivity is not compromised.

Table VI.1 Proposed VLA Cassegrain Observing Bands

Band	Range (GHz)	BW (GHz)	BW ratio	
L	1.20-1.75	0.55	1.46	Upgrade
S	2.13-2.70	0.57	1.27	New
C	4.80-6.70	1.90	1.40	Upgrade
X	8.00-9.10	1.10	1.14	Upgrade
Ku	12.00-18.00	6.00	1.50	Upgrade
K	18.00-26.50	8.50	1.47	Upgrade
Ka	26.50-40.00	13.50	1.51	New
Q	40.00-50.00	10.00	1.25	Complete

Other specific proposals for prime focus systems include:

- A new system covering 580-640 MHz, matching that of the VLBA.
- A broadband UHF (150-600 MHz) system, including a simple system suitable for solar work.
- A sensitive 800-1200 MHz system.

Sensitivity Goals

Table 1.2 compares the continuum sensitivity of the current instrument to that we hope to achieve. We assume a maximum useable bandwidth with RFI excision at the lower frequencies, and add an atmospheric contribution where relevant. The number under δS refers to the continuum sensitivity in μJy/beam achieved in 12 hours' integration, summing over two orthogonal polarizations. The total bandwidth assumed for 0.33, 0.60, 1.0, 1.4, and 2.4 GHz is 50, 100, 200, 500, and 1000 MHz, respectively. All other estimates assume 2 GHz net bandwidth.

Table VI.2: VLA Sensitivity

	Enhanced VLA		Current VLA	
Band (cm)	T_{sys} (k)	δS (μJy)	T_{sys} (K)	δS (μJy)
90	80-135	40-70	150	120
50	45-90	13-25		
30	25-32	5.3		
20	30	2.7	33	6.0
11	31	1.9		
6	29	1.3	45	6.7
3.6	31	1.3	31	4.4
2	37	1.7	110	20
1.3	50-70	2.6	160	37
0.9	38	2.0		
0.7	55	3.5	80	165
0.6	170	15		

New LO/IF Transmission System

To transmit 2 GHz of bandwidth from each antenna, we will use optical fiber links to all of the VLA stations, to the nearby VLBA antennas, and to additional new antennas located between the VLA and the present VLBA stations. Separate fibers will carry the LO reference signal and the wideband IF signal. Between four and six single mode fibers will run to each antenna station. Although low temperature coefficient fiber will be used on runs exposed to ambient temperature, a round trip phase correction system probably will still be needed.

A New Correlator

The specifications for a new correlator are still under discussion, as is the architecture best suited to meet them. It is not yet clear whether the more appropriate architecture is a lag correlator, as presently used at the VLA, or an FX correlator, as used by the VLBA. A detailed design study is needed to choose between the two options. Note that the product of the number of antennas, N, and the maximum bandwidth, B, analyzed by the correlator is NB = 66 GHz. This figure of merit for the correlator is comparable to that of the Millimeter Array (NB = 80 GHz); both correlators will be at least an order of magnitude larger than the existing VLA correlator (NB = 5.4 GHz) or the VLBA correlator (NB = 2.6 GHz).

The new correlator should be able to process data from at least 33 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 four new antennas on baselines between those in the VLA and in the VLBA.

High Surface-Brightness Sensitivity – the E-Configuration

When the VLA was designed, most astronomers were not aware of the necessity to image with high brightness sensitivity, or to image very large fields, or to image with an angular resolution below that provided by the D configuration. Mosaicing techniques did not exist and it was believed that, in any case, these issues were better addressed with large single dish instruments. It is now recognized that compact arrays with total power capabilities fill a gap between the imaging capabilities of conventional interferometer arrays and those of large single dishes. A super-compact E configuration with maximum baseline lengths of a few times 100 meter 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 three times more sensitive than the proposed E configuration. The advantages of the E configuration lie in its mapping capabilities, where the E configuration is more than 20 times faster. Hence, the role of the E configuration is 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 it will also provide frequency coverage up to 50 GHz. As an interferometric instrument, the VLA also has lower systematic errors than a large single dish; i.e., it is less susceptible to pointing errors, and ground pickup is uncorrelated between antennas, so that the spectral baselines are flat.

High Angular Resolution – The A+ Configuration

There is a serious gap in u-v coverage between the 35 km longest baseline of the VLA and the 200 km shortest baseline of the VLBA. We plan to bridge this gap by allowing some VLA, some VLBA and some new antennas to be used interchangeably as members of either array. These will (a) increase the resolution of the VLA at all frequencies and enlarge the range of resolutions over which it has scaled-array capability, (b) improve the dynamic range, field of view and extended source sensitivity of the VLBA, and (c) provide the VLBA with a scaled-array capability similar to that of the VLA; currently such a capability is lacking in the VLBA.

New antennas would be built in New Mexico and Arizona to make the density of u-v coverage in the 40-400 km baseline range similar to the VLBA now beyond 400 km. The first step would be to complete the Pie Town ring around the VLA by adding antennas near Dusty, NM, and Bernardo, NM. (Linking just the Pie Town antenna to the VLA would double the resolution of the A configuration for northern sources only. Linking the Dusty and Bernardo antennas extends this capability to the whole sky.) The second step would be to add further antennas in the Los Alamos ring: two possible sites are near Holbrook, AZ, and Vaughn, NM. The VLA's delay and fringe rotation systems would be expanded to correlate these signals in real time with the present A configuration (processing would be done at the new 33 station VLA correlator).

Sub-arc-second resolution observations with the present VLA are possible only at the higher frequencies where, unfortunately, the brightness sensitivity needed to detect nonthermal phenomena is usually inadequate because of the source spectra. These frequencies may also be inappropriate for any projects in which Faraday depth effects, wide-band spectral shapes, or low-frequency spectral lines are needed to probe source physics at these resolutions. There also are many instances where studies of normal stellar radio emission will benefit greatly from increasing both the resolution and sensitivity of the VLA at higher frequencies.

The reconfigurability of the VLA (its capacity for scaled array observations with the same angular resolution at several frequencies) has been vital to its astrophysical success. This distinctive capability of the VLA is now present across the whole frequency range from 330 MHz to 22 GHz only at resolutions near 5". No problem that requires higher angular resolution than 5" and full frequency coverage can now be tackled in scaled-array mode. This situation changes dramatically if we can add data from longer baselines in the A+ configuration or the VLBA.

Finally, we note that the availability of optical imagery at 0"1 resolution from the Hubble Space Telescope is emphasizing the need for better coverage of this resolution regime over a full range of radio frequencies. This resolution falls squarely in the uncovered gap between the VLA and VLBA at just the frequencies where imaging would be least corrupted by atmospheric and ionospheric phenomena.

Other Capabilities

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

Table VI.3 Illustrative Budget

	Cost ($M)	Subtotal (SM)
PHASE 1:		
Antenna LO/IF	5.5	
Antenna Mechanical	2.3	
LO/IF Transmission	2.5	
Central LO/IF	2.5	
Correlator	7.5	
Test Equipment	0.2	
CASSEGRAIN:		
1.20-1.75 GHz	0.8	
2.13-2.70 GHz	1.6	
4.80-6.70 GHz	1.4	
12.0-18.0 GHz	1.5	
18.0-26.5 GHz	1.5	
26.5-40.0 GHz	2.2	
40.0-50.0 GHz	1.5	
NRE	0.5	
PRIME FOCUS:		
75-300 MHz	0.8	
300-800 MHz	1.2	
800-1200 MHz	3.5*	
SUB-TOTAL		37
E CONFIGURATION:		
18 Stations	4.0	4
SUB-TOTAL PHASE 1		41
CONTINGENCY PHASE 1	6.0	
PHASE 1 TOTAL		**47**
PHASE 2:		
4 new antennas	25.0	
Fiber to DS, PT	2.0*	
Fiber to BN, HL, VN, LA	8.0*	
SUB-TOTAL PHASE 2		35
CONTINGENCY PHASE 2		6
PHASE 2 TOTAL		**41**

*cost is very uncertain

3. AIPS++ Project

The AIPS++ Project has the goal of creating the next generation data reduction and analysis package for radio astronomy. It is a collaboration between a number of radio observatories, the major partners in the AIPS++ consortium being the Australia National Telescope Facility, the Berkeley-Illinois-Maryland Association, the Netherlands Foundation for Research in Astronomy, and the NRAO. The Project Center is at the Array Operations Center in Socorro, and an NRAO staff member, Tim Cornwell, is the Project Manager.

The goals of the Project for the next year to eighteen months are the consolidation and testing of the AIPS++ library, and development of a few key applications chosen to provide unique astronomical capabilities. The long-term goal of the Project has been defined to be the achievement of functional equivalence to AIPS by the year 2000. At that point, AIPS will be a very small subset of AIPS++ and most applications areas will look quite different from the corresponding areas in AIPS. Work is now proceeding in many different areas to support these project goals. A road map is available in the AIPS++ Development Plan (URL http://aips2.nrao.edu/aips++/docs/html/devplan.html).

AIPS++ is supporting the testing and development of the GBT Monitor and Control System on the 140 Foot Telescope. This will continue and transition into the development of fully-featured analysis packages for observations using the GBT and other consortium single dish telescopes.

In synthesis processing, AIPS++ will develop software for calibration and imaging of interferometric data using a very general formalism for describing the measurements made by a synthesis array. It is expected that this formalism will cover most known synthesis arrays.

Further information on AIPS++ is available from the AIPS++ Home Page (URL http://aips2.nrao.edu/aips++/docs/html/aips++.html).

VII. NON-NSF RESEARCH

1. United States Naval Observatory

A new 20 meter telescope has been completed for use in the USNO NAVNET VLBI array. This array makes VLBI observations to provide fundamental data on earth rotation and polar motion needed for timekeeping and navigation. The data are essential to the analysis of observations from the VLA and VLBA. The new 20 meter has replaced an 85-foot telescope in Green Bank which has been used for several years for the USNO VLBI network. The new 20 meter has a better reflecting surface, greater sky coverage, and higher slew rates than the 85 foot. It is also equipped with a new, more stable receiver, designed and built by the NRAO at Green Bank.

In 1996 an addition to the Jansky Lab building funded by the U.S. Navy to support its activities in Green Bank will be completed. The addition will have space for the USNO 20 meter and 85 foot control room and VLBI facilities, offices and lab space for engineers, operations personnel and scientists associated with USNO activities. USNO related operations are expected to move into the building in mid-1996.

2. Naval Research Laboratory

The three 85-foot telescopes at Green Bank are funded by the Naval Research Laboratory for long-term monitoring of radio sources. One of them is used for timing a set of 35 pulsars and measuring their flux density variations at 327 and 610 MHz. These data are used by researchers at NRL, NRAO, Princeton, Oberlin, and Berkeley. A recently improved fiber optic transmission system can send the RF signals from the 85 foot to the 140 Foot Telescope building, where they can be recorded by the spectral processor if it is not in use with the 140 Foot. This allows better time and frequency resolution than is possible with the filter bank system at the 85 foot.

The other two 85-foot telescopes are used as a single baseline interferometer to do daily flux density monitoring of about 80 variable sources at S and X band. Most of the sources are extragalactic, but the set includes Cygnus X-3, SS433 and Algol. In 1996 a new telescope control system will be put in place, replacing the DDP-116 computer which has been in service since 1968.

3. NASA-Green Bank Orbiting VLBI (OVLBI) Earth Station

Early in 1996, the OVLBI Earth Station project will complete its interim phase and will start its operations phase. The operations phase begins several months before launch of the first VLBI satellite, now expected to be the Japanese VSOP in August 1996. The Russian Radioastron satellite is expected to be launched in late 1997. In full operations phase the station will carry out routine tracking and data acquisition activities through the scientifically useful lives of the two satellites.

During the first half of 1996 we will complete testing of interfaces to the other mission elements. A first Russian compatibility test and a second Japanese compatibility test with flight hardware are planned for this period. The NASA SURFSAT transponder satellite will be tracked to test the OVLBI time transfer link and the NASA/JPL orbital determination system. During periods when the tracking station is not following a satellite, it will be used to monitor the entire northern sky for bright variable radio sources at 8.35 and 14.35 GHz.

4. NASA-OVLBI Science Support

The NRAO Space VLBI Project, based at the Array Operations Center includes the NRAO activities funded by NASA through the U. S. Space VLBI Project at JPL, in support of the international Space VLBI missions VSOP and Radioastron. After some significant reductions in scope arising from NASA budget constraints, the Project now comprises the following tasks. All these areas will experience major activity in 1996 as the VSOP mission is launched (scheduled for September 1996) and is commissioned.

Management and Science

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

VLBA Correlator Enhancements

Modification of the VLBA correlator to support Space VLBI observations will be substantially complete by the end of 1995. Two specific exceptions for which work will continue into 1996 are the implementation of (1) corrections for the putative rapidly-varying component of the phase-transfer-link corrections, and (2) the digital output filter to retain an adequate fringe-rate window at orbit perigee, within the correlator's overall output data-rate capacity. Testing of all aspects of the correlator enhancements will be the major activity in the second half of 1996, with tests of the entire space-earth interferometer system beginning about the end of the year.

AIPS Enhancements

A new half-time programming position, aimed principally at maintaining and extending the Classic AIPS infrastructure in support of Space VLBI, will be filled. New software will be written to generate realistic simulations for tests of Space VLBI imaging, and to provide displays of Space VLBI data beyond those currently available in AIPS. The interactive model fitting task will be completed, and further enhancements added to the baseline-oriented fringe-fitting tasks. As in the case of the correlator, testing of the AIPS enhancements will be a major activity in the second half of 1996.

Operations Support

One sub-task in this area, already beginning in 1995, will reach its full level in 1996: scheduling of the VLBA for joint observations with VSOP. All other activities, which are related to operation of the VLBA correlator and shipping of tapes, will be limited to occasional tests.

User Support

Two user support staff members will be hired early in 1996, to insure that adequate training can be completed before the results from VSOP's first scientific observations must be analyzed. The initial complement of computing hardware provided for visiting users also will be procured.

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.

Public Education

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

In 1996 both of the NRAO visitor centers will be enhanced. The VLA visitor center will receive a major upgrade in all its displays: This badly needed improvement is being financed by a significant private donation. The Green Bank visitor center will be expanded and relocated, thanks to space made available as a result of the new addition to the Jansky laboratory building. The instrumentation collection in Green Bank will be augmented by the collection of historical instruments recently donated to the NRAO by one of the founders of the science of radio astronomy, Grote Reber.

Guided tours of all the NRAO facilities, including each of the VLBA sites, are conducted throughout the year upon request. Groups that annually visit the NRAO include the interpretative staff of Chaco Canyon National Monument, the New Mexico Amateur Astronomers Society, the National Youth

Science Camp, the Governor's Honor Academies, the Glenville State College Project, the Society of Amateur Radio Astronomers, Hands on Science, Elderhostel and Chatauqua.

For those who cannot visit the NRAO, or those wishing a more in-depth exposure to radio astronomy, the NRAO maintains a collection of annotated slides illustrating the telescopes, techniques and research images of radio astronomy. These slides are made available to students, classroom teachers, professional colleagues, the media, and the public. A collection of more than 3500 astronomical images called "Images from the Radio Universe" is available on compact disk. These images are easily displayed on a computer screen and may be manipulated by students or others seeking to explore radio astronomy in their home or classroom. Software allowing people to *browse* these images is also provided by the NRAO. Each of these images is fully documented and calibrated – they are not *toys* or illustrations. These are research quality images in every respect.

Pre-College Education

Pre-college students receive their exposure to the intent and breadth of scientific studies from their science teachers. It is on the basis of the guidance and instruction they receive from these same teachers that they make a decision on whether or not to pursue a career in science. If students are to be encouraged to see the rewards of science education, their teachers must first have this awareness.

In recognizing the value of *teaching the teachers*, the NRAO annually sponsors the Science Teachers Institute in partnership with West Virginia University. Two 2-week programs a year bring high school science teachers from around the United States to the NRAO. While in residence at the Observatory, the teachers are taught how to make radio astronomical observations, and they do their own research using a dedicated 40 foot radio telescope. In addition, they receive lectures on general astronomy and on current avenues in radio astronomy research, they build a scientific instrument to use in the classroom, and they participate in education discussions and activities. The program is led by NRAO staff scientists and engineers as lecturers and as hosts and advisors.

The teacher/participants have academic year duties as well. Each of them must host at least four workshops for teachers in their home states and develop and implement project-based units with their students. It can be estimated that more than 100,000 students have benefitted from the NRAO institute over the past eight years.

Undergraduate Education

According to the American Institute of Physics, the typical undergraduate curriculum for a student majoring in physics or astronomy includes six hours or fewer in required laboratory courses. This means that, as seen by the student, science research is largely a pursuit of theoretical studies. As a way of broadening the exposure, the NRAO conducts a summer research program under the auspices of the NSF Research Experiences for Undergraduates (REU) program. At least twenty students participate each year. Each student is assigned a NRAO staff scientist or engineer as a supervisor and each participates with his or her supervisor as a professional colleague for the summer. This provides an intense exposure to real research that serves to complement and enhance the intellectual understanding of the role and purpose of scientific discovery that the student acquires in the classroom.

A second avenue of student involvement at the NRAO is the program of cooperative education also done with NSF sponsorship. The co-op students are in residence for three to six months a year and are given intellectually creative tasks to do, and they are provided with the resources needed to complete the tasks. In 1996, co-op students at the NRAO will experimentally investigate the source of radio interference from automobiles and try and devise methods to eliminate it. They will build and test parts of the laser metrology system being built for the Green Bank Telescope.

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 ten resident Ph.D. thesis students at the NRAO doing research in astronomy, microwave engineering, and computer science. This program principally benefits the student, but it has a salutary effect as well for the NRAO staff supervisor.

In addition to the thesis students resident at the NRAO, more than 125 Ph.D. thesis students use the NRAO facilities each year for their research. While these latter individuals receive no direct salary support from the NRAO, their stay of one to a few weeks at the Observatory is supported directly by a housing subsidy (in Socorro), travel reimbursement, computer time, and supplies; and it is indirectly supported by assistance from the NRAO scientists and staff as needed. Many of the students using NRAO facilities this year will receive their introduction to radio astronomy from NRAO staff scientists.

Postdoctoral Education

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

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

Scientific Workshops and Symposia

One important measure of the success of the VLA is the number of scientists who use the telescope each year, viz, more than six hundred. That so many people could use it speaks to its operational ease and convenience. At the same time sophisticated users seek to push the VLA to its limits; they recognize that one needs to understand its subtleties in order to do so. We attempt to communicate this information to users, particularly student users, by workshops held in Socorro on synthesis imaging.

Synthesis imaging workshops are held every three years. More than 100 students (mostly graduate students) attended the most recent workshop, the fifth in the series that includes similar workshops held previously in 1982, 85, 88, and 91. Thirty NRAO staff scientists developed the theory and application of aperture synthesis in various lectures that were given over a ten-day period. The proceedings of all the workshops have been published. We expect this series to continue.

The VLBA promises to make VLBI readily accessible to the large number of users accustomed to observing with the VLA. In order to accelerate the process, the NRAO focussed a 1993 synthesis imaging workshop on the techniques of VLBA imaging. Thirty-one lectures were presented by twenty-four lecturers. About one hundred graduate students and others attended for approximately ten days. We expect to sponsor synthesis imaging workshops in the future that highlight both VLA-related and VLBA-related imaging theory and practice.

In the last few years, the NRAO in Tucson has hosted a number of international, specialist scientific and technical workshops. These have been well attended by the leading world authorities in the respective fields, as well as representatives from high technology industries. The various workshop proceedings have been published. Recent workshops have included the topics of *Observing at a Distance* (World Scientifc Publishing), *Next Generation Digital Corr*elators, and *Infrared Cirrus and Diffuse Interstellar Clouds* (ASP Conference Series No. 58). In 1994, the topic was *Multi-feed Systems for Radio Telescopes* (ASP Conference No. 75).

In May 1995, a major five-day scientific symposium took place, sponsored jointly between the NRAO and the SMT of Steward Observatory, with support from the IAU (Symposium No. 170) and URSI. This symposium, *CO: Twenty-Five Years of Millimeter Wave Spectroscopy*, celebrated the discovery of CO by R. Wilson, K. Jefferts, and A. Penzias in 1970, with the then 36 Foot Telescope. The meeting was attended by approximately two-hundred thirty scientists from around the world. The proceedings are to be published by Kluwer.

NRAO will be host to the Sixth Annual Conference on Astronomical Data Analysis Software and Systems (ADASS) in 1996. ADASS '96 will be held in Charlottesville, Virginia, September 22-25, 1996, at the Omni Hotel. The ADASS conferences provide a forum for scientists and programmers concerned with algorithms, software systems employed in the reduction and analysis of astronomical data. ADASS is an international meeting with published proceedings. We expect about 250 attendees from institutions around the world to attend, with interests covering most areas of astronomy.

IX. 1996 PRELIMINARY FINANCIAL PLAN
by Budget Category

(NSF Funds, $ in thousands)

	New Funds	Uncommitted Carryover of 1995 Funds	Total Available for Commitment	Commitments Carried Over from 1995 Funds	Available for Expenditure
Operations					
Personnel Compensation	$17,783		$17,783		$17,783
Personnel Benefits	5,690		5,690		5,690
Travel	643		643		643
Material & Service	7,839		7,839	700	8,539
Management Fee	625		625		625
Common Cost Recovery	(500)		(500)		(500)
CDL Device Revenue	(100)		(100)		(100)
Total Operations	$31,980	0	$31,980	$700	$32,680
Research & Operating Equipment	600		600	120	720
Total NSF Operations	$32,580	0	$32,580	$820	$33,400
Design & Construction					
GBT	0	3,000	0	6,000	9,000
TOTAL NSF PLAN	$32,580	$3,000	$32,580	$6,820	$42,400

IX. 1996 PRELIMINARY FINANCIAL PLAN

by Function/Site

(NSF Funds, $ in thousands)

	Personnel	Salaries Wages and Benefits	Materials Supplies & Services	Travel	Total
Operations					
General & Administrative	27	$1,649	$955	$110	$2,714
Research Support	51	4,256	1,210	264	5,730
Technical Development	23	1,513	130	20	1,663
Green Bank Operations	85	4,296	547	35	4,878
Tucson Operations	26	1,555	553	34	2,142
Socorro Operations	210	10,204	4,444	180	14,828
Management Fee			625		625
Common Cost Recovery			(500)		(500)
CDL Device Revenue			(100)		(100)
Research & Operating Equipment			600		600
Total NSF Operations	422	$23,473	$8,464	$643	$32,580

IX. 1996 PRELIMINARY FINANCIAL PLAN

NRAO Non-NSF Funding

($ in 000's)

Organization/Project	1996 Funds
USNO:	
Ops & Maintenance	$412
GB/HA Repairs	212
Hardware	106
NRL Interferometer	162
NASA:	
Science OVLBI	400
Earth Station OVLBI	400
Miscellaneous	100
TOTAL	$1,792

APPENDIX A - NRAO SCIENTIFIC STAFF ACTIVITIES

There are approximately 80 individuals with Ph.D. degrees at the NRAO. Most of these people are astronomers, some are engineers, and some are computer science professionals. All of them include a strong research program as one important component of their Observatory responsibilities. In carrying out their tasks these individuals see ways to enhance the observing equipment, to streamline observing techniques, and to improve the software. They take the opportunity to do so by conducting challenging observations or otherwise experimenting within the bounds of a competitively reviewed observing program. In so doing the NRAO staff scientists develop a proficiency with the instruments and data analysis procedures that can be communicated to NRAO users. This has been, and continues to be, an effective mechanism to expand the horizons of radio astronomical research.

The specific astronomical research planned by the NRAO scientific staff in 1996 is summarized below by area of research.

1. Sun and the Solar System

The Solar System

Radio observations of objects in the solar system provide information about the temperature, the composition and the structure, roughness or texture, of the material of which they are comprised. In 1996 observations are planned of several planets. These data will complement data obtained at other wavelengths and with other space and ground-based instruments.

The 1994 collision of the comet Shoemaker-Levy/SL9 with Jupiter had the very unexpected consequence of causing the non-thermal emission from Jupiter to increase. This result was particularly surprising because the non-thermal radiation comes from relativistic particles spiraling in the magnosphere of that giant planet. The comet, largely a mass of ice and dust, has no relativistic particles and no magnetic field. It is therefore unexpected that any effect on Jupiter's relativistic particles or magnetic field would be seen. But such was the case. In fact, the non-thermal radio emission remains elevated, decaying only slowly with time. In 1996 observations at 1400 MHz with the 140 Foot Telescope will continue to monitor the decay in the hope that these observations will help to unravel the source and mode of transport of the energetic electrons in Jupiter's magnetosphere. These observations will be especially important when made at the time of the passage of the Galileo spacecraft into and around Jupiter.

Investigations of the surface composition of Mercury will be made using radar observations that were obtained in 1995. The radar data, obtained from signals transmitted by the JPL antenna at Goldstone and imaged upon reflection at the VLA, will be used in concert with 13 cm data of the polar regions obtained with the Arecibo Telescope. The hope is to understand whether Mercury's surface is dusty, rocky, rough, or smooth.

The peculiar spot on Mars known for its exceptionally low radar reflectivity, a spot called stealth, will be investigated by means of its microwave emissivity. Observations of Mars will be made at 43 GHz in the hope of establishing the disk brightness temperature at 7 mm wavelength and to determine the surface and near-surface composition of the body. In the course of this study stealth should show up with an emissivity near unity—we shall see.

2. Stars and Stellar Evolution

The youngest stars we know of are identifiable by their thermal infrared emission as localized warm spots in an otherwise cold molecular cloud. Such young stars are commonly associated with maser emission from OH, H_2O, or CH_3OH. In either case the emission is from thermally heated gas or dust. Throughout their *youth* and *middle age*, while stars are on the main sequence, the light they emit is again the result of thermally heated gas, but not entirely so. Some stars, and some regions of nearly all stars, are sources of non-thermal radiation which is reflective of the production of relativistic particles and strong magnetic fields in the stellar atmosphere or environment. At the end of their nuclear-burning lives, stars expel the successive outer regions of their atmospheres until they reach the point that most of the stellar mass has been removed. For such evolved stars the residual stellar atmosphere cools and radiates thermal molecular line emission as well as thermal dust continuum emission. Each of these three stages of stellar evolution will be investigated at the NRAO in 1996.

Early Evolution of Young Stars

Water masers trace out regions of the densest gas that has not yet gravitationally collapsed to the extent that a self-luminous star has formed. Monitoring of the water maser emission with the VLBA in 1996 will be used to try and understand the kinematics of the regions that are conducive to the formation of stars. Toward the low-luminosity maser emission regions which are seen in regions with high-velocity molecular outflows, the understanding is that the masers arise as flow impacts on quasi-stationary objects such as proto-planets. A program of monthly observations of water masers will be used to determine the actual luminosity function of the water masers and the correlation between the molecular outflows and the water maser presence. These VLBA observations will help to determine the cause of the rapid spatial and temporal maser variations, and they will be used as tools to track the motions and hence the possible orbits of the dense clumps that may be proto-planets.

Still another probe of the early phases of evolution of the most massive stars is the wind blown by the radiation pressure of a newly formed star. It is now believed that the ring nebulae around Wolf-Rayet stars (the most massive stars known) result from three different epochs of mass loss—an O-star phase, a luminous supergiant phase and the W-R phase itself. The interaction of the wind and the surrounding interstellar medium occurs primarily in the first phase. There has been considerable interest in measuring the neutral material associated with the outer rings, since the mass and dynamics of this material provide information about the duration and extent of the mass-losing phase of the progenitor O-star, but the large angular extent of the rings has made molecular line studies difficult. With the advent of on-the-fly mapping with the 12 Meter Telescope, it is possible to map the interstellar region into which the wind is expanding. The study in 1996 will entail observations primarily in CO, but if the CO work is successful some observations of a shocked gas, such as SO or SiO, would be undertaken.

Active and Main Sequence Stars

Studies of the binary X-ray star Cognosce X-3 will continue in collaboration with astronomers who have been taking daily variability data with the Green Bank interferometer. Data taken prior to the 1980s are being reprocessed to recover low amplitude measurements. Very low levels of quiescent radiation (<100 mJy) often precede large radio outbursts. Scenarios to explain this phenomenon are being investigated in the context of merged X-ray and IR models of the X-ray binary star. When the density of the stellar wind from the W-R star increases, the X-ray luminosity increases, and a radio outburst is more likely owing to increased accretion in a disk around the compact member of the binary. Temporary quenching of the radio emission by dense ejecta from the W-R star may account for the low radio flux prior to an outburst. The source continues to be monitored daily.

Simultaneous VLA, VLBA, and ASCA (X-ray) observations of the active star UX Ari will be made to combine the two main indicators, X-ray and radio emission, with high spatial and spectral resolution. Using phase-referencing, very low levels of radio emission can be reliably detected. Further observations will be made to confirm the existence of an extended halo of emission surrounding UX Ari and the similar AR Lac star HR1099. A likely model for the phenomenon involving gyrosynchrotron emission from a diffusing cloud of mildly relativistic electrons generated by a compact flare on the cooler secondary star will be studied. A thorough observational program will investigate the evolution of one of the halos during an entire orbital period.

Evolved Stars

The circumstellar envelopes of mass-losing evolved stars will be studied by means of emission from the SiO molecule in the circumstellar wind. Because of the high excitation required for SiO maser emission, the masing region must be very close to the stellar photosphere. This location and their intense emission from spatially confined areas make the masers ideal diagnostics of the stellar mass-loss mechanism. The SiO masers will be studied with the 12 Meter and its polarimeter to track polarization features during one or more stellar cycles. Studies will be made of multiple transitions so that the excitation of the molecular emission can be investigated, also over an entire stellar cycle.

The SiO masers will also be studied at high angular resolution using the VLBA. Such observations provide unique insights into the maser physics as well as the kinematics of the maser flows and the magnetic field distribution in such objects. Polarization information also enhances the reliability of proper motion identifications for pairs of maser components in separate epochs. The scientific problems which can be addressed include the nature of post-AGB evolution towards planetary nebula status, the origin of polarized maser emission, and the onset of asymmetric outflows in proto-planetary nebulae. For the circumstellar SiO masers, which occur in the extended atmosphere of the central star, there are opportunities to determine the kinematics and magnetic field distribution close to the photosphere, as well as the change in maser morphology throughout the pulsation cycle.

Observations are also planned of H_2O masers around evolved stars. The water masers to be studied have been chosen to overlap strongly with the sample of SiO masers being investigated. The aim is to use all these data, plus similar observations of OH masers, to produce a synthesis of stellar maser emission that will lead us to a complete picture of the circumstellar envelope around late-type stars.

In 1996 attempts will also be made to verify a possible detection of ammonia in the circumstellar envelopes of a carbon star with oxygen-rich dust. If the tentative detection can be verified, it will offer the best evidence to date for an explanation of the oxygen-rich nature of the circumstellar dust in these unusual stars. Previous models have suggested binary companions and even a complete overhaul in underpinning theories of late stages of stellar evolution may be responsible. The alternative model suggests instead a chemical explanation for the oxygen-rich dust and is based on these stars having lower luminosity than other asymptotic giant brand stars. The chemical model predicts an abundance of ammonia, whereas in other AGB stars of high luminosity the nitrogen is bound up in HCN and CN. It will be possible to discriminate between these two possibilities observationally.

Finally, the structure of the magnetic field in circumstellar envelopes will be studied by means of VLBA observations of the OH masers toward a large sample of mass-losing stars. Observations will be made of a complete sample of circumstellar OH masers. With such a data set it will be possible to determine the prevalence of magnetic fields in late-type stars and to build up statistics on stellar OH maser sizes.

3. Supernovae and Supernova Remnants

There has been no supernova recorded in the Milky Way for the past 400 years. All our information on the supernova phenomenon comes from the study of supernovae in other galaxies and, indirectly, from observations of the sites of very old supernovae in the Milky Way. Observations of both recent supernovae beyond the Galaxy and of the remnants of historical supernovae nearby will be made in 1996.

The earliest stages of supernovae can be studied only by observing supernova events in distant galaxies. At this time fourteen radio supernovae have been detected with ages less than 25 years. Multi-wavelength radio light curves have been determined for ten of these objects as part of the observational program with the VLA. The goals for the continued study in 1996 include:

- Attempts to establish the density distribution of the pre-supernova circumstellar envelope and thus the mass-loss rate for the progenitor stars. This can only be done if the supernovae are detected early in their development. The optically thick multi-frequency radio light curves are a powerful probe of the physical conditions of this medium.
- Efforts to establish the range of the radio luminosity distribution of supernovae. Supernova Types Ib and II have been detected as radio emitters with 6 cm luminosities between 10^{26} and 10^{28} ergs/sec/Hz. No Type Ia supernova has ever been detected. The low end of the SNII luminosity range can only be studied by observing nearby supernovae.
- Studies of the prompt radio emission that will eventually fade completely or enter the phase of a traditional radio supernova remnant, where the radio emission is produced by interaction with the interstellar medium. It is hoped that this transition can be observed in older supernovae such as SN1979C and SN1970G.

In addition to the search for new radio supernovae, monitoring will continue of six supernovae to establish their radio light curves. Supernova 1979C in M100 remains the definitive example of the SNII class and has shown flux density variation with a four-year period during its decay phase. Supernova 1980K is still being intensely monitored optically and in its X-ray emission. Supernova 1986J and 1988Z are examples of the Type II optically peculiar subclass. Supernova 1993J is strong, still evolving and will be the best studied supernova to date. The supernova 1994I in M51 is a recent well-studied Type Ib supernova which is being monitored through its decay phase.

The later stages of the evolution of supernova remnants can be best studied by observations of historical remnants in the Galaxy. The flux density of the 900 year old remnant Cassiopeia A is known to decrease at about one percent per year; however observations in the mid-1970s indicated that its flux density at 38 MHz actually increased. Little has been done in the intervening years to pursue this surprising result. A special 3-element interferometer has been built in Green Bank to monitor the Cas A flux density over the range 30 to 120 MHz so that the flux density variation can be reliably measured. If the low-frequency flux density is increasing, this would be firm evidence for continued particle acceleration nearly a thousand years after the supernova outburst.

The interaction of the supernova remnant with dense molecular clouds in the vicinity of the event will be studied by observing the OH line emission from material near galactic supernova remnants. It appears that the maser lines observed in W28 and other remnants are collisionally excited by molecular hydrogen heated by the supernova shock wave. Work continues to search for OH masers in a complete sample of remnants. It appears that the OH line will give a powerful diagnostic of the interaction of supernova remnants with molecular clouds.

4. Pulsars

Observations of pulsars have the capability to tell us about the statistical properties of the final stages of stellar evolution, and they can be used as probes of the interstellar medium, of general relativity, and of the physics of neutron stars. All of these things will be pursued observationally in 1996.

The widths of pulsar average profiles tend to broaden with decreasing radio frequency, but above a break frequency the pulse width remains constant. In what may be a related phenomenon, the linear polarization averaged over a pulsar's pulse is constant at low frequencies but rapidly decreases above another break frequency. Such behavior may be caused by the birefringence of the plasma above pulsar polar caps. A model has been developed of pulse broadening and depolarization to investigate the observational consequences of the birefringence hypothesis. A prediction of the model is that the break frequencies of the width and polarization spectra should be correlated. Such a correlation appears to be observed; further tests are underway.

The radio emission from pulsars typically has a high degree of linear polarization with very little circular polarization. When present, the circular polarization tends to change sense symmetrically about the center of the pulse profile. This effect is generally attributed to the geometry of the radio emission region. However, the circular polarization of a few pulsars such as PSR 1823-13 and PSR 1702-19 is not only high but possesses the same sense of polarization. A possible explanation for the polarization of these objects is the conversion of linear to circular polarization by propagation effects in the pulsar magnetosphere. Assuming that propagation effects should be frequency dependent and that a geometric origin of circular polarization should also be frequency dependent, observations of these two pulsars on the 140 Foot will be used to explore the physics of the polarization phenomenon.

It is expected, but unproved, that gamma ray bursters are somehow related to pulsars. This idea will be pursued in 1996 by coordinated searches for gamma ray bursts and radio outbursts. The radio search is aimed at detecting radio emission in the days and weeks following the gamma ray events. Cosmological models for the gamma ray bursts predict time-variable radio emission in the range of 1-10 mJy. The clues as to where to look and when will come from the High Energy Transient Explorer satellite; the VLA will be used to search for the radio counterparts.

5. Molecular Clouds and Star Formation

Star formation is such a profoundly complicated process because it involves the chemistry, density, temperature, magnetic field, and kinematics of the material that will make up the star. Our knowledge of all these parameters of a molecular cloud is still poor. Nevertheless, we can make some progress in our understanding by probing molecular clouds, and young stars, both on the large scale in molecular clouds and on the smallest scales characteristic of the protostars themselves. Both such investigations will be conducted in 1996.

The chemistry of molecular clouds can best be studied in isolated translucent molecular clouds that are at low galactic latitude, near but not in the galactic plane. More than 38 molecular species have been observed and are being modeled with hydrostatic equilibrium polytrope structures which allow a complete specification of physical conditions needed to understand the excitation of the various chemical species. The results so far indicate that ion-molecule chemistry provides a sufficient framework for understanding all molecular species with the exception of formaldehyde. H_2CO requires grain chemistry starting with the adsorption of CO onto grains.

This idea can be checked via observations of the silicon analogue of H_2CO, H_2SiO (silanone). It is believed that all Si in the gas phase forms SiO which then freezes onto grains in dense clouds, and it is evaporated again only near massive stars. On grains SiO is expected to form H_2SiO analogously to the formation of H_2CO from CO. These ideas will be tested by observations of H_2SiO which is yet undetected in astrophysical environments.

The variation of chemistry from one molecular cloud to another will be revealed by a spectral survey of the 2 mm band (135-170 GHz) of seven distinct clouds. The survey, of unprecedented sensitivity, will allow the first comprehensive comparative study of the chemistry of several star-forming regions of various evolutionary phases. The survey contains an enormous density of lines. The survey will be complete in 1996, and will be used to extract the maximum information about the physical conditions and the chemistry in each molecular cloud.

The chemical variety of interstellar clouds is also revealed by absorption observations toward extragalactic continuum sources. These studies allow us to study a single line of sight through galactic molecular gas with an extremely small angular diameter; the studies amount to a needle probe of interstellar gas. Observations are being made of about a dozen simple molecules toward seven sources. One of the molecules, OH, is particularly important because its reactions with C^+ are important in the early development of diffuse cloud chemistry. Remarkably, it is found that there is a component of OH emission which overlays deep HI absorption but which is typically unseen in other molecules or in OH absorption. This is being attributed to chemical processes in the cool atomic portions of the interstellar medium which may be only weakly molecular. The converse situation is found in the diffuse cloud toward the star Zeta Oph: the relatively strong CO and HCO^+ emission from this interstellar cloud has no OH counterpart even though both CO and HCO^+ are chemical derivatives of OH! Interstellar chemistry is very complicated, indeed.

The signpost of low mass star formation is an infrared dust spectrum that resembles a cold, single-temperature greybody. Such a spectrum reflects very little heating from a central source. However, observations of the protostar HH24MMS show, contrary to this idea, that there may exist star/disk systems embedded in envelopes of gas and dust which become optically thick in the far infrared. An initial investigation suggests that such an envelope would have a very narrow spectrum, giving the appearance of a low dust temperature. This result will be studied further, because it has an important implication on the widely used classification of protostellar continuum spectra.

The formation of high mass stars is found in and adjacent to HII regions; the Orion complex being the prototypical example in the Galaxy. Observations of the 7 mm continuum dust emission from the Orion complex will be made with the VLA to investigate the dynamics and chemistry of the hot core region and IRc2. Preliminary results indicate that the proximity of the nearby HII region catalyzes star formation with the older protostars located closer to the HII region/molecular cloud interface.

Several observations in 1996 will be addressed to the question of how some dense molecular cores form stars of all masses and how the cloud material is transformed by the stars within them. The coldest cores have been shown to be sites of the youngest stars. The cores have been targeted in VLA surveys of ammonia emission with more than a dozen such objects identified so far. In objects so young that a bipolar flow is not yet evident, ammonia structures are always to be seen. In another group of objects, somewhat more evolved but still quite young, very cold ammonia exists but it shows little correlation with cold dust structures enveloping the star. In a final group of sources, older still, warm ammonia is seen that correlates spatially with dust IR emission and may show up in outflowing gas as well. It appears that ammonia becomes severely depleted, perhaps thought freezing onto grains, in the final stages immediately preceding stellar ignition. These correlations will be further pursued in the coming year using VLA molecular images, images of the dust emission in the submillimeter band and through observations made at high angular resolution with the OVRO millimeter array. Because the star formation process is so complex, the tools one needs to investigate it are also necessarily diverse.

6. Emission Nebulae

Ionized gas excited by bright stars is both a conspicuous component of the galaxy and it is a physical environment well-suited to a comparison of our understanding of physics with our understanding of astronomy. Several such tests will be carried out in 1996.

High resolution VLA observations of radio recombination lines, water vapor, and hydroxyl masers, and the radio continuum from selected compact and ultracompact HII regions will be used to investigate the gas surrounding the most luminous stars in the Galaxy. The recombination line observations will permit a study of the kinematics and dynamics of the ionized gas leading to models of the evolution of HII regions. Observations of water masers and OH masers will facilitate an examination of the interaction of the ionized gas with the natal molecular cloud. Finally, high-resolution observations of the radio continuum emission will allow us to study the ionized gas very close to the exciting star, and it will help us determine the source of the ionization. These studies will focus on several different regions of the Galaxy in an attempt to assess the variation of the HII region physical parameters across the Galaxy.

One parameter of cosmological importance is the ratio of the abundance of ^3He to that of atomic hydrogen. This particular ratio is related to the baryonic mass density in the universe and can be used to establish that ratio if it can be reliably determined. Observations are planned of the $^3He^+$ line, the H^+ recombination lines and the $^4He^+$ lines in a wide variety of galactic HII regions. Observations of the $^4He^+$ lines are of critical importance in establishing the ionization structure and the density structure of the HII regions, both of which are needed in the analysis of the $^3He^+$ data.

7. The Galaxy

Gas in the interstellar medium continually changes its phase in response to local conditions. Gas closely exposed to starlight is ionized or heated, cold tenuous gas will be neutral but largely atomic, cold dense gas will combine into a molecular form or find itself deposited onto dust grains. Understanding the quantity of gas in each form and understanding the large-scale processes which cause changes between them are the subject of several studies by NRAO staff in 1996.

The galactic extent and distribution of warm ionized gas in the Milky Way will be explored by means of observations of recombination line emission in the diffuse ionized medium using the 140 Foot Telescope. Emission and absorption observations of the low frequency recombination lines toward pulsars can be compared with numerous observations of HI and other species in the same directions. This will permit comparisons to be made between such things as the pulsar dispersion and the HI column density as determined from HI absorption measurements. More direct observations will also be proposed to permit us to understand the vertical distribution of this ionized component of the interstellar medium and its association with the HI.

Observational searches will also be made for the coldest gas in the Milky Way. Following up on suggestions that a large mass of molecular gas could exist undetected if that gas had an excitation at or near the temperature of the microwave background, 3 K, a survey will begin in search of molecular absorption lines toward 15 extragalactic continuum sources in the direction of the Galactic anti-center. Observations will first be made in the OH lines with the VLA and, once the more interesting lines of sight are determined, CO emission will be sought with the 12 Meter in order to determine excitation temperatures of the gas.

The physical state of the gas that is well removed from the Galactic plane will be studied by means of observations combining HI spectroscopy with soft X-ray and ultraviolet data. The goal is to understand the properties of high-velocity HI clouds and their relationship to the soft X-ray background. Even the simplest questions, for example the relationship of the halo gas to the disk gas in the Galaxy, are still without answers.

Observations of the single unique location in the Milky Way, the galactic center, will be made in several creative ways in 1996. A study is being made with 3 mm continuum maps from the 12 Meter of the distribution of non-thermal and thermal continuum emission in the central degree of the Galaxy. Preliminary data show that the non-thermal arc is clearly seen in the observations, and investigations are underway to establish the spectral index along the arc. It is hoped that these studies will lead to an estimate of the age of the electrons responsible for the emission along the arc. This age should be that of the time since the last major outburst or explosion at the galactic center.

The compact non-thermal source at the galactic center that is thought to be the blackhole at the center of our galaxy, Sgr A*, will be studied using millimeter-wave VLBI observations. The goal is to determine the physical size of the radio emission region surrounding this unique accretion-driven blackhole source of relativistic particles and magnetic fields. In 1996 the observations will be extended to higher frequencies, 150 and 230 GHz, which represents a considerable technical challenge. It will also establish a record for the angular resolution achieved in astronomy at any wavelength with either ground-based or space observations.

8. Normal Galaxies and Clusters

Elliptical Galaxies

Elliptical galaxies are dominated by older stars and show little evidence for gas and dust. Nevertheless, it is the ellipticals that host the bright nuclear sources that power the most luminous radio galaxies. The elliptical galaxy M84 is such a galaxy. It hosts a FR-I radio continuum source. Its two VLA jets are initially asymmetric, but they become symmetric about 1 kpc from the nucleus. A non-relativistic turbulent jet model can describe the brightness and spreading rate evolution of individual jets in FR-I sources, but it cannot account for the trends in the symmetry properties of the jets seen in the VLA image of M84. Is the VLBA or parsec scale, brightness asymmetry an extrapolation of the asymmetry decline seen in the VLA jet? If so, this would imply a common physical origin for the symmetrization process between VLBA and VLA scales. Observations with the VLBA will be used to evaluate the parsec-scale brightness asymmetry for comparison with VLA symmetrization results that could result from Doppler boosting in a relativistic flow. These ideas will be assessed.

Spiral Galaxies

Dusty, gas-rich, spiral galaxies are active sites of star formation, their interstellar medium is loosely bound to the gravitational potential of the gaseous disk, and the gaseous material responds to the gravitational tidal forces as one galaxy passes by another. Study of the interstellar disk gas therefore provides a diagnostic of the gravitational dynamical history of a galaxy. There are a number of important questions that can be addressed with radio observations.

Preliminary observations have been made, but not fully analyzed, of the CO distribution within the central degree of the nearby galaxy M31. These data are expected to yield certain large-scale parameters of the molecular distribution within M31 at an unprecedented high resolution. The intention is to follow up on these initial observations with the hope eventually of covering most of this large object. This project has only become possible with the advent of the on-the-fly rapid mapping technique and sufficiently sensitive receivers. It has been necessary to develop further existing observational and analysis algorithms which will benefit all future users of the 12 Meter as well.

A recent study of the Sa galaxy NGC 1291 has shown that there is a striking spatial anticorrelation between the hot and cold gas, supporting the suggestion that the hot gas is a bulge phenomenon and the cold gas is concentrated to the disk. Additional observations of the cool gas in the X-ray galaxies NGC 2775 and NGC 3623 have now been completed. The CO in NGC 2775 is concentrated in a ring of approximate radius 5 kpc , a region of the disk which lies outside the prominent central bulge. Both CO(1-0) and CO(2-1) are detected over a large radial range in NGC 3623. The analysis of these data, and of HI synthesis data, will concentrate on the region where the cold and hot components apparently come together, to explore whether a hole in the distribution of cool gas generally corresponds to the region of the hot gas, or whether the hot gas has an embedded cool component. Additional observations at high angular resolution of the emission both X-ray and CO will be made.

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

There is a further on-going and extensive research program to study the properties of the interstellar medium in early-type galaxies. Observations at radio, optical, and X-ray wavelengths are being obtained. These data sample both the cold, HI and CO, as well as the hot, X-ray, gas. The former is a measure of the potential for future star formation while the latter is thought to measure the gas shed by evolving stars. The relative masses of these two components will reflect the rate at which mass is cycled through stars.

Irregular and Dwarf Galaxies

Low mass, gas-rich galaxies that lack a clear morphological structure are referred to collectively as irregular galaxies. Among the properties they share are these: the star-formation rate is low even though the ratio of gas mass to stellar mass is as high as, or higher than, that in active spiral galaxies; the metallicty is low. Understanding the history and evolution of irregular galaxies is a high priority for a detailed understanding of those spiral galaxies that are gravitationally influenced by irregular or dwarf galaxies.

Some irregular galaxies have been identified as undergoing bursts of star formation for the first time. Of these galaxies, the HI-rich, low luminosity dwarfs may be precursors of normal spiral and elliptical galaxies. As systematic study with the 140 Foot Telescope of the HI envelopes of low luminosity galaxies should help determine which among these are the best examples of such precursor galaxies.

A survey of 20 HII galaxies, star-forming dwarf galaxies, showed that over half of them have a companion HI cloud. This implies that the hypothesis that interactions with HI clouds triggers the violent star formation which we see in HII galaxies seems to be valid. Observations have begun of a comparison sample of low surface brightness dwarf galaxies with properties identical with those of the HII galaxies, except that the control objects are not forming stars. The goal is to compare the properties of the HII galaxies with those of the control sample to see if there are intrinsic differences between the two groups of galaxies which might explain the lack of star formation in the control group. An additional data set for the two samples will be obtained from CO observations of all the galaxies in both groups. If the only difference between the HII galaxies and the control sample is the presence of HI companions to the former group, then the cause of the origin of star formation in HII galaxies will have been established.

An innovative way to determine the abundance of heavy elements in dwarf galaxies makes use of both VLA HI observations and HST observations of OI absorption spectra. The abundance of OI depends on knowledge of the intrinsic (unbroadened) absorption line which cannot be determined with the instruments on-board HST. Using the VLA to get an HI a line profile, and then using that profile width to apply to the HST observations, the metallicity of the dwarf galaxies can be established.

Finally, the molecular component of the interstellar gas in the Magellanic clouds will be investigated by means of a survey of selected ultra-compact HII regions for methanol maser emission. The purpose of this survey is to examine the effects of low metallicity on the existence of methanol masers and to identify a sample of masers for subsequent VLBI studies. These same observations will permit a determination to be made of the transverse motion of the Magellanic clouds relative to nearby extragalactic sources. With these observations of the transverse velocity together with the spectral observations that give the radial velocity, we can determine the orbit of the Magellanic clouds around the Milky Way, and from this the mass of the Milky Way can be unambiguously established.

Galaxy Formation, Interactions, Physics and Dynamics

The interacting, far-infrared luminous galaxy Arp 105 is a magnificent example of a spiral galaxy in the process of merging with an elliptical galaxy. Huge gas tails stretch 100 kpc to either side of the spiral. All HI is found in these tails, with major concentrations seen near the tips. No HI is detected in the merging objects. The HI clumps near the tips contain newly formed stars. These objects could become self-gravitating and detach from the tails, making them dwarf galaxies in their own right rather than being tidal debris. Strong CO emission is found exclusively at the center of the merging activity. The physics of the interaction will be modelled in 1996 in an attempt to generalize the interaction seen so clearly in this system.

Ocular galaxies are interacting systems which are caught at a very particular time in their interaction, when one of the objects displays a strong double arm which gives it the appearance of an eye. Hence the name ocular galaxy. Probably the best example is the galaxy IC2163 which is interacting with NGC 2207. Because the ocular structure is short lived and because it calls for a prograde tidal interaction in the plane of the disk, this reduces the number of possible orbits when attempting to model the interaction. It should be possible to obtain an accurate model of the entire interaction in this system, including the mass and kinematics of both component galaxies.

A VLA search will be conducted for non-luminous HI clouds in the vicinity of Seyfert galaxies. Such clouds would not have been detectable in optical searches but, should they exist, they could provide the gaseous material needed to power a supermassive object with an accretion inflow. This hypothesis will be tested in 1996.

To understand galaxy structure and to have insight on galaxy formation and evolution, it is essential to understand the distribution and characteristics of molecular gas in galaxies. In 1996 there are several ways to obtain this understanding. For example, the distant galaxy IRAS F10214+4724 at $z = 2.3$ is apparently one of the most luminous and gas-rich galaxies known. Although recent observations suggests that it is magnified by an intervening gravitational lens, it remains an important test case for theories of galaxy formation and structural and chemical evolution. Analysis will continue of interferometric and single dish observations of molecular gas in this galaxy and searches will continue for other high redshift, gas rich objects.

Anomalies in the physical and chemical conditions of molecular gas in active infrared galaxies may provide insight into their nature. To this end a multi-line study of several chemical species and isotopomers in Arp 220, the prototype ultraluminous galaxy, will be undertaken. The mass of the different chemical species and their distribution will provide an important clue as to their structure and evolution.

Further, by analyzing interferometric and single dish maps of CO in contrasting galaxies, an effort will be made to understand the connections between galaxy morphology and global galactic properties.

Observations for galaxies in their earliest stages will also continue via searches for HI emission with the VLA. The redshifted 21 cm line occurs at a frequency accessible to the VLA, 305 to 335 MHz, for redshifts of 3.1 to 3.7. Searches for such galaxies will be made; the VLA sensitivity is such as to allow detection of gas-rich protogalaxies with approximately 10^{12} solar masses of hydrogen.

Galaxy Clusters

Observations of luminous clusters at z = 0.02 to 0.08 will be carried out using wide format CCD detectors on the telescopes of the Wyoming Infrared Observatory and KPNO. A tessellating technique has been developed in order to produce 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 of this work 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.

VLA observations of 43 intermediate Abell clusters near z = 0.2 will be used to search for lensing of more distant background sources. A secondary objective is to examine the evolution of the radio luminosity function for cluster sources.

9. Radio Galaxies, Active Galaxies and QSOs

The physical element that ties together the active galaxies that include radio galaxies and, we suspect, the quasi-stellar objects as well, is the presence of a supermassive blackhole in the galactic nucleus. Gaseous matter falling onto that black hole somehow, by a process we don't understand, gives up its gravitational energy to the acceleration of relativistic particles that are expelled from the vicinity of the black hole. The observational ramifications of the process include the presence of radio jets very close to the Schwartzschild radius of the black hole. The VLBA is the instrument to make these observations.

Source Physics

The first detailed observation made by the VLBA was an image of the radio galaxy 3C 84 (NGC 1275) which revealed, for the first time, the presence of a counterjet. A simple relativistic jet model of the source can account for the jet/counterjet brightness ratio at high frequencies, the jet to counterjet length ratio, and the observed motions of the jets. At frequencies below about 10 GHz the counterjet becomes undetectably weak. A model in which the counterjet is absorbed by free-free absorption in a medium outside of the jet, a medium perhaps associated with an accretion disk, is consistent with the observed flux densities. This opens the exciting opportunity to use VLBI observations to study the accretion region, outside of the jets themselves, on spatial scales of less than a parsec. Observations are planned in 1996 at high frequencies to characterize the absorbing region and to study the time evolution of the jet structures.

The time variability of still other objects, the QSOs 3C 345 and 3C 273, will be studied at regular intervals with the VLBA. The goal of these observations is to understand the variability in terms of the structural evolution of the brightness distribution of these objects. In addition the spectral properties of these objects will be investigated with the VLBA. These measurements will be used to test directly the predictions of the shock model for compact radio sources. The same objects will be observed at the highest VLBA frequencies, 43 GHz, to produce very high fidelity images of the prominent jet for comparison of observations obtained with the Hubble Space Telescope. Together with the VLBA observations the acceleration of relativistic particles in these sources can be explored in detail.

The apparent source physics of energetic extragalactic sources can be deceptive if those sources are viewed in the background through an intervening galaxy that acts like a gravitational lens to modify the appearance of the source. Galaxy modeling for VLBA observations of the gravitational lens system MG 1654+1346 will begin in 1996. The observations will be used in an attempt to detect the extended structure of the source itself and in order to measure the magnification of the lens as a function of angular distance to the lens. Since the background objects are viewed through the intervening galaxy, one can hope to observe absorption by the neutral hydrogen in the foreground galaxy. This idea also will be tested observationally in 1996.

A complete sample of 120 radio sources at a common resolution of 0.5 milli-arcseconds will be observed on regular intervals in order to study their relative motions. Detailed studies will be made of selected sources as examples of a nearby powerful subluminal source, 3C84, of a compact double source, CTD 93, of an extended radio galaxy with superluminal motion, 3C390.3, and of the enigmatic object 2134+004 in an attempt to reveal the underlying cause of the differences between these sources.

Source Environment

One can use VLA and VLBA observations to search for the effects of gravitational lensing in an unbiased way by comparing the total intensity images of the radio structure with the corresponding position angle images of the same objects. An extended program of imaging at both radio and optical wavelengths the jets of distant quasars will be conducted in order to find and use the symmetry breaking properties of gravitational lensing. The total intensity image of the radio jets will be bent by passage of a large gravitating mass (i.e., an intervening galaxy), while the position angle of the polarized brightness is not rotated. This combination leads to an observational signature of an intervening galaxy, which can be used to determine its mass, independent of the amount of light produced by that galaxy.

By good fortune, the line-of-sight toward the radio galaxy PKS 0454+039 passes within 3.7 kpc of the center of an intervening dwarf galaxy. Absorption measurements can tell us about the interstellar medium of that intervening galaxy, and such measurements are planned of HI using the VLA and of the optical and UV lines from the HST spectra. Together these data will give a unique opportunity to see if the QSO absorption lines, which normally occur at much higher redshifts, are similar to the absorption we see in this local dwarf galaxy. The hope is that it may be possible to conclude that absorption in dwarf galaxies, rather than absorption in the extended halos of normal galaxies, can be responsible for most QSO absorption systems.

10. Radio Surveys and Cosmology

In 1996 survey observations are planned on the largest possible scales, the whole sky, and on the milli-arcsecond scale. Both of these should provide unique insights into the structure of the universe and the origin of energetic objects within it.

Observations for the 1.4 GHz NRAO VLA Sky Survey (NVSS) will cover the sky north of declination -40 degrees by the end of 1996. The principal data products will be a set of 2326 continuum map cubes of the sky with three planes containing Stokes I, Q, and U images, plus catalogs of discrete sources. Production of new NVSS maps and catalogs will continue through 1996.

The IRAS Bright Galaxy Survey (BGS) of extragalactic sources stronger than 5.24 Jy at 60 microns has recently been extended to cover almost the entire sky apart from the Galactic plane. This fundamental sample is the far-infrared equivalent of the radio 3C survey. Unfortunately, most of the sources are only marginally resolved by IRAS. Since the far-infrared and radio brightness distributions of these galaxies are usually quite similar, high-resolution radio maps can be used as substitutes for the nonexistent far-infrared maps to indicate the sizes, structures, and precise positions of the far-infrared sources. VLA observations of the BGS are being made and, when complete, they will be used to complete a radio/IR atlas of the entire sample.

In a similar manner, the ROSAT X-ray All-Sky Survey has been cross-correlated with the IRAS point source catalog to yield a sample of nearly 300 galaxies emitting at both X-ray and far-infrared wavelengths. These identifications are complete but somewhat unreliable owing to large position uncertainties, the sources are not well resolved, and the dominant energy-generation mechanism is not known in most cases. High resolution VLA maps of all galaxies have been made to confirm or reject the identifications on the basis of accurate radio positions plus accurate optical positions measured on optical prints. The radio morphologies and flux densities will be used to distinguish between starbursts and active galactic nuclei as the principal energy sources and to better characterize the population of nearby X-ray galaxies.

On the arcsecond, angular scale surveys will be made by the VLA of fields being studied with the highest possible sensitivity by the Hubble Space Telescope. The goal is to correlate the faintest, and presumably most distant, optical objects with the faintest radio sources. A secondary goal is to establish new limits on the fluctuations in the cosmic microwave background on the arc minute angular scale.

On the smallest, milli-arcsecond, angular scales a survey will be completed of the compact structures seen in a complete sample of bright radio sources. The work aims at studying the morphology and structural variations of strong, flat-spectrum sources. The results will allow a meaningful application of cosmological tests, in particular the angular size-redshift test and the proper motion-redshift test.

11. Instrumentation and Observing Techniques

Among the advantages of being close to the telescopes at the NRAO, staff scientists are able to experiment with new observing techniques and to make the effort to make new instrumentation suitable for use by others. In 1996 many specific observations and instrumentation development programs are planned.

The new 43 GHz receiving system on the VLA has brought with it a need to establish a flux scale for calibration sources. To this end, all of the planets except Pluto have been observed together with many of the flux calibrators often used at millimeter-wave and submillimeter-wavelengths. In 1996 the planetary observations will be used to establish an absolute flux scale for some of the unchanging extragalactic and galactic sources. The flux densities of other possible sources will be bootstrapped from these data. Polarization calibration at 43 GHz will be even more difficult and will rely on polarization observations of Mars and on an understanding of the bulk dielectric constant of the Martian surface. This will be the basis of the flux scale and the flux densities of the other objects will be related directly to that of Mars.

Non-thermal calibration sources will be established from a sample of 4000 flat-spectrum sources obtained at both MERLIN and at the VLA. All of these objects will be observed to assess their structural data and to obtain positions of high precision. This should significantly increase the number of phase calibrators available to radio interferometers, and it should also yield some interesting new gravitational lens candidate objects.

The flat-spectrum calibration sources can be employed for phase-referencing of the VLBA, a technique that will increase the coherent integration times. The precise positions of these objects will also play an important role in defining the VLBA astrometric reference frame and in enabling routine VLBA phase-referencing to occur. The expectation is that the typical positional accuracy achieved by the survey should be less than 1 milli-arcsecond.

Calibration at the lowest VLA frequencies depends on an understanding of the Faraday rotation that occurs in the Earth's ionosphere. In 1996 experiments will be conducted to use the total phase delay predicted by the GPS system to correct the Faraday rotation of astronomical signals propagating through the ionosphere. The same system should assist the phase transfer system between observations made with the VLA 327 MHz and 74 MHz systems.

The most compact radio sources, the ones most suitable for use as calibrators because of their small size, often exhibit a variety of strange variability including radio to X-ray variability on a timescale down to days, superluminal motion, and possibly evolution with redshift. Observations combining VLA and VLBA shapshots of 120 sources will be used to provide uniform and contemporaneous measurements at 7 mm and 2 cm. The goals are to identify sources with the highest brightness temperature for subsequent observations with space VLBI observations and for VLBA observations at 3 mm wavelength.

Instrumentation developments proceed on a number of fronts, many of which are discussed elsewhere in this Program Plan. However, instrumentation research continues also on the next generation of SIS mixers, high frequency noise sources, and characterization of semi-conductor devices.

A broadband sub-millimeter (475-700 GHz) waveguide SIS mixer has been developed. This is a very simple fixed-tuned integrated mixer design that can be easily scaled to operate at any millimeter-wave frequency. At present four sets of the mixer block have been successfully fabricated. These devices will be evaluated soon.

Millimeter-wave noise sources are needed for telescope calibration and receiver testing in the lab. However, there are no noise sources currently available for frequencies greater than 120 GHz. Experiments are in progress using a frequency multiplier to upconvert noise power generated from a microwave noise diode to the millimeter-wave bands. Using this technique we may be able to produce sufficient noise power at 230 GHz from a L-band source and a frequency tripler and frequency multipliers. Tests will also be made using a harmonic mixer in place of the frequency multiplier. The further feasibility of extending the technique to 300 GHz range will be explored.

Characterization of SIS devices in terms of the junction's specific capacitance, critical current density, dielectric constant and the thickness of the insulator film and London penetration depth of the superconducting thin film play a very important role in designing of the SIS mixer circuits. It is crucial to have a good knowledge on these parameters so that we can explore and develop more sophisticated mixer circuits for the next generation SIS receivers for the MMA. A joint NRAO, UVa device characterization project has been established. This work is done in collaboration with AT&T Bell Laboratories, TRW, Conductus Inc., Hypres Inc., and NIST of the U.S. Department of Commerce.

APPENDIX B - SCIENTIFIC STAFF

(Does not include visiting appointments)

D. S. Adler — Interstellar medium; dynamics of spiral galaxies; clusters; star formation

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

C. S. Barnbaum — Evolved stars: kinematics, isotopic abundances, circumstellar structure

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

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

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

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

A. H. Bridle — Extragalactic radio sources

E. Brinks — Interstellar medium in nearby galaxies; HI studies of galaxies; star-forming dwarf galaxies

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

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

E. Carrara — Active galactic nuclei; VLBI

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 — Theory of synthesis telescopes; millimeter receivers; radio astronomy from space

V. Dhawan — Extragalactic radio sources; VLBI; instrumentation

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

D. T. Emerson — Nearby galaxies; star formation regions; millimeter wave instrumentation

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

C. Flatters — VLBI polarization studies of extragalactic radio sources

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

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

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

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

B. E. Glendenning — Starburst galaxies; scientific visualization

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

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

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

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

P. R. Jewell — Evolved stars and circumstellar envelopes; interstellar chemistry; millimeter-wave instruments and observing techniques

K. I. Kellermann — Radio galaxies; quasars; VLBI

A. R. Kerr — Millimeter-wave instrument development

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

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

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

H. S. Liszt — Molecular lines; galactic structure

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

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

M. M. McKinnon — Plasma astrophysics; pulsars; stellar radio emission; signal processing

A. H. Minter — Interstellar turbulence; space VLBI

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

J. Navarro — Pulsar astrophysics; instrumentation and techniques in radio astronomy

D. J. Nice — Pulsars; interstellar medium; interstellar scintillation

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

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

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

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

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

M. S. Roberts — Properties and kinematics of galaxies

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

A. Roy — Nearby galaxies; extragalactic radio sources

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

E. R. Schulman — Distribution of cooled gas at outer regions of galaxies

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

R. A. Sramek — Normal galaxies; quasars; astrometry; supernovae

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

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

J. M. Uson — Clusters of galaxies; cosmology

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

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

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

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

J. J. Wiseman – Galactic and extragalactic molecular clouds

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

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

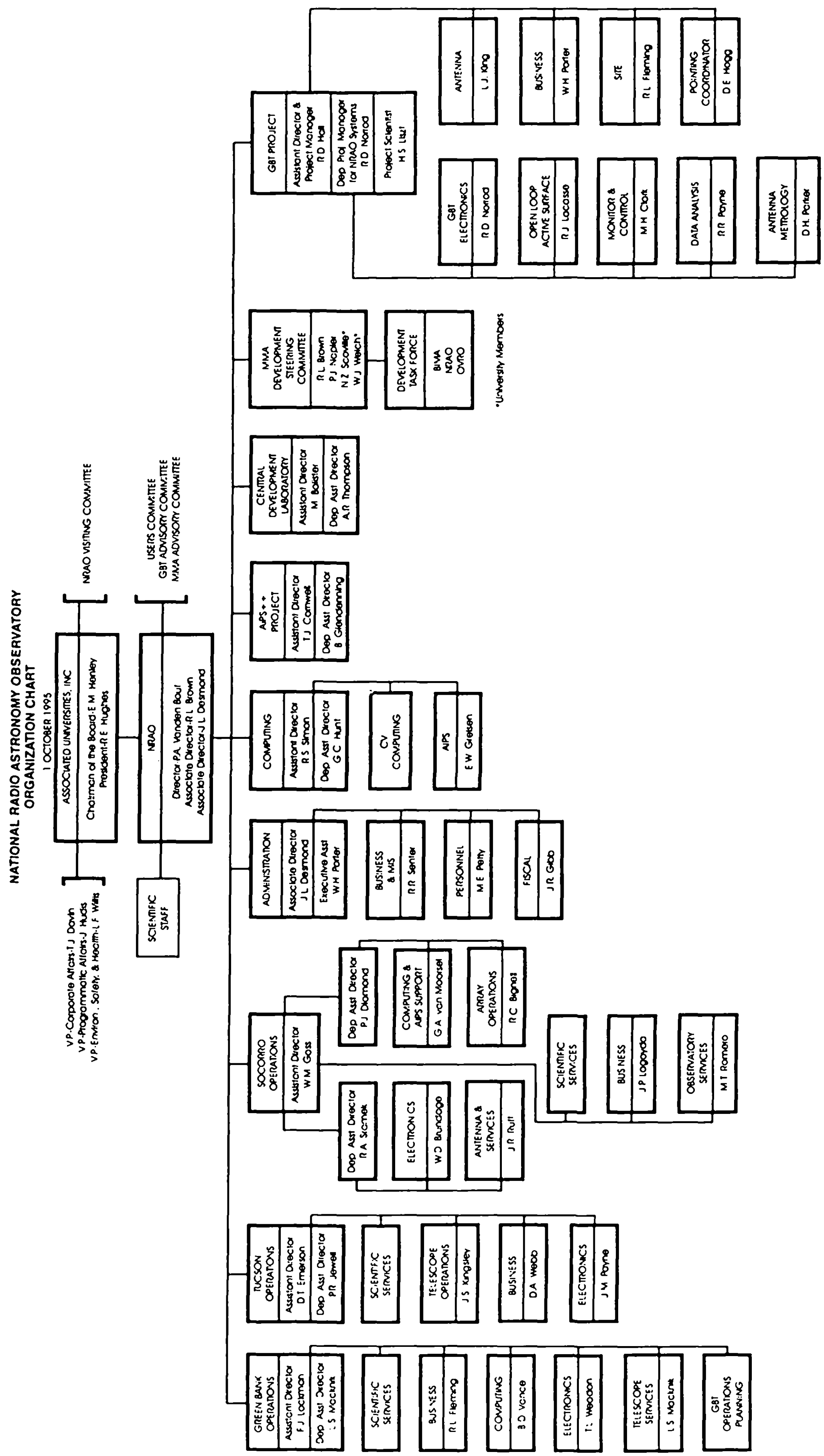
J. M. Wrobel — Normal galaxies; active galaxies; polarimetry

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

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

A. Zensus — Active galactic nuclei; compact extragalactic radio sources; high resolution interferometry; space VLBI

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:

D. B. Campbell	Cornell University
E. B. Churchwell	University of Wisconsin, Madison
N. J. Evans	University of Texas, Austin
R. Hanisch	Space Telescope Science Institute
K. Y. Lo	University of Illinois
J. Pipher	University of Rochester
M. J. Reid	Center for Astrophysics
L. F. Rodriguez	Instituto de Astronomia UNAM
A. I. Sargent	California Institute of Technology

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:

D. C. Backer	University of California, Berkeley
M. A. Barsony	University of California, Riverside
M. Bell	Herzberg Institute of Astrophysics
J. H. Black	University of Arizona
J. E. Carlstrom	California Institute of Technology
J. M. Cordes	Cornell University
J. M. Dickey	University of Minnesota

D. M. Elmegreen	Vassar College Observatory
R. S. Foster	Naval Research Laboratory
A. S. Fruchter	Space Telescope Science Institute
R. A. Gaume	U. S. Naval Observatory
R. Giovanelli	Cornell University
L. A. Higgs	Dominion Radio Astrophysical \Observatory
D. Hough	Trinity University
C. J. Lonsdale	Haystack Observatory
K. M. Menten	Center for Astrophysics
L. G. Mundy	University of Maryland
R. Mutel	University of Iowa
M. J. Reid	Center for Astrophysics
S. C. Unwin	California Institute of Technology
J. Van Gorkom	Columbia University
R. A. Windhorst	Arizona State University

3. Millimeter Array Advisory Committee

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

Current membership is:

F. C. Adams	University of Michigan
T. M. Bania	Boston University
J. H. Bieging	University of Arizona, Steward Observatory
E. B. Churchwell	University of Wisconsin
E. Erickson	University of Massachusetts
N. J. Evans	University of Texas, Austin
P. Goldsmith	Cornell University
R. Hills	Cavendish Laboratory
G. R. Knapp	Princeton University
C. R. Masson	Center for Astrophysics

F. P. Schloerb	University of Massachusetts
P. Solomon	State University of New York
J. Turner	University of California, Los Angeles
E. van Dishoeck	University of Leiden
R. W. Wilson	Smithsonian Astrophysical Observatory
G. Wynn-Williams	University of Hawaii

4. GBT Advisory Committee

This committee priodically 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:

C. Heiles	University of California, Berkeley
R. Hills	Cavendish Laboratory, UK
R. L. Jennings	University of Virginia
J. E. Nelson	University of California, Santa Cruz
V. Radhakrishnan	Raman Research Institute
S. Von Hoerner	NRAO, Retired
S. Weinreb	Martin Marietta Laboratories
R. W. Wilson	Smithsonian Astrophysical Observatory