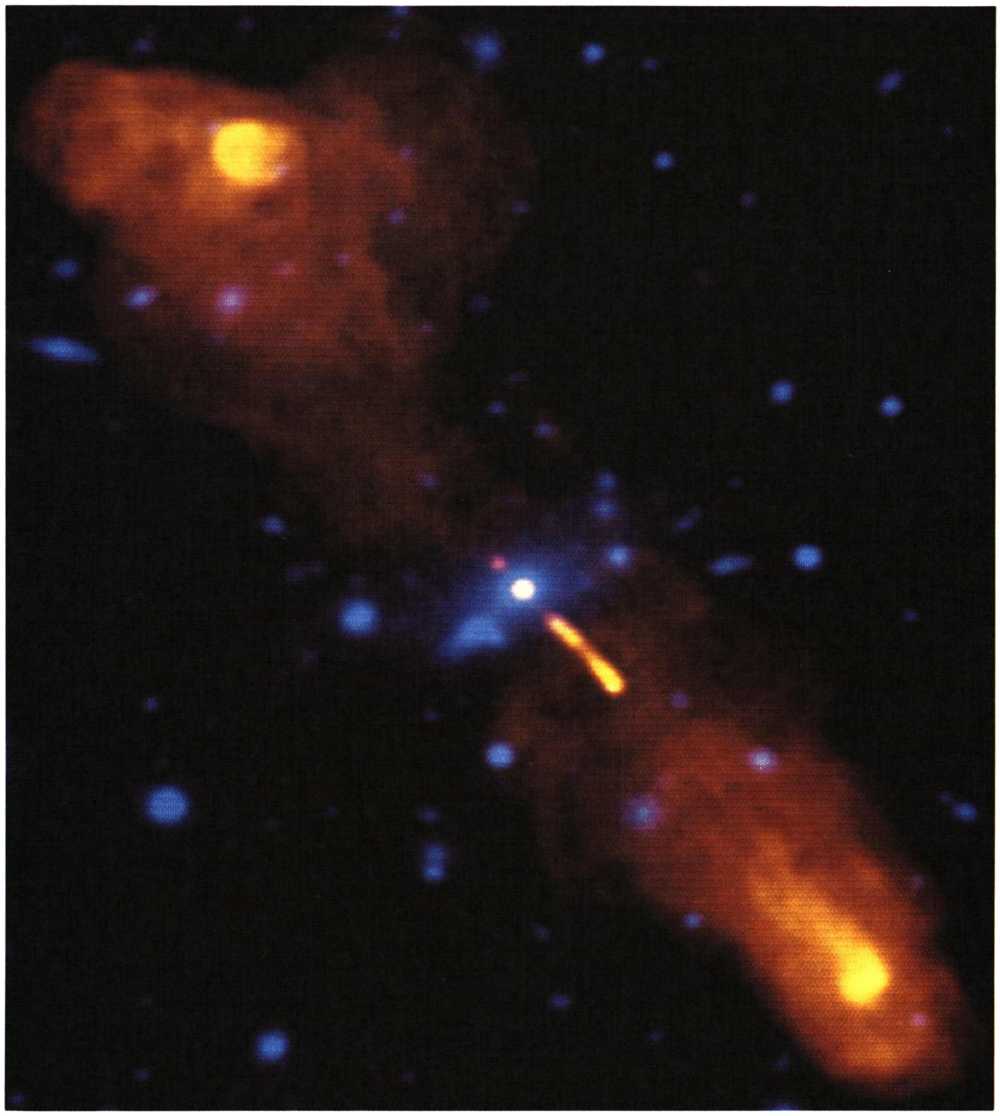
PROGRAM PLAN



LONG RANGE PLAN
1994

NATIONAL RADIO ASTRONOMY OBSERVATORY

Cover: An image of the radio galaxy 3C 219. The radio Image, made with the NRAO Very Large Array, is colored red and yellow and is shown superposed on an optical image (colored blue) of the parent galaxy. Thin jets of radio emission can be seen carrying energy from the nucleus of the galaxy to giant radio lobes that are much larger than the entire visible galaxy. The major features seen here--nuclear jets transporting energy to a network of magnetic filaments within large radio lobes--is characteristic of many bright radio galaxies. VLA Observers: D. Clarke, A. Bridle, J. Burns, R. Perley, M. Norman.

NATIONAL RADIO ASTRONOMY OBSERVATORY

CALENDAR YEAR 1994

PROVISIONAL PROGRAM PLAN

AND LONG RANGE PLAN

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I. INTRODUCTION

In 1994 the astronomical community will have access to the first third of the VLA all-sky survey. The complete VLA survey, made in the D-configuration at 1400 MHz, will provide positions and radio flux densities for more than two million radio sources spread over 82 percent of the sky. While in progress, the VLA sky survey will identify more radio sources in a week than had been identified in all previous radio surveys combined. The VLA survey goes on for nearly thirty weeks. Maps of the radio sky will be made available via file transfer on the Internet to astronomers as rapidly as they are made — there are no proprietary rights to the data. This gives all interested astronomers access to a database more extensive at radio wavelengths than is the IRAS point source catalog at infrared wavelengths for statistical, cosmological, and astrophysical investigations.

The VLA all-sky survey is the culmination of a long process to improve the sensitivity and speed of the VLA that has included replacement of the 21 cm receivers on all 28 antennas with modern HFET amplifiers, improvements to the array control software that points and drives the antennas, and sufficient enhancements to the NRAO computing capability that allow the data from such an ambitious project to be calibrated and imaged. A large amount of work has gone into preparation for the VLA sky survey, work that will benefit the users of the VLA as well as those who will simply use the data from the survey. This is a good example of how substantive enhancements to the observing capabilities and data handling techniques lead to genuinely new scientific capabilities, not just incremental increases in speed or convenience. Plans for continued enhancements to all the NRAO observing facilities are described in this Program Plan and Long Range Plan.

Each year more than 850 scientists and students use the major observing facilities at the NRAO: the Very Large Array (VLA), the Very Long Baseline Array (VLBA), the 12 Meter Millimeter-Wave Telescope, or the 140 Foot Telescope. The scientific interests of such a large group of astronomers includes objects as near as the sun and planets and as distant as the quasars and last scattering surface of the primordial background radiation. Astronomers seek to understand how stars and galaxies form, what physical mechanism powers the quasars and radio galaxies, and the chemical signatures of planetary formation. A summary of the rich variety of research to be pursued at the NRAO in 1994 is given in Section II.

The NRAO observing facilities are described in Section III. Each instrument provides astronomers with a different probe of the astrophysical environment or phenomenon that they are investigating. Each instrument as well can have its capabilities enhanced through a considered program of instrument modernization or replacement. The specific plans to do so are presented in general terms in Section III and in specific terms as part of the research equipment plan outlined in Section IV.

Encouraging progress continues to be made on construction of the Green Bank Telescope (GBT) as noted in Section V. Specifications for the GBT receiving system, as well as for the capabilities of the GBT spectrometer, have been established in consultation with prospective telescope users. Good progress on all these areas can be reported already.

Looking further into the future, the NRAO anticipates the opportunity to build the Millimeter Array (MMA). The MMA was one of two major ground-based projects recommended by the Bahcall report (the Decade Review of Astronomy) for construction in the 1990s. Design studies for the MMA have been going on, at an accelerating pace, at the NRAO for more than ten years as reported in Section VI. Summarized also in this section are plans to upgrade the correlator, IF, and receiving systems of the VLA and to provide three or four new antennas near Socorro to meld the longest VLA interferometer spacings smoothly into the shortest VLBA interferometer spacings, thereby creating a single continuous array.

Sections VII, VIII, and IX, respectively, describe on-going programs at the NRAO in support of the research of government agencies other than the NSF, work done in collaboration with universities and foreign observatories, and NRAO programs specifically designed to further the educational pursuits of science students. The financial tables for 1994 and for the successive five years are given in Sections X and XI.

We expect 1994 to be a year of great excitement at the NRAO, stimulated not only by the availability of the first third of the images from the VLA all-sky survey as well as by the availability for the first time of a dedicated VLBI array, the VLBA. Already we see this new facility put to innovative uses not anticipated in the original proposal. As the VLBA settles into routine full operation throughout 1994, we expect a stream of new results illustrating the potential of this new capability for VLBI science.

II. 1994 SCIENTIFIC PROGRAM

1. Very Large Array

The VLA is a highly flexible instrument supporting research across a wide range of specialties. Its capabilities will expand even further in 1994. The scientific value of the VLA, described by Freeman Dyson as "the finest general-purpose radio telescope in the world," is demonstrated by the fact that, over the past year, there have been nearly 2.6 hours of observing time requested for every hour of observing time available. In addition to purely radio studies, the VLA is used heavily for multi-spectral research, in conjunction with both ground- and space-based instruments observing in other wavelength regions.

In 1994, a large amount of observing time will be devoted to the VLA Sky Surveys, which began in 1993. This will include time for both the D-configuration survey, which will observe five-sixths of the sky between now and 1996, and the B-configuration survey, which will observe one-fourth of the sky at higher resolution. While these surveys will impact the amount of time available for other projects, they will produce data of great value to the astronomical community. Together, these surveys will catalog approximately two million radio sources. The data from these surveys is being made available to the community as soon as it is reduced, via electronic data transfer over the Internet. Eventually the surveys will be distributed on CD ROMs.

Since 1979, the VLA has contributed to planetary science, through both passive observations and bistatic radar studies done in cooperation with NASA's Goldstone Solar System Radar in California. In 1994, planetary scientists are eagerly anticipating a unique event — the predicted collision of comet Shoemaker-Levy (1993e) with Jupiter in July. This will be the first time that scientists have had the opportunity to observe a large impact on a planet, and the VLA will play a major role in observing this event. Anticipated VLA observations will begin well ahead of the event to measure undisturbed planetary characteristics. The impact is expected to have major effects on Jupiter's magnetosphere and synchrotron radiation, and VLA observations can yield unique information about those effects. This collision will be a main occupation of the planetary science community in 1994, and NRAO will seek to maximize the VLA's contribution to the international observational effort. As in the past, the VLA will observe planetary targets of opportunity such as comets and asteroids. Recently developed software allows the VLA to participate in bistatic radar studies of near-earth-passing objects. Continuing software development will improve this capability.

VLA studies of the sun in 1994 will include use of mosaicing techniques to make the first high-resolution, full-disk image of the sun at 6 cm, as well as full-disk images at 20 and 90 cm with conventional single-field mapping. These studies of large-scale structure in the solar atmosphere, in conjunction with satellite X-ray studies, will yield information on the properties of coronal holes, filament channels, filaments, and the solar polar regions. The VLA, in cooperation with other ground-based optical and radio observatories and with the Japanese solar-dedicated satellite Yohkoh, will study flare-associated microwave emission with high-time resolution. The high-time resolution studies should help resolve questions about the transport of the emitting electrons and the evolution of their energy distribution function.

Stellar research at the VLA covers the evolutionary sequence from protostars to supernovae. Nineteen ninety-four will see the completed installation of Q-band (7 mm) receivers on nine VLA antennas. One of the first projects using this new capability will seek to make images of dust emission from protoplanetary disks surrounding young stars. The VLA, which was used to observe the region of supernova 1993J in the galaxy M81 within hours of the supernova's announcement on 30 March 1993, will continue to frequently observe this object. The VLA was the first instrument to observe radio emission from SN 1993J, and observations done in 1994 will add further to the high-quality multiwavelength set of light curves that is providing a crucial test for models of the progenitor star and its evolution prior to the explosion. The volume and quality of data from radio and other wavelengths is making this object a watershed event in supernova research. Other planned stellar research will include observations to seek young, low-mass protostars. Additional studies will investigate line emission from protostars, a young stellar object with a puzzling spectral index, stellar mass loss from young, solar-type stars, and an object that may be a protostar, or it may be a young stellar object, or perhaps it is simply molecular debris from a failed episode of star formation.

Pulsar timing experiments will continue, with expected results to include more mass measurements for binary pulsars and added information on a system that may consist of the first binary pulsar with a planet. Pulsar studies also will include observations aimed at producing images of the regions around young pulsars. These images may reveal previously undetected supernova remnants and other useful information about the pulsars and their birthplaces.

Supernova remnants will receive considerable attention from VLA investigators. Several small-diameter SNRs will be observed to produce the first high-resolution images of these objects. Tycho's supernova remnant (3C 10) will be observed in HI to determine the distance to this object. Another project will use the VLA to observe an X-ray knot associated with the Vela SNR. A scheduled VLA study of the galactic supernova remnant G10.0-0.3 has been prompted by the fact that this object is the only radio source within the error box of a soft gamma-ray repeater. This, and observation of the error box of another gamma-ray repeater, could provide important information about the still obscure nature of gamma ray bursters.

Galaxies have been an extremely productive research field at the VLA, and 1994 will once again see a large variety of investigation in this area. Galaxy studies will include observations of star-forming regions within galaxies, gas kinematics of galaxies, the disk-halo interfaces of galaxies, and a number of detailed investigations of particular objects. Galactic mergers and encounters also will receive attention from a number of investigators. A study of very small dwarf galaxies will seek to confirm earlier VLA observations indicating that these small galaxies have little or no dark matter. Confirmation of this finding could have profound cosmological implications. A study of giant radio galaxies at high redshift is expected to provide new information on the structure of these objects, their environments, and the nature of the intergalactic medium.

Planned studies of quasars in 1994 will seek to answer structural, evolutionary, and cosmological questions about these objects. A study of quasar radio luminosities will seek to determine if the form of cosmological evolution at radio wavelengths can be unified with the form of the evolution at optical wavelengths. Another study will search for molecular emission from the host galaxies of very high redshift quasars. If successful, this search will provide information on the infrared emission mechanism, the relationship of quasars to IRAS galaxies, possible information on the radio loud/quiet dichotomy among quasars, as well as the first direct information on the amount of baryonic matter which condensed at very early epochs corresponding to redshifts between 4 and 5.

Finally, the VLA will be used along with the Ryle Telescope to search for primordial anisotropies in the microwave background on scales of 30-180 arcseconds.

2. Very Long Baseline Array

The VLBA will reach full operation in 1994. This instrument will operate both independently and as a contributor to global VLBI network observations. An important VLBA observing project will involve a survey of about 3,000 sources selected from the MERLIN phase-calibrator catalog as candidates for phase-reference calibrators for use both by the VLBA and the entire VLBI community. While the primary purpose of this project is to produce a VLBA calibrator list, it also will produce results directly impacting research in areas such as gravitational lensing and cosmology.

Like the VLA, the VLBA also will monitor supernova 1993J in M81. This supernova was observed repeatedly by the VLBA in 1993, and new observations at regular intervals are planned for 1994. It is hoped that a high-quality "movie" of the supernova's expanding shell can be produced. These data, taken in concert with optical determinations of the remnant expansion velocity, can provide a reliable determination of the distance to M81. The fully-operational VLBA will serve as a ready resource for the astronomical community in observing future extragalactic supernova explosions.

The VLBA's combination of high resolution and 7 mm observation capability will support some exciting studies involving SiO masers. One study will measure the positions, lifetimes and proper motions of individual maser features associated with a star in the Orion star-forming region. These masers are thought to be part of a disk surrounding a very young star. The VLBA observations are planned to test the model and, if it is confirmed, to trace the kinematics of the disk. This will help us understand the nature of the individual masers and of such protoplanetary disks in general. Another experiment will monitor already observed SiO masers around evolved stars in an attempt to learn about the time-variable environment close to the surfaces of these stars.

Other studies will include observations of H_2O masers associated with low-mass, young stellar objects; monitoring the structure of H_2O masers; and monitoring the proper motions of H_2O masers in W43 (OH).

A number of investigators will use the VLBA to observe pulsars. One team will make astrometric observations of pulsars and extragalactic sources to determine the positions, proper motions, and parallax distances of pulsars, with the hope of refining the pulsar distances to uncertainties of less than five percent. These measurements can then be used to study the properties of the interstellar medium, to help calibrate the dispersion-based galactic distance scale, and, coupled with pulse time-of-arrival measurements, to determine accurately the earth's orbit. Another study will examine alternative methods of determining the motion of pulsars with respect to nearby background sources.

Active galactic nuclei and quasars will come under the full high-resolution scrutiny of the VLBA through a number of projects in 1994. From observations of the nuclei of low-luminosity radio galaxies, to seeking the mass of a Seyfert nucleus, to monitoring the evolution of quasars at sub-parsec scales, investigators will explore the full range of AGN activity with the VLBA. One investigation will seek to test the relativistic accretion disk model for objects with double-peaked, broad H-α lines by measuring proper motions, jet position angles, and jet-counterjet ratios. If this study yields results consistent with the prevailing accretion-disk-jet model, the VLBA work, together with measured proper motions and known inclinations, could be used to constrain the Hubble constant. Another project will make the first VLBI continuum polarization observations at 7 and 13 mm of two quasars and two BL Lac objects.

The VLBA promises to be a valuable resource for the geodetic and crustal-dynamics communities, and work in 1994 will focus on developing the techniques to exploit this capability. A number of experiments will be conducted to refine the knowledge of the VLBA baselines and to test the performance of the VLBA in these types of observations. Experiments with both the VLBA and other geodetic networks will involve simultaneous, but independent, observations to determine if the different networks obtain similar earth-orientation results on hourly scales. Astrometric VLBA experiments will help maintain the reference frame for high-precision geodetic work.

3. 12 Meter Telescope

During the last observing season, a four-year effort to produce state-of-the-art, dual-channel SIS receivers for all the primary wavebands of the telescope, from 68 to 300 GHz, was completed. Attention has now turned to completing the 230 GHz, 8-beam SIS receiver, which is expected to be available for testing by early 1994. Planning for a 32-beam system continues, and a program to increase the bandwidth of the single-beam systems is underway. The scientific program at the 12 Meter will exploit the capabilities of these systems.

Studies of the molecular content of galaxies will comprise a significant portion of the 12 Meter research effort in the coming years. Although progress towards the understanding of the process by which stars are formed in molecular clouds in the Milky Way is steady, the analysis is made difficult by the great complexity of the molecular radio emission arising because of the superposition of many clouds in a typical line of sight in the Galactic plane. More and more studies of the physical processes involved in star formation are exploiting observations of the distribution of molecules in galaxies. Ultimately, when it is necessary to study individual cloud complexes in galaxies, the observations will have to be done with imaging telescopes, but for the next few years there will be heavy demand on the 12 Meter Telescope to measure the general distribution of molecular gas, with emphasis on the relationship between the molecular gas and atomic hydrogen. Other studies will search for the densest clouds using molecular emission from molecules such as CS, HCO, and HCN. A promising approach is to study galaxies currently in the throes of an event, perhaps episodic, in which new stars are formed at a prodigious rate. The galaxies have been identified by their bright infrared emission, and the 12 Meter will be used to make an inventory of the molecular gas from which it is believed the new stars are forming. It is of interest as well to explore the possible reasons for the onset of this period of rapid formation of stars, and a number of avenues will be explored. For example, one theory postulates that star bursts are triggered by the merging of two galaxies, and observations will be made of the strength of the emission of CO as a function of the separation of galaxies in carefully selected pairs.

The 12 Meter has been a leader in the detection and study of high-redshift line emission from galaxies, and significant effort will continue in this area. Studies of CO and CI are used to investigate the process of galaxy formation itself. So far, infrared-bright, molecular rich objects have been seen at redshifts as large as $z = 2.3$, with tentative detections at even higher redshifts. The objects thus far detected in CO will be examined for emission from other molecules, and from atomic carbon, and searches will be made to find other forming galaxies.

The field of astrochemistry was pioneered with the 12 Meter (at that time the 36 Foot) Telescope and that area continues as one of the Observatory's most active and fruitful. The detection and study of interstellar and circumstellar molecules provides tests for theories of molecule formation and destruction, and new diagnostic tools for the full spectrum of millimeter-wave astronomy. A promising new area of astrochemistry research at the 12 Meter Telescope is the study of refractory and metal-bearing molecules. Chemical models based on cosmic abundances suggest that numerous metal-bearing molecules should be present in detectable amounts in both the interstellar and circumstellar media. Yet, very few such compounds have been found so far. It is hypothesized that most of these molecules may have condensed onto dust grains, but a few refractory species — namely silicon compounds — are found in abundance in the gas phase. The whereabouts of gas phase metal-bearing molecules is one of the outstanding mysteries of astrochemistry. Recently, there has been some progress in this area and several observers are intensely pursuing this line of research at the 12 Meter.

One of the most active areas of research at the 12 Meter in the coming years will be wide-field, rapid imaging of both continuum and spectral line sources. New techniques and instruments will facilitate such research. Specifically, an "on-the-fly" observing mode has been developed for continuum observations and will soon be applied to the spectral line case. In this mode, data are taken continuously while the telescope is scanned across a source, which is a much more efficient mapping mode than the traditional "step and integrate" technique. This new method is currently being applied to a 3 mm continuum map of the Galactic Center. Preliminary results have produced good images of the "arc," "bridge," and central continuum source features. This technique will be applied to other continuum sources and will soon be available for spectral line imaging. The technique will ultimately be used with the 8-beam receiver to provide an extraordinarily efficient mapping tool.

During the past year, a real-time link was established between the 12 Meter Telescope and the Kitt Peak VLBA antenna. The link allows the 12 Meter to receive the maser local oscillator signal from the VLBA control room, and allows the 12 Meter to transmit an IF signal back to the VLBA tape recorder. This link greatly reduces the work involved in configuring the 12 Meter for millimeter wavelength VLBI observations. Beginning this year, routinely scheduled VLBI sessions will commence. In previous *ad hoc* sessions, several extragalactic sources have been detected on a 50 micro-arcsecond angular scale. This new flexibility will allow objects to be time-monitored, among other advantages.

Finally, the 12 Meter Telescope has been shown to be a powerful tool for the study of important constituents in the upper portion of the middle atmosphere of the earth. These regions are poorly sampled by both ground-based and spacecraft measurements. Microwave observations with the 12 Meter have provided the first measurements of mesospheric HO_2, HDO, and an isotopomer of O_3. Analysis of these data provides new information on the photochemistry which directly affects the ozone content in the 40-80 km region. New observations will build on these results by investigating both the photochemical and the transport processes in the thermosphere, mesosphere, and upper stratosphere. Particular emphasis will be on the diurnal variations of HO_2 and O_3 in the mesosphere, and in solar cycle variations in lower thermospheric NO.

4. 140 Foot Telescope

The 140 Foot Telescope is equipped with receivers that cover almost all frequencies between 100 MHz and 35 GHz, and has several versatile backends that can be configured for specific observations. In addition, it has excellent sky coverage and good instrumental sensitivity for spectroscopy. These properties will be exploited by many programs in 1994 in the areas of pulsar studies, galactic and extragalactic HI, high-resolution VLBI observations and studies of hydrogen and molecules in distant galaxies.

Pulsar astronomy will continue to be a mainstay of the 140 Foot. Several long-term pulsar monitoring programs will measure the arrival times of pulses, and their change, over time scales ranging from a few hours to many years. In some cases the pulsars are known to have companions, and study of the orbital variations provides information on the interaction of the two objects, or even of the presence of other massive objects in the system. Continued observations of an array of pulsars spaced across the sky can establish an extraterrestrial time reference frame, that in turn can be used to monitor the acceleration of the earth due to perturbations of the orbit by the planets or even by gravitational waves.

Timing of specific pulsars is also the first step in multi-wavelength studies of the pulsar emission mechanism. Pulsars emit detectable gamma rays, but at such a low level that even with the orbiting Compton Gamma Ray Observatory fewer than one gamma-ray photon per pulse period can be detected. Synchronous integration over several weeks is necessary to detect the pulsar in gamma rays, and this requires knowledge of exact pulse arrival times over the same interval. This information will be supplied by precise timing observations from the 140 Foot.

Several systematic searches for new pulsars will also be done in the coming year. One approach to discovering hitherto undetected pulsars is to survey the entire sky and cast a wide net, though one which is of limited sensitivity. The other approach is to target specific directions suspected to harbor a pulsar based on other observations, e.g., in the X-ray or radio continuum, and observe with the 140 Foot to great sensitivity. Several interesting pulsars in odd environments have been discovered in recent years, and the 140 Foot will be involved in this work for some time to come.

Pulsars are also used as background sources for probing the intervening interstellar medium. The angular size subtended by a pulsar is so small that its radiation cone traverses a narrow path through the interstellar medium. Conditions along this path can change from year to year as the pulsar's proper motion carries it across the sky. Observation of HI absorption toward the pulsar, or of the pulsar's scintillation and refraction, gives information about interstellar gas on very small angular and linear scales, scales not easily studied by another method.

There is increasing interest in studies of redshifted radio lines. The most popular of these is HI. In some experiments the HI that is searched for is from clouds randomly located between the sun and a background radio source. These clouds would be the high column density end of the Lyman alpha forest. In another experiment observers will try to detect HI toward objects that are gravitationally lensed in hopes of identifying the redshift of the lensing galaxy. Detection of HI would give not only an accurate and unambiguous redshift for the lens, but would provide information on the internal kinematics of the lensing galaxy. In some galaxies very luminous maser emission is observed in the main lines of OH. This has been observed to a redshift of 0.26, and might be detectable at even greater redshift. Studies of both HI and OH at great redshift are greatly helped by the National Radio Quiet Zone that surrounds Green Bank, for the limitation on these kinds of observation is almost always terrestrial radio interference. The combination of low interference levels and the frequency coverage of the 140 Foot make it uniquely suited for these observations.

There is continued demand for use of the 140 Foot for studies of galactic HI in the 21 cm line. Some of this research is prompted by work at other wavelengths. For example, the soft X-ray ROSAT space observatory has been providing increasing evidence that some HI clouds are producing shadows in the soft X-ray background, implying that the clouds lie between much of the X-ray emitting gas and the sun. Study of the clouds, by combining 140 Foot HI maps with ROSAT data delineate the distribution and properties of the hottest phase of the interstellar medium. In another experiment, HI emission measured with the 140 Foot is being correlated with emission in the CII line at 157 microns to measure the total heating rate in diffuse interstellar gas.

HI spectra measured with the 140 Foot are being used to interpret the ultraviolet absorption lines seen by HST toward quasars, and to disentangle galactic from extragalactic contributions to their UV spectra. Galactic HI observations are also used to estimate the amount of foreground extinction or absorption toward extragalactic sources. This information is necessary in analyzing the X-ray spectra of AGN and QSOs. There is also interest in mapping high latitude HI in search of gas accelerated by recent supernovae. Several projects are underway to measure the interstellar magnetic field by observing the Zeeman effect in HI clouds. These are challenging observations and make the most of the 140 Foot's excellent 21 cm receiving system, which is the world's most sensitive.

Extragalactic HI programs that will be run on the telescope include searches for HI in selected galaxies, mainly dwarf irregulars and compact blue dwarfs, and accurate measurement of redshifts and fluxes. In some cases the 140 Foot spectra are used to complement aperture synthesis maps made with the VLA. The 140 Foot data can supply very accurate total HI fluxes to assess the degree to which large-scale emission is resolved out by the interferometer.

Galactic ionized gas is studied by the 140 Foot through measurement of radio recombination lines. Here again, the frequency agility of the 140 Foot is particularly advantageous. There are searches for compact HII regions associated with water vapor masers. These observations are best done at high frequencies. In addition, there is interest in the study of more diffuse ionized gas, which is now known to comprise a substantial fraction of the mass of the interstellar medium. This gas is best observed at the long centimeter wavelengths.

A wide range of spectroscopic activity takes advantage of the excellent receivers at the 140 Foot and the good instrumental baselines. There is an effort to determine the ionization state of helium in diffuse interstellar gas by measuring recombination lines of helium and hydrogen in directions not associated with bright HII regions. The ^{3}He line was first detected at a significant level on the 140 Foot, and there is continued demand for the telescope to study this very faint line. ^3He is a fundamental nucleon whose abundance is determined by events in the early universe and by subsequent nucleosynthesis in stars.

Spectroscopy of interstellar molecules is a continuing activity. The interest of some groups has turned from study of giant molecular clouds to study of the much smaller, simpler molecular clouds that are occasionally found at high galactic latitude. These might be excellent sources in which to understand chemical evolution, and they are observed in a number of lines of various molecular species.

About one-fourth of the 140 Foot time is used for VLBI work, in conjunction with the VLBA and other instruments. The 140 Foot is very useful when there is a need for extra sensitivity or a link to European baselines. In addition to VLB network runs, the 140 Foot participates in special VLBI sessions devoted to the mapping of the evolution of supernova 1993J in M81, and to high-resolution mapping of methanol masers in the Galaxy.

III. USER FACILITIES

1. Very Large Array

Status of Present System

More than 625 scientists used the VLA for their research work in 1993, and a similar or larger number will do so in 1994. 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, or X-ray wavelengths. Radio observations 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 to 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 seven frequency bands, remotely selectable; the five upper bands by means of subreflector rotation. The table below summarizes the parameters of the VLA receiver system.

VLA Receiving System

Frequency (GHz)			T_{sys} (K)	Amplifier
0.070	-	0.075	1000*	Bi-Polar Trans.
0.308	-	0.343	150	GaAsFET
1.34	-	1.73	35	Cryogenic HFET
4.5	-	5.0	60	Cryogenic HFET
8.0	-	8.8	35	Cryogenic HFET
14.4	-	15.4	110	Cryogenic GaAsFET
22.0	-	24.0	180	Cryogenic HFET

* Eight antennas equipped; T_{sys} includes galactic background.

The VLA receives two IFs, 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.

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. Since that time, the VLA has been an extraordinarily productive scientific instrument, and has been used by more than 1200 astronomers for a wide variety of investigations, including solar system, galactic and extragalactic research. However, as a result of technological advances during the past decade, much of the instrumentation needed to keep the VLA at its current leading position among the world's radio astronomy facilities has yet to be installed.

When designed in the mid-1970s, the VLA used state-of-the-art technology. Over the last fifteen years, however, there have been major advances in receiver sensitivity, correlator design, and the transmission of broadband signals which have already been incorporated into other, new radio telescopes such as the VLBA, the Australia National

Telescope, and the Nobeyama millimeter interferometer. In its current configuration, the VLA can still observe radio sources which are two orders of magnitude fainter than have been observed by any other radio telescope. By using modern, low-noise radiometers, fiber-optics transmission lines, and a broad bandwidth correlator, it will be possible to gain *another* order of magnitude improvement in sensitivity. New receivers are also needed at wavelengths not presently covered in order to extend both the spectral coverage and the range of sensitivity to low surface brightness observations.

The program to modernize the VLA electronics amounts to a major overhaul of the entire receiving instrumentation. It is described in Section VI of this Preliminary Program Plan as a Major New Initiative. The first step has been accomplished with the completion of the upgrade of the VLA L-band receivers to HFET instrumentation in individual cryostats. Also, the first of the VLA 43 GHz receivers are now in place. The remainder of the ten-year program to upgrade the VLA is outlined in Section VI.

VLA - Repair and Maintenance

The long-term physical deterioration of the VLA was reversed in 1992 with the infusion of new NSF money to repair the infrastructure. The funds available for material and equipment nearly tripled from 1991 to 1992. These funds were for the most part split between the rail system, the power distribution system, and the purchase of new maintenance equipment. A comparable amount of money was made available for infrastructure repair in 1993. If these funding levels continue into 1994 and beyond, the effort at the VLA can enter a mode of normal maintenance, repair, and the replacement of worn out equipment.

In 1993, replacement of the aging fleet of rail vehicles began. In addition, a skid loader has been acquired for the track crew. The surplus market is being searched for fork lifts, road vehicles, and a rail mounted crane. Rail system maintenance in 1992 concentrated on replacing 5000 rail ties on the north and east arms and rebuilding or overhauling nine intersections. This level of maintenance had not been seen since the 1987 effort which was accomplished with external contractors. In 1993 effort was concentrated on the VLA west arm. There were 7 kilometers of sand covered track beyond AW7 that needed to be cleaned before the ties could be inspected. The west arm had gotten little attention over the past couple of years. The sand was cleared and over 5000 ties were replaced in that area in the summer of 1993. On many parts of the array, there is a growing problem of one track settling with respect to the other. This unevenness between the tracks put strains on the loaded transporter. In 1994, in addition to the normal tie replacement program, the most critical areas of track will be re-leveled with new ballast.

The VLA underground power distribution system has been deteriorating since the mid 1980s. A project to replace the entire 620,000 feet of buried cable was started in late 1987. At the end of 1991 only 241,000 feet (39%) of cable had been replaced. Using the new NSF infrastructure funds, an additional 205,000 feet of cable were installed in 1992, bringing the project to 72 percent completion. In 1993 another 105,000 feet was installed to complete the recabling out to stations AW9, AE8, and AN8. A final purchase of about 70,000 feet of cable will complete the project in 1994.

A program for painting the VLA antennas was initiated in 1993. Various systems of surface preparation and painting were investigated, procedures developed, and the quadrupod of one antenna was painted. In 1994, a few of the antennas requiring urgent attention will be painted. Antenna painting will be a regular maintenance item in future years.

In 1991 the azimuth bearing in Antenna 21 failed, putting the antenna out of service for almost a year. For all the other antennas, a program is underway to monitor the metal content of the bearing grease and the vertical play of the azimuth bearings. Although none appear in immediate danger of mechanical failure, a few antennas do show signs of bearing deterioration. We anticipate replacing the azimuth bearing of Antenna 9 as part of its regular overhaul in mid 1994. As improved high-frequency receivers are put on the VLA, we will eventually need to upgrade both the reflector surface accuracy and replace more worn bearings to get acceptable pointing accuracy.

2. Very Long Baseline Array

Status

The VLBA will be essentially fully operational in 1994. All antennas were completed in 1993, and the correlator will be fully checked out in the first part of 1994. The full complement of thin tapes will have been purchased and placed into use. Global VLBI Network sessions will continue and full-time VLBA observing will take place. In addition to straightforward VLBI observations, such as those of continuum and spectral line emission, some of the more advanced capabilities of the array, such as observations of polarized emission and gated pulsar observations, will become fully available to the general astronomical community.

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 (u-v 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 Array Operations Center in Socorro. 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 the table below. All receivers are dual polarization. The receivers at 1.4 GHz and above contain cooled 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.

VLBA Receiving Systems

Band Designation (Note 1)			Frequency Range (GHz)			Aperture Efficiency (Note 2)	System Temp [K] (Note 3)
330	90	P	0.312	-	0.342	0.45	195
610	50	P	0.580	-	0.640	0.40	200
1.5	20	L	1.35	-	1.75	0.57	32
2.3	13	S	2.15	-	2.35	0.50	34
4.8	6	C	4.6	-	5.1	0.72	40
8.4	4	X	8.0	-	8.8	0.70	35
14	2	U	12.0	-	15.4	0.50	73
23	1	K	21.7	-	24.1	0.60	100
43	0.7	Q	41.0	-	45.0	0.45	100

Notes: 1) MHz/GHz frequency; centimeter wavelength; conventional radio (or VLA) letter codes.

2) Overall aperture efficiency, and total system noise temperature, at zenith. Values are representative of those measured on several VLBA antennas.

3) Single-frequency performance (without dichroic) shown.

VLBI requires highly accurate frequency standard 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 future 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 to the station 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 up to twenty sites. 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.

VLBA postprocessing is done in the AIPS system. Software development for VLBI in AIPS is largely complete but will continue to evolve as the VLBA itself evolves. Astrometric/geodetic processing will be done primarily in the system developed by the Crustal Dynamics Project, now Dynamics of Solid Earth (DOSE), at NASA. Over the next few years, the postprocessing will shift to the AIPS+ + system as that system acquires the necessary capabilities. 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

For the immediate future, much of the available effort will be focused on obtaining the best possible performance from the VLBA. Two main areas of development exist: achieving the full potential efficiency of the correlator and improving the antenna performance. The VLBA correlator, when fully operational, will be capable of correlating data from the 10-element VLBA at four times faster than real time (a factor of two from the number of correlator inputs available compared to the number of VLBA stations, and another factor of two by replaying the tapes at twice the recording speed). Attaining this level of efficiency will require fine-scale debugging of the correlator real-time software and streamlining of correlator operations. Studies will be made of ways to improve the antenna pointing, the efficiency, and system temperature at both the lowest frequencies and at the dual-frequency system (S/X band), the amplitude calibration, the system phase calibration, and many more items. The performance of the VLBA as a geodetic/astrometric instrument will be tested and improved as the geodesy community works toward their goal of station motion measurements accurate to 1 mm per year. Most of these projects will not involve significant funding. Some hardware may be needed;[28] for example, tilt meters may be needed on the antennas to improve pointing.

A vital continuing project is to make the Array "phase stable." With a connected element array such as the VLA, the phase of the array elements are found by observations of phase-calibration sources of known structure. This allows images to be made without using the self-calibration techniques upon which VLBI normally depends. Weak sources, which require coherent integrations over the whole time of an experiment and over all baselines, can thus be observed, and imaging of complex sources is simplified. Accurate relative positions can be measured which allows for proper motion and parallax studies and for alignment of images made at different frequencies or different times. If phase calibration using nearby calibrators can be used on the VLBA, it will have a major impact on the science that can be done. The success of phase-calibration for the VLBA will depend critically upon the accuracy of the geometric model for the array, the earth, and the celestial sources. A simple geometric model can be used to extend the phase-coherence time from tens of minutes up to several hours. During 1994, we expect to achieve full phase coherence by using a more complete and accurate geometric model based upon extensive geodetic and astrometric observations.

One of the major advantages of the VLBA over the older VLBI Networks is its ability to work at high frequencies. The antennas were designed for good performance at 43 GHz, and receivers for that frequency have been installed and are working well. The antenna structures were designed to work to 86 GHz, and the surfaces were figured as well as possible, within the technologies used, to allow some performance at this frequency. Early measurements, with a substandard subreflector, gave an efficiency near 20 percent at 86 GHz, which is adequate. Some problems with the high-frequency performance of the antennas have been uncovered. An extensive series of holographic measurements of the antenna surfaces is in progress. In addition, the pointing performance of the antennas must be improved. Once these problems have been addressed, it will be possible to start upon the exciting project of building and installing 86 GHz receivers, thereby doubling the maximum angular-resolution of the instrument and making the VLBA the instrument of choice for high-resolution observations at the longer millimeter wavelengths.

A number of other technical developments will take place in 1994. For sensitivity-limited observations, the instantaneous recording rate of the Array can be doubled for a short period of time by recording simultaneously on both tape drives. This requires substantial work in a number of areas, principally the correlator. In addition, the FX architecture allows frequency-dependent gating of the correlation for a pulsar. This requires software development in the correlator.

Scheduling and Observing

Astronomical observing on the VLBA will consist 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 indefinite 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, Green Bank, the VLA, and antennas of the European VLBI Network. 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.

Three tape recording formats have been in use for Global VLBI and VLBA observations: MkII, MkIII and VLBA. The old MkII system will still be used occasionally by those who have access to a MkII correlator, but the principal recording formats will be VLBA and MkIII.

Scientists Housing in Socorro

When the Array Operations Center (AOC) in Socorro was occupied in 1989, much of the VLA scientific activity moved from the VLA site to Socorro. In particular, the data reduction and imaging computers used by astronomers were installed at the AOC. This meant that users of the VLA, subsequent to their observations being made, came to the AOC to complete their work. The advice of NRAO staff scientists was also readily available in Socorro but much less so at the VLA site. In addition, the work environment at the AOC was carefully designed as part of the AOC building, and VLA users benefit from the arrangement of AOC facilities. Housing for visitors in Socorro is a problem.

Visitors to the AOC presently stay in Socorro motels, in NRAO rental apartments, and until recently, rooms were made available in the dormitory of the New Mexico Institute of Mining and Technology (NMIMT). None of these is suitable for the needs of astronomers processing data at the AOC. Visiting astronomers, attempting to keep their time away from home to a minimum and seeking to minimize costs, work intently for long hours each day. Frequently they work all night and sleep part of the day. Motels and especially college dormitories are not conducive to such living patterns. The NRAO users need housing better suited to their needs in Socorro.

A proposal by NRAO to build a modest housing facility, or "Guest House," on the NMIMT campus received approval in April, 1993. As a separate facility in a quiet location near the AOC, the NRAO Guest House offers the seclusion and amenities AOC visiting scientists seek. The facility, totalling 5800 square feet in living space, will have twelve rooms, two apartments, a kitchen, lounge, and laundry. It will be connected to the AOC computer network so the visiting astronomers can monitor the status of their computing. Construction on the NRAO Guest House was started in August, 1993 with completion anticipated in February, 1994. Construction was financed principally by a no-interest loan from AUI to be repaid over five years, largely by user fees.

3. 12 Meter Telescope

The NRAO 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 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

As many as four receivers are mounted simultaneously at offset Cassegrain foci on the 12 Meter 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. 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 SIS receivers is operational over the entire range 70-310 GHz. The arrangement of several receivers sharing the same dewar is extremely effective in terms of cost, manpower, and in operational demands. This new generation of receivers, available on the telescope now, represents the culmination of a four-year joint development plan between Tucson and the Charlottesville CDL.

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 SSB for most of the band, increasing somewhat at the high-frequency limit.

2. The 8-feed Schottky system is being upgraded to an SIS system. First testing on the telescope is expected in early 1994. Given noise performance is based on a rototype tunerless SIS mixer.

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

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, namely, 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 the planned implementation of the hybrid spectrometer will be completed by the end of 1993.

The eight-feed Schottky system is being upgraded to use SIS mixers, thereby giving state-of-the-art sensitivity in all feeds. This upgraded system should become available to observers early in 1994. An extension to a 32-feed SIS system is planned at a later date. The key to this development is the backend electronics. We have experimented with a prototype acousto-optic spectrometer (AOS), which might eventually have become an 8-spectrometer system to extend the usefulness of the 8-feed system and be expanded to serve a 32-feed system. However, new developments in high-bandwidth digital correlator systems have caused us to abandon this project in favor of new digital technology. We have made and tested a prototype for a new-generation digital correlator card. This system could provide the foundation for both the 32-feed system. Of course, a 32-feed system puts 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. During 1993 we concentrated on improving the observing efficiency of the telescope, and developing and implementing new observing techniques. The data acquisition rate will have increased by between 1 and 2 orders of magnitude. Construction of a suitable postprocessing environment based around a network of modern workstations is in progress.

Future Single-Beam Systems. Experimental HEMT amplifiers have been tested in the CDL which may capable of a performance which is competitive with SIS devices at 3 mm. As soon as feasible, a specialized continuum receiver using HEMT devices will be built 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

Surface Accuracy. During the summer of 1992, the 12 Meter Telescope was measured holographically. Using an improved receiver package, a more accurately determined satellite ephemeris, and a new "on-the-fly" observing technique, high resolution data was obtained at more elevation angles and with fewer systematic errors than ever before. The on-the-fly observing technique allows a continuous scanning movement of the telescope while taking data. The reduction in data-taking overhead was so dramatic that a map could be taken in about two hours that was better than one requiring 3-4 days of the traditional observing technique! From these high-quality data, in spring of 1993 the telescope primary surface was adjusted. The results were outstanding; the efficiency of the primary dish has been doubled at the most important wavelength of 1.3 mm. The 12 Meter Telescope now has a higher aperture efficiency than ever before, at all wavelengths.

Pointing. 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, several upgrades have been implemented in the past year. First, the azimuth inductosyn angle resolver mount and cable wrap assembly were rebuilt to eliminate some mechanical hysteresis problems. Second, an improved real-time monitoring system for movements of the prime focus, utilizing a laser and x-y translation detector, has been installed. Finally, 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

A polarimeter is under construction 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 should become available early in 1994. The design uses an adjustable grid and plane reflector combination, and can be adjusted to cover both the 1 mm and 3 mm bands. The design is reasonably compact, and will become a prototype design able to give similar capability to the MMA.

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. The option of "batch sequencing" of the telescope will be introduced during 1993. The new on-the-fly observing mode, which was so successful during the holography session, will now become a routine mode for continuum observing. This technique will be made available for spectral-line observing in 1994. Such observing techniques as this will require more advanced data-handling facilities than presently available.

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. Many of the projects already underway in support of the 12 Meter Telescope will become prototypes for, or otherwise contribute to, the eventual MMA project.

4. 140 Foot Telescope

The 140 Foot Telescope will continue to operate as a visitor facility through 1995, until the end of construction of the GBT. It is being maintained at an adequate level and improvements are being made where they increase reliability of systems or are otherwise necessary. In addition to serving as a visitor instrument, the telescope is also being used to test GBT concepts, hardware and techniques. It is the testbed for the GBT Monitor and Control antenna positioning system, and in 1994 will be used to field-test the laser-ranging pointing system of the GBT.

There have been low-level but steady improvements to the 140 Foot system. A new IPX workstation and greatly expanded disk capacity insures that there is adequate online space for all spectral line observations and adequate computing power to reduce the data. The laser printers have been upgraded and extra workstations bought for use of visitors at the lab building. Data at the telescope will be archived on 8 mm tapes, eliminating the 9-track tapes and also bypassing the Modcomp computer for this task. The spectral processor is being upgraded by the addition of more memory and a faster control computer. This will result in additional capabilities for pulsar observations. The UNIPOPS data reduction system is now mature, stable, reliable and in constant use at the telescope. It has been upgraded so that it can receive and analyze data from the spectral processor. It has new facilities for constructing and manipulating spectral line data cubes. It is now easy to export data to other data reduction packages. Both channels of the 7.5-12 GHz and 12-18 GHz Cassegrain receiving systems have now been replaced with HFET amplifiers. These have increased stability and lowered average noise over the band. Complete coverage of the 7-26 GHz range is now possible with two independent local oscillators. Infrastructure funding has allowed repairs to be made to cracks in the concrete base of the telescope. A backup air conditioning system has been installed.

In the coming year, the K-band masers in one receiver channel will be replaced by an HFET amplifier in the 18-26 GHz receiver. If this works satisfactorily, a second channel will be installed. This would give continuous coverage of all frequencies from 7.5 to 35 GHz with at least 1 HFET channel, and over most of the range with two. In addition, the 800 MHz receiver that is being constructed for the GBT will be used on the 140 Foot, giving a significant increase in sensitivity at this much-used frequency. The 140 Foot will be connected to the site-wide fiber optics network. This will distribute precise time and frequency standards over the entire site, and will allow transmission of control and IF signals from various telescopes to common points where equipment might be shared.

IV. EQUIPMENT PLANS

1. Research Equipment

For the past two years the major enterprise involving improvements to the NRAO observing instrumentation was a wholesale replacement of the VLA 21 cm (L-band) receivers with modern HFET amplifiers. This project was completed in 1993. All 28 VLA antennas now have wideband, stable, receivers with system temperatures of approximately 35 K. Since the previous L-band system temperatures were near 60 K, the VLA is now $(60/35)^2 = 2.9$ times faster, or more sensitive, than previously at the frequency of the 21 cm line of neutral hydrogen. This improvement will have a dramatic effect on VLA observations of the gas content of nearby galaxies and on studies of the effect of galaxy interactions and mergers. Improvements as dramatic as this are possible at several of the other principal VLA observing bands. In 1994 we plan to begin realizing the benefits of a new generation of VLA receivers by beginning a repackaging of the VLA K-band (22 GHz) receivers. Observing equipment at the other NRAO observing facilities will be improved as well in 1994, as described below.

VLA Equipment

22 GHz Receiver Repackage. The installation of HFET amplifiers in the VLA 1.3 cm receivers gave an average system temperature of 180 K. This is a four-fold improvement in system temperature over the old, cooled mixer design, and has led to a steady increase in ammonia line and thermal continuum experiments. Losses in the waveguide and the room temperature polarizer now contribute a large fraction of the total system temperature. An improvement of about 70 K can be achieved by repackaging the amplifiers in a VLBA-type receiver which is mounted directly onto the feed, with the polarizer located in the cryogenic dewar.

Pulsar Processor. Studies of pulsar emission mechanisms, millisecond pulsar timing, and testing of radio source candidates for pulsed emission require finer frequency channelization, faster on-line processing, and higher speed recording than are currently available at the VLA.

To increase the VLA capability for pulsar observations, a VME-bus computer will be added to the on-line system. It will be equipped with a large memory, disk and display controllers, plus two dual processor DSP VME-bus cards, four fast analog-to-digital converter cards (or "frame grabbers"), operating system software and a C compiler. This will allow immediate utilization of the full bandwidth channelization afforded by the video converters, and will allow narrow-band digital channelization of four video converter channels for pulsar studies at P-band. This approach will minimize the development time by using as much commercially available hardware as possible, making the system modular, upgradable, and extensible.

RFI Shields. The utility and sensitivity of the 327 MHz and 75 MHz systems are limited partly by radio frequency interference locally generated at each antenna. Enclosing the radiating components with RFI shields is necessary and effective. There are currently 12 antennas outfitted with B-rack shields, eight of which are a new, inexpensive, in-house design. Shields on ten more antennas will be installed in 1994.

12 Meter Telescope Equipment

SIS Receivers. The biggest change in receivers during 1993 will be the upgrade to a 3 GHz center IF frequency. This will support a 1 GHz total bandwidth for each polarization. The existing hybrid spectrometer supports up to 2.4 GHz of total bandwidth, 1.2 GHz per polarization, but because of the receiver IF systems we have been limited to 600 MHz until now. The change affects IF filters, circulators, and our fundamental LO reference.

Although we now have state-of-the-art receivers covering all atmospheric windows from 65 GHz to 300 GHz, it is not at present possible to have all single-beam receivers and the 8-feed system simultaneously in place on the telescope. The SIS upgrade will combine some pairs of SIS mixers into fewer dewars to remove this limitation.

Hybrid Spectrometer. The hybrid correlator spectrometer has been in use for two years now. Users have requested some enhancements that will be implemented in 1994.

We will complete modifications already underway to cure the "end of passband" sampler problem. It has been found that errors are introduced at the sampler if the input has a significant gain slope within the passband of a given sampler module. A similar problem has been found on other correlators. The sampler boards will be redesigned to reduce this problem. We also intend to install computer-controlled attenuators, which will alleviate some operational problems.

Green Bank Telescope Equipment

GBT Prime Focus Receiver. The GBT will be used in prime focus mode for frequencies below about 1 GHz. The GBT construction is now building the first prime focus receiver that is planned for use on the GBT. The cryogenically cooled receiver, when fully implemented, will provide four operating bands covering 290 to 920 MHz. In each band, the receiver will provide rapidly switched Stoke parameters at certain frequencies for polarimetry.

The receiver construction is funded primarily through the GBT project. The 1994 RE plan will fund the construction of a 140 Foot Telescope feed. Installation of this receiver on the 140 Foot will benefit both the GBT project by thoroughly testing the receiver and users of the 140 Foot by providing improved sensitivity.

GBT Gregorian Receiver. There are fourteen separate frequency bands covered by the GBT Gregorian receiver system. By the time the telescope is ready for scheduled astronomical observations in 1996, all the Gregorian receivers should be in place. The RE funding supplements GBT construction monies and speeds the completion of the Gregorian system.

Time and Frequency Distribution. NRAO Green Bank will soon have exceptionally accurate time and frequency standards made up from several hydrogen masers. The distribution system will consist of a network of single mode fiber optic cables buried at a depth to reduce the effects of diurnal temperature variations, a laser transmitter with the capability to transmit maser quality signals, and the electronics to correct for phase variations.

Common 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 suitable for amplifiers above 40 GHz are not commercially available at the moment, we will continue our cooperation with several industrial laboratories involved in HFET development. NRAO's expertise in evaluating devices and then building amplifiers has resulted in productive associations with these organizations.

A significant part of the funds for amplifier development will go towards frequency sources and components necessary to build test setups for the 60-115 GHz amplifier development.

SIS Mixer Development. Our present mechanically tunable SIS mixers give acceptable performance in the bands 68-90 GHz, 90-115 GHz, 130-170 GHz, and 200-260 GHz, although there is room for substantial improvement in the 68-90 GHz band. Fixed-tuned SIS mixers are used in the 260-300 GHz band, and will be used in the 8-beam 230 GHz receiver now under construction. The best mixers of the present fixed-tuned design have low noise in the 200-260 GHz range, comparable with the best tunable mixers, but worsen rapidly from 260-300 GHz. Because of the limitations of the SIS fabrication process, it appears impractical to scale this design to higher frequencies.

This year we plan to develop two new designs for higher frequencies: a tunable mixer based on the successful NRAO-581, 2 mm mixer and a fixed-tuned mixer of a completely new design we are now exploring. Also, we hope to improve the 68-90 GHz mixer.

Research Instruments

	1993(est)	1994
Laboratory Test Equipment	0	50
Miscellaneous Projects	128	125
Very Large Array		
1.3-1.7 GHz Improvement	125	
23 GHz Repackage		200
RFI Shields	0	50
Pulsar Processor	5	50
12 Meter Telescope		
SIS Receivers	25	45
Spectrometer	35	75
GBT Telescope		
Prime Focus Receiver (supplemental)	5	20
Gregorian Receiver (supplemental)	10	60
Spectrometer	-	-
Time/Frequency Distribution	42	40
Common Development		
Millimeter SIS Mixer Development	50	55
HFET Amplifier Development	25	30
Total	$450	$800

2. Computer Equipment

Computing systems at the NRAO are indispensable for NRAO operations and support of 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. Radio astronomy is unlike many other scientific disciplines, in that computer analysis is fundamental to the process rather than merely a useful adjunct to scientific analysis.

Maintaining observational and scientific capability is the fundamental goal of computing at NRAO. Implicit in this goal is the necessity of constant striving to keep ahead of computing demands at the NRAO. Computing systems and software should not be the limiting factor in the science which users are able to accomplish with NRAO facilities. This means that 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 1994, the following areas are priorities for computing equipment:

Control/Analysis Computing

During 1994, approximately one-third of the workstations at NRAO will need to be upgraded to more capable systems. This is necessitated by the increasing demands on computational capability at the NRAO from both increased demands from NRAO users and increased observational capabilities brought about by technological advances and improved observational techniques. This level of replacement will allow most workstations at NRAO to be replaced at the end of their useful lives (typically 3-4 years for scientific workstations). If this level of replacement and upgrading is not maintained, NRAO risks returning to the situation of a few years ago, where use of observational facilities was restricted solely to prevent overloading of data reduction capabilities. The cost of this effort will be $480,000 for hardware acquisition during 1994.

Networking

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. The installed networks are beginning to show their limitations, however, particularly in the area of data bandwidth between machines on the networks. One of the salient features of radio astronomy is the large sizes of typical data sets. Medium bandwidth links between machines on the Local Area Networks result in a bottleneck, and 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 is to begin the process of upgrading the networks at the sites to provide T1 capability to most of the workstations at each of the sites. This process should be accomplished by the end of 1995 in time for major new observational capabilities and opportunities at NRAO associated with the GBT and OVLBI. A related goal is providing high speed links between the sites. This capability would yield dramatic improvements in the ability of NRAO to share data between the sites, and would allow the current software distribution methods between the sites to be improved. Presently, major packages are upgraded via distribution of software in a batch mode. Wide bandwidth links would allow more centralized software distribution, and would result in improved user support.

The estimated cost for improving the performance of the computer networks at NRAO will be $450,000, spread over 1994 and 1995.

Computational Imaging

During 1993 an internal committee has been formed to look at the problems which require computer resources beyond those available within NRAO. The results from this study will guide acquisition of computing systems capable of addressing the computational problems that the current mix of workstations at NRAO cannot address. A number of important scientific problems are being neglected because of the lack of large scale computing at NRAO. During 1994, a detailed initiative will be undertaken to develop appropriate solutions, which will result in major acquisition late in 1994 or early 1995. Final costs of this initiative are presently undetermined. During 1994 approximately $50,000 will be needed to explore the capabilities of existing large computer facilities and identify the most cost effective solutions for NRAO to pursue. This effort will be complementary to the upgrade effort described above.

Engineering Computing

NRAO is pursuing several major initiatives leading to development of major new observational instruments. Chief among these efforts are the Green Bank Telescope (GBT) project and the Millimeter Array (MMA). These projects are heavily dependent on the use of advanced engineering workstations to carry out various aspects of the design and fabrication for these instruments. Presently, many engineers 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 reduce costs over the long term. Estimated cost of this effort during 1994 will be approximately $160,000. This will allow both the acquisition of appropriate workstations and the required software.

Computing Equipment

	Expenditures (k$)		
	1993 (est)	1994 (requirement)	1994 Plan
Control/Analysis Computing	52	480	165
Networking	-	225	50
Computational Imaging	55	50	25
Engineering Computing	-	160	40
Total	$107	$915	$280

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. The procurement of new communications equipment, personal computers, and other major office equipment has been substantially reduced for several years. Funding for this equipment has come predominantly from budget transfers from regular operations. These transfers effectively reduce the funds available for operations.

The NRAO has supplemented its funds for Operating Equipment by acquiring property under the Government surplus program. 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. In addition, much of the equipment needs a considerable amount of maintenance and repair work prior to placing it in operation.

During 1992, NRAO obtained approximately $410k in surplus equipment. An additional $205k in equipment was purchased with proceeds from special funding for infrastructure improvements and $16k was transferred from operating funds. Thus far in 1993, we have acquired $57k in Government surplus equipment and another $173k of equipment with the use of special infrastructure funds.

The 1994 funding requirements are estimated at $300k, but the expenditure planned at the request level is no more than $100k. During the five-year period 1995-1999, a total of $1.6M will be necessary to adequately fund the purchase of operating equipment.

V. MAJOR CONSTRUCTION: THE GREEN BANK TELESCOPE

Antenna

During the past year, the Green Bank Telescope (GBT) project has seen considerable progress made on all facets. Certainly the most visible progress may be found at the construction site itself. During the last quarter of CY 1992, the antenna contractor, Radiation Systems, Inc. (RSI), completed the placement and grouting of the 48 track sections and splice plates, each weighing approximately 17,500 pounds. The track was leveled and packed with dry-pack grout. Subsequent inspections have shown the track has been installed level to within ± 0.0125 inches over the 210 foot diameter track ring and the grout exceeds the specified 10,000 psi bearing capacity, in some segments reaching as high as 15,000 psi.

The contractor completed installation of the derrick crane and has used it to continue erection of the alidade through out the year. Currently all azimuth wheel assemblies are in-place, including the four wheels at each corner, the whiffle beams, spherical bearings, and corner weldments. Levels 1 through 3 of the alidade are installed and in excess of 85 percent of the joints have been welded. The contractor is preparing to proceed upward with Levels 4 through 7, the elevation bearing level, over the next two months. The alidade is scheduled to be completed by the end of CY 1993.

Work at the site will be limited during the winter months, due to both winter conditions and a delay in fabrication of elevation structure components, discussed below. Erection is expected to resume in earnest in April 1994. Construction of the elevation shaft and wheel, the reflector box structure, portions of the counter-weight, and the feed arm will be completed in 1994. The back-up structure trial erection will also be carried on in the fall of 1994. The back-up structure is scheduled to be assembled on the telescope during the spring and summer of 1995, with the reflector panel installation completed during the fall of 1995.

The challenge to the contractor of designing a complex elevation structure that meets the specifications for the Green Bank Telescope has resulted in a delay in the scheduled completion date. Antenna delivery is now scheduled for December 1995. As was indicated in the Program Plan 1993, NRAO was not confident that the contractor would be able to complete the design of the "offset feed" elevation structure within the scheduled dates. The elevation structure design required many iterations to remove overstressed members and attain joint configuration and fatigue requirements, while maintaining acceptable levels of weight, pointing accuracy, surface accuracy, and other parameters. At this writing, following an optimization of the members in the structure, the design is complete and is being detailed for fabrication. However, the delay in completing the design has led to a delay in the fabrication of the structure which will ripple through the entire project schedule and lead to the one year slip in the antenna delivery mentioned above. There will be no slip in the schedule of construction for NRAO-built systems: electronics, active surface, and precision pointing will continue apace.

Electronics

Receivers for the GBT at frequencies of 1.15 GHz and higher will be mounted at the Gregorian focus, whereas the low frequency receivers will be combined into two receiver packages at the prime focus. There are fourteen Gregorian receivers covering the frequency range 1.15 to 52 GHz. Priorities for the construction of these receivers have been set by the GBT Scientific Working Group. Some are under construction, others are being designed. A complete list of the GBT Gregorian receivers, and their priority and status, is given in Table 1. Both of the prime focus, low frequency, receiver packages are under construction. Box 1 will be complete in early 1994; Box 2 will be built in the latter half of the year. Table 2 gives the specifications of the prime focus receivers.

Table 1. Gregorian Receivers

Receiver	Freq. (GHz)	Dual Feed	Rank	Status
1	1.15-1.73	No	1	Under construction
2	1.73-2.60	No	4	
3	2.60-3.95	No	3	
4	3.95-5.85	No	2	Under development
5	5.85-8.20	No	3	
6	8.00-10.0	No	2	Under construction
7	10.0-12.4	No	3	
8	12.0-15.4	Yes	1	Under construction
9	15.4-18.0	No	4	
10	18.0-22.0	Yes	2	Done - testing
11	22.0-26.5	Yes	1	Done - testing
12	26.5-33.0	Yes	3	Construction in 1994
13	33.0-40.0	Yes	3	
14	40.0-52.0	Yes	1	Under design; ordering parts

Blank = No current effort; pending design/construction; or design/construction 1994/95

Table 2. Prime Focus Receivers

Rx No.	Box No.	Freq. (MHz)	Feed Type	Polarizer
PF-1	1,2	290-395	Coaxial Fed Cavity-Backed Dipoles or Backfire Antenna	Crossed Dipoles
PF-2	1,2	385-520	Coaxial Fed Cavity-Backed Dipoles or Backfire Antenna	Crossed Dipoles
PF-3	1,2	510-690	Coaxial Fed Cavity-Backed Dipoles or Backfire Antenna	Crossed Dipoles
PF-4	1	680-920	Waveguide Fed Corrugated Horn	Waveguide OMT
PF-5	2	910-1230	Waveguide Fed Corrugated Horn	Waveguide OMT

A prototype Gregorian feed rotator mechanism and the turret cable wrap assembly have been fabricated for evaluation. The receiver room local oscillator rack is assembled and the IF rack is under construction. A microwave optical fiber link has been selected and tested for IF transmission from the front-ends to the control room. A correlator for holographic surface measurements has been completed and used in surface measurements on the OVLBI antenna in Green Bank. The existing Spectral Processor spectrometer is being upgraded with additional memory and for compatibility with the GBT Monitor/Control technology. A continuum backend and new spectrometer are being designed.

During 1994, the electronics group will continue the hardware design and construction tasks currently underway, and strive to complete construction of the set of electronics planned to be ready at initial outfitting of the telescope. The initial set of feeds and receivers will be completed. The racks which will be installed in the receiver room will be assembled and tested and made ready for installation. Cabling plans and other preparations for outfitting the antenna will be completed, and materials required will be purchased.

The IF, LO, and receiver subsystems will be tested together, and replication of IF modules will be completed after evaluation of first articles in the system tests. The continuum backend will be completed, and development of the new spectrometer will continue.

The new spectrometer under development is based on a high-speed correlator chip being developed by the NASA Space Engineering Research Center. The spectrometer architecture being developed has 256k total channels, can be configured to provide up to 16 independent 1024 channel spectra, each covering 1 GHz, or 64 independent 4096 channel spectra, each covering 62.5 MHz, or many intermediate arrangements.

The spectrometer consists of four identical quadrants. Each quadrant contains four correlator boards; each correlator board contains 16 chips; each chip contains 1024 channels and can clock at 125 MHz. Thus, for input bandwidths of 62.5 MHz (sample rate of 125 MHz, the chip clock rate), we obtain the full complement of channels: 4 quadrants times 4 correlator boards times 16 chips times 1024 channels = 262144 channels. For higher sample rates, individual chips are fed at their maximum rate of 125 MHz and each correlation function is spread over more than one chip. This makes the obtainable size of the final correlation function 62.5 MHz/bandwidth times 262144. At the maximum bandwidth of 1 GHz, we obtain a total of 16384 channels — 4096 per quadrant.

The quadrants are identical and can be operated independently or together. Thus, each quadrant can run at its own bandwidth and can be divided into sections, independently of the others. Each quadrant can be divided into 16, 8, 4, 2, or 1 equal pieces, and one could have as many as 64 independent correlators by dividing each quadrant into 16 pieces; this sets the maximum possible number of inputs to the correlator. With 64 independent correlators at 62.5 MHz bandwidth, one obtains 64 independent spectra, each with 262144/64 = 4096 channels. Alternatively, one can do the equivalent of hooking one or more quadrants together in series, with the extreme being a single correlator having 262144 channels for bandwidths less than 62.5 MHz.

The mirror mechanical design underwent major refinements, and a third generation prototype was built and tested. It is expected that the final production units will be very close to this design. It was decided to make the lasers an absolute measurement instrument, instead of a relative measurement as originally proposed. This calls for a much higher precision mechanical design and metrology calibration requirements that stretch the state-of-the-art. The basement of the old 300 Foot Telescope control building has been renovated and a calibration lab has been set up. The goal of the work is to model the mechanical mirror design with a set of parameters, which will allow a laser unit to be mounted on any ground or telescope mounting, and point to a 3-D coordinate without experimental field calibrations. The laser lab will also be used to set zero point offsets, check linearity, establish traceability to NIST, and mount the retroreflectors.

Software development for the individual laser control systems (ZY) has progressed steadily and is nearing maturity. The software development activities have moved from the basement of the interferometer building to the 300 Foot Telescope control building. This proximity to the calibration lab and experimental hardware, as well as the visual perspective of the experiment, helps keep the software well rooted in the application and enhances communication between the metrology/hardware/software engineering. Three lasers (ZY1-ZY3) have been operating through an evolutionary series of more advanced programs since January 1992. The lasers now operate over Ethernet, and point to 3-D real world coordinates (necessary for tracking/pointing). Many additional features have been added, based on operational experience, to enhance the robustness, data interpretation, and system diagnostics. Work started in mid 1993 on a Sun-based version of the central computer (ZIY). PC/Windows development has been driven by the need to support experimental work and ZY software development. The Sun-based software development represents the transition to a common architecture and design, at the higher level, to interface to the various groups involved in the GBT control systems. An acoustic thermometry experiment was started to correlate the laser temperature-induced phase shifts with the speed of sound over a common path. It is anticipated that the system can be demonstrated by the last quarter of CY 1993.

The design is now being refined to match detailed scientific requirements.

Open Loop Active Surface

The actuators and associated motors will continue to be manufactured by NRAO subcontractors, Industrial Devices Corporation and Sierracin/Magnedyne, with a projected completion time of early 1994. Also in 1994, transorb boards, whose function is to interface between actuator cables and control modules and to provide lightning immunity, will be manufactured and tested by a vendor yet to be selected. Additionally, mounting panels for the control modules will be manufactured in the Green Bank shop and wired and tested in the lab.

Software will be developed which will close actuator loops and provide an interface to the monitor and control system and to engineers and technicians. The integration of hardware and software will begin. The commercial actuator control modules will be configured and tested. NRAO hardware will be integrated into a rack and tested.

Closed Loop Active Surface

In the first three quarters of 1993, significant progress was achieved on the GBT laser metrology project. A 16-month outdoor test of various retroreflectors was concluded, and a purchase order was placed for 2400, 1" retroreflectors to be delivered by July 1994. A contract was awarded, to The University of Arizona Optical Sciences Center, to design and build two wide angle retrospheres. Delivery is expected by late 1993. The individual laser control system (ZY), final test of the ethernet interface to a Sun computer was completed. This opened the way for the purchase of the components for the construction of 20 control panels. The laser design was refined by the Central Development Lab and production began on 25 units. Twenty laser detector units are near completion. Specifications for the oscillator system were developed, and one successful prototype was tested. A purchase order was placed for 25 units for delivery in late 1993. Experimental data revealed a low frequency (57 Hz) phase noise problem inherent in the 100 MHz maser reference. It was decided to use a rubidium frequency reference (delivery in late 1993).

NRAO is committed to completing the hardware portion of the project on schedule (January 1995). Start-up and complete closed-loop and precision pointing software are dependent on the antenna contractor's schedule.

Servo

Development of hardware and software by RSI's Precision Controls Division will culminate in a factory acceptance test scheduled for March 1994. Servo system installation on the telescope will commence in late 1994, and will end with NRAO acceptance of the field tests in 1995.

Monitor/Control

During 1994, all software for basic control will be finished. This software is generic in the sense that it is used throughout the telescope system: whenever software is needed to interface a person through a computer to some digital interface controlling any of the many devices which make up the telescope, the one software package is used. The only thing that changes from device to device are the lists of control parameters defining the hardware and user interfaces. and the definitions of the methods (1) for calculating one parameter from other parameters, (2) for checking if a parameter value is legal, and (3) for loading a parameter value into hardware. Such device-specific software will need to be written as each new instrument is introduced into the system. Also included under basic control is software for coordinating the various devices for observations; hardware drivers for the MCB, IEEE-488, and IRIG; error response modules, and real-time sequencing code as part of the basic package.

The universal local oscillator software will be finished and operational by the end of 1994. The monitoring software infrastructure is already complete as is a display and analysis frontend (based on PV-Wave). The software frontend for integrating monitor streams into the control consoles will be finished, as will a frontend for the message system, e.g., error messages to the operator and observer. With the completion of the basic control software, NRAO should be able to interface the new telescope backends as they are completed, for monitor and control purposes.

During 1994, work will begin on the observer's interface. Also, NRAO will be putting together hardware and documentation for various M&C sub-systems including IRIG Timing distribution, MCB, Position Computer Chassis, Servo Monitor Chassis, Telescope MCB and IEEE-488 Chassis, Control Room MCB and IEEE-488 Chassis, IEEE-488 distribution, and telescope Local Area Network.

The antenna control system software consists of two major components, the antenna positioning and pointing. The antenna positioning system will be completed during the year, with initial interfaces for the pointing system. The pointing system will include a traditional pointing model for initial telescope operations. Progress will be limited on the completion of data collection, transportation, integration, and associated sub-projects, though work on the data handling software infrastructure will begin.

In 1995, installation of hardware design, documentation, and construction will continue, but now the various racks and chassis used by M&C will be installed on the telescope as access is made possible by construction schedules. Additionally in 1995, the pointing correction modules will be integrated into the antenna software with their related sensors (such as the ground reference laser system, autocollimator, and quadrant detector) as these systems come on-line. Further development will occur on the observer's interface and observer utilities.

Finally for 1995, accelerated development on the observer's interface will begin, including integration with the analysis system, sequencing scans, handling calibrators, accepting all coordinate reference systems, VLBI observations, and remote observing. Heavy use of the simulator is planned in order to improve the user-interface by both getting feedback from astronomers and by making the system more familiar to potential observers before the GBT is scheduled for astronomical observations.

VI. MAJOR NEW INITIATIVES

1. The Millimeter Array

Design of the Millimeter Array (MMA) was begun at the NRAO in 1983 and was assembled from the ideas of more than 70 astronomers at three scientific workshops held at the NRAO from 1985 to 1989. A formal proposal for the MMA submitted to the NSF in 1990 culminated this phase of the effort. The MMA was highlighted by the Astronomy and Astrophysics Survey Report (the "Bahcall Report") as one of the four major astronomical facilities for the decade of the 1990s.

The MMA is a high-resolution imaging array comprised of forty 8-meter transportable antennas located at a high altitude site. The Millimeter Array combines the sensitivity provided by the collecting area of a telescope fifty meters in diameter with angular resolution $< 0''.1$, superior to that of the design goals of the Hubble Space Telescope, and it operates at frequencies 35-350 GHz at which thermal processes illuminate the sky. This unprecedented combination of sensitivity and angular resolution at short wavelengths will make available for astronomical investigation a wealth of unique opportunities and new science, including the ability to:

— Image the redshifted dust continuum emission and gas spectral line emission from evolving galaxies at epochs of formation as early as $z = 10$;

— Reveal the kinematics of optically obscured galactic nuclei and QSOs on spatial scales smaller than 100 pc;

— Reveal the isotopic and chemical gradients within circumstellar shells that reflect the chronology of stellar nuclear processing.

Recent Progress

Within the last twelve months the NSF Advisory Committee for the Astronomical Sciences (ACAST) gave its enthusiastic endorsement to the MMA and suggested that the Foundation proceed with a three-year research and development phase for the project. We were asked to provide the NSF with a plan for the MMA design and development;

we presented the plan to them in September 1992. The plan describes all aspects of the technical and environmental/site work that needs to be accomplished to put us in a position to begin construction for the array. We have attempted to make the MMA Design and Development Plan comprehensive: the plan incorporates not only the work that must be done to develop the hardware needed by the array but it also highlights the need for us to develop techniques for hardware fabrication and testing that will enable us to produce multiple copies of the various components that have nearly identical performance characteristics. The MMA Design and Development Plan anticipates initial funding in FY 1995.

Site Evaluation. Three sites are under active investigation for the MMA, two in the continental southwest and the third on Mauna Kea on the island of Hawaii. A transportable 225 GHz site-testing radiometer has been operated for a year or more on all three sites, providing us with a measure of the millimeter-wave transparency and stability. All the sites seem capable of satisfying the scientific requirements for the MMA.

Antenna Design. Phase coherence of the array on the longest baselines on all the sites will often demand a crude form of "adaptive optics." In the case of the MMA, this means switching rapidly between source and calibrator. The switch cycle may need to be as rapid as 10 seconds. Given this need, the antenna design has been concentrated on a very stiff slant-axis concept. Present work is being concentrated on an evaluation of materials given realistic thermal measurements we are currently making under the auspices of the MMA Joint Development Group (JDG) at Hat Creek on the BIMA antennas.

Receiver Design. The current generation of SIS mixer receivers now on the 12 Meter Telescope meet the performance specifications for the MMA receivers. They do so however with mechanical tuners. Progress on simple tunerless mixers for the MMA is coming along well at the NRAO Central Development Laboratory (CDL).

The first performance specifications for millimeter-wave 60-80 GHz HFET receivers are also available from the CDL and look encouraging for the prospect of MMA HFET receivers throughout the 3 mm band.

MMA Advisory Committee

A MMA Advisory Committee has been appointed to provide continuing advice on all aspects of the project to the NRAO Director. The Committee meets at least once annually and shares with the NRAO and the JDG the responsibility for all major decisions affecting the array.

The initial meeting of the Advisory Committee was in September 1993. The emphasis of this meeting was on the site evaluation process, antenna design work, and receiver development efforts.

2. Upgrade of the VLA

Recognizing the scientific potential of the VLA equipped with more modern instrumentation, the Report of the Radio Astronomy Panel of the Bahcall Committee emphasizes the need for a comprehensive upgrade. Specifically, the operation and maintenance of the VLA should be brought to a level appropriate to its broad scientific impact and great capital investment, and the out-of-date instrumentation should be replaced with modern, low-noise radiometers; fiber-optic transmission lines; and a modern, broad-band correlator. These upgrades will improve the sensitivity by up to an order of magnitude, improve the frequency coverage and spectral resolution, and increase the maximum allowable image size in certain cases.

The significant instrumentation improvements discussed below form the basis of the plan to upgrade the VLA. It can be funded incrementally over a decade and yet be useful at each stage of its development. A plan for the upgrade is being prepared for presentation in early 1994.

Receiver Sensitivity

New receivers based on cooled, low-noise, HFET amplifiers are needed to lower the system temperature at all bands except 21 cm and 3.6 cm where these devices already are installed. The proposed receivers are based on designs already implemented at the VLBA.

New Frequencies

Three new observing bands, at 610 MHz, 2.7 GHz, and 43 GHz, are being considered for the VLA, and one at 86 GHz for the VLBA. The 610 MHz and 2.7 GHz bands are intended to fill in the gaps in existing coverage, while the 43 GHz system will improve the resolution by a factor of two. The additional frequencies are important for continuum studies of spectra as well as the effect of Faraday rotation and depolarization which are tied to: specific critical frequency regimes that are determined by source physics, for pulsar work where the critical frequencies of observations are determined by the spectra and dispersion, and for unique spectral lines such as SiO at 43 GHz. Construction of an initial set of ten 43 GHz receivers was started in 1993 with funding from the National Autonomous University of Mexico. It is planned to complete this project on all 28 antennas in succeeding years with NSF funding.

Fiber-Optics IF Transmission System

In order to distribute 2 GHz of bandwidth from each antenna (two polarizations, each with 1 GHz), the current waveguide transmission system needs to be replaced with a modern fiber-optics link. This will also permit future expansion to even wider bandwidths, and will allow inclusion of signals from other, more widely dispersed antennas. For the first stage, a fiber-optics link will replace the waveguide connection between VLA antennas and, in addition, it will connect the Pie Town VLBA antenna to the VLA.

Broad-Band Correlator

The VLA correlator provides a maximum bandwidth of 100 MHz (per polarization), obtained by a pair of separately tuned, 50 MHz wide bandwidths. These bandwidths were set by technological limitations current some fifteen years ago and cannot be greatly expanded. In conjunction with greatly improved IF transmission capability, a full 1 GHz bandwidth in each polarization can now be implemented by building a new correlator. A 2 GHz capability is also possible in the future.

Modern correlator design based on the FX approach, used successfully by the VLBA, is especially suited to arrays with large numbers of elements, such as the VLA. With an FX correlator and good spectral resolution, it should also be feasible to delete narrow-band RFI and thus exploit the full bandwidth of the IF system.

3. VLA-VLBA Connection

A plan to bridge the gap in angular resolution between the maximum achievable by the VLA, ~0."1, and the minimum provided by the VLBA, ~0."01, was endorsed by the report of the Astronomy and Astrophysics Survey Committee as one of the recommended moderate programs. Connection of the two arrays will increase the resolution of the VLA at all frequencies; improve the dynamic range, field of view, and extended source sensitivity of the VLBA; and give a scaled array capability at 0."1 resolution for all frequencies from 300 MHz to 22 GHz.

The VLA/VLBA connection will be accomplished with a phased plan which includes the following three steps:

— Placing four VLBA recorders at the VLA so that the antennas at the ends of the wye arms can be used as independent VLBA telescopes;

— Constructing four new VLBA antennas (at Dusty, Bernardo, and Vaughn, New Mexico and at Holbrook, Arizona) for measurement of short VLBA spacings;

— Providing fiber-optic links from the VLA to the four new antennas as well as to the VLBA antennas at Pie Town and Los Alamos. These six outrigger antennas would then be used as part of the VLA. The VLA correlator will be expanded from 27 to 33 stations to accommodate the additional baselines.

Together, these improvements will provide a greatly enhanced imaging capability and brightness sensitivity over a wide range of frequency. The scientific applications will include observations of the sun and planets, radio emission from stars, novae, protoplanetary nebulae, and stellar winds, as well as from star-forming regions, active galactic nuclei, and quasars. The VLA/VLBA connection is a long-term goal of the Observatory — beyond the five-year budget and personnel schedule presented in Section XI.

VII. NON-NSF RESEARCH

1. United States Naval Observatory Operations

In 1994 the NRAO will continue to operate an 85-foot telescope in Green Bank for the United States Naval Observatory (USNO). The antenna is part of the NAVNET system which uses VLBI techniques for earth orientation measurements. The data are used to determine the roation rate and pole orientation of the earth. The accurate time and orientation information form the fundamental data needed for various radio and satellite-based navigation systems around the world, and for analysis of observations from synthesis radio telescopes like the VLA and VLBA. In addition, research in terrestrial science is based on these observations through the correlation of variations in earth rotation with large-scale weather patterns. When the telescope is not being used for VLBI, it is used to monitor the arrival time and flux density of a select group of pulsars. This activity is coordinated by astronomers at Princeton and Oberlin. Pulsar observations are made between 20 and 50 hours each week at 610 MHz using a feed placed in an offset position on the telescope.

In 1994 a new 20 meter antenna will be constructed for use of the USNO at Green Bank. It will have faster slew rates and greater sky coverage than the 85 foot telescope now in use which it will replace. It will be equipped with new receivers and electronics. Along with the new antenna, the USNO will install two hydrogen masers in Green Bank as a frequency standard. The output from these masers will be available for general use around the site.

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

The Green Bank OVLBI Earth Station is scheduled to reach the initial operational phase by April 1, 1994. At this date all the station hardware will have been installed and tested, all communication links that are in place with other mission elements will be verified, and the antenna control software will be complete and tested. For planning purposes, we assume that the implementation phase of the Green Bank OVLBI Earth Station will end April 1, 1994.

Launch of the first of the two OVLBI spacecraft, the Japanese VSOP satellite, is currently scheduled for August 1996. In the time between completion of the Earth Station implementation and start of the scientific missions, the operations staff of the station will perform the following tasks:

- Thorough tests will be conducted of the interfaces between the Green Bank Earth Station and other mission elements. This includes the interfaces to the VSOP and Radioastron operations centers for communication of the master sequence of events, transmission of simulated timing residuals to the orbit determination centers, and preparation of timing correction files in a format that can be read over the internet by the OVLBI correlators. Several of the critical interfaces are still to be defined by the cognizant mission elements and will not be defined until after the first quarter of 1994.
- The broadband Ku-band and X-band receivers will be tested, and their reliability assessed, by periodic surveys of the sky. As a subsidiary benefit, brighter radio sources monitored in this work may prove to be suitable candidates for later OVLBI science observations.
- The digital hardware, data formatters, and wideband recording system will be verified by means of ground-based VLBI astronomy tests. The data from the Earth Station will be correlated with the VLBA correlator in Socorro as a final end-to-end test of this part of the Earth Station functionality.
- Tests of the narrowband uplink transmitters will be made to the Student Undergraduate Research Facility Satellite (SURFSAT). This satellite, to be launched in January 1995, has transponders suitable for verification of the OVLBI station transmitting system. Tracking passes of SURFSAT will also be used to measure and verify the round-trip timing. In addition, the timing residuals will be retrieved from the station by the orbit determination centers and used to reconstruct the precise spacecraft orbit and to predict the orbit for subsequent

passes. This will fully test the two-way interfaces with the orbit determination centers.

— Compatibility of the wideband station receivers with the spacecraft transmitters will be verified via tests made with prototype downlink systems provided by the Japanese and Russian space agencies for VSOP and Radioastron, respectively. The spacecraft hardware will not be available until after the first quarter of 1994.
— Operations staff will be hired and trained so that they can be ready to support the final testing and operation six months prior to VSOP launch.
— Operational procedures will be developed, tested, and thoroughly documented.
— The near real-time (NRT) single baseline correlator will be interfaced to the station and tested; operational procedures will be established.
— Optional station equipment (e.g., emergency electrical power) will be implemented as needed.

3. NASA-OVLBI Science Support

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

Management and Science
VLBA Correlator Enhancements
Near-Real-Time Correlators
VLBA Data Acquisition Systems and Tapes
AIPS Enhancements
User Support
Operations Support

The subsequent presentations of the 1994 and long-range plans for OVLBI science are organized according to this task outline.

Management and Science

This activity, which will continue 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 will be 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 each mission.

VLBA Correlator Enhancements. Final implementation plans will be completed for modifications to the VLBA correlator to support space-VLBI observations, and work will start to realize the plans. It is expected that the modifications will include: incorporation of spacecraft ephemeris software imported from JPL; development of new software to accept and interpolate phase-transfer-link correction data; changes to the FFT Control Card to apply these corrections, and to extend the delay rate range of the wavefront model generators; addition of more output DAT recorders; and possibly redesign of the output transversal filter to approximately quadruple its capacity.

Near-Real-Time Correlators

Fabrication of the two near-real-time correlator systems will begin. These are to be two-station versions of the VLBA correlator design, using identical hardware and software modules. The only significant engineering effort, redesign of the backplane to accommodate the small number of boards in a single bin, will also start. Planning for installation of one of these systems at NRAO's Green Bank site will be undertaken in cooperation with Green Bank personnel responsible for the space-VLBI earth telemetry station and the Green Bank telescope.

OVLBA Data Acquisition Systems and Tapes. The first of four units to be procured for loan to Russia in support of the Radioastron mission will be received. This unit is destined for the Russian deep-space tracking station at Ussurijsk as a replacement for a similar unit previously lent by the VLBA project. In lieu of actually exchanging the equipment, the new unit will be installed at the Green Bank Telescope, and that already at Ussurijsk converted to the NASA loan program. The second and third such units, variants on the basic VLBA design suitable for use at space-VLBI earth telemetry stations, will be ordered.

AIPS Enhancements

Testing of the basic versions of the baseline-oriented fringe-fitting tasks, BLING and BLAPP, will be completed. Work on further enhancements, most importantly the ability to let the parameter windows track results already obtained, both forwards and backwards in time, may begin. Design of an interactive source model-fitting task will be completed, and implementation started.

User Support and Operations Support

There will be no activity in these areas in 1994; activity will begin in 1995, closer to the mission launch dates.

VIII. COLLABORATIVE WORK

1. AIPS++

The consortium of radio astronomy organizations that is developing AIPS++, the successor to AIPS, comprises the Australia Telescope National Facility, the Netherlands Foundation for Research in Astronomy, the Nuffield Radio Astronomy Laboratories at Jodrell Bank in the United Kingdom, the Canadian Herzberg Institute (operating the James Clerk Millimeter Telescope and Dominion Radio Astrophysical Observatory), the Tata Institute of Fundamental Research in India, the Berkeley-Illinois-Maryland Array consortium, and the NRAO. Each member organization has a seat on the steering committee which reviews the progress of the project. It currently meets three times a year at sites rotating among the consortium members, although the meeting frequency is expected to decrease as AIPS++ nears completion.

The AIPS project has broad international support, and represents an important effort to pool resources among the participating institutions for development of advanced data reduction and analysis software in astronomy. NRAO's continued participation is essential for the success of this collaborative effort. The project also is providing NRAO an opportunity to leverage its limited resources, participating in the development of a software package that is more ambitious and will solve more problems than would have been otherwise possible.

Our initial effort was to do a complete analysis of the astronomical requirements, concentrating on the need for calibration and imaging of both single dishes and interferometric arrays. The ultimate goal is to be able to process most radio astronomical observations using AIPS++ and to allow users easily to combine data observed by different instruments. We aim to make use of AIPS++ for data processing both on-line and off-line.

From the initial designs developed from the astronomical requirements, we have developed the specifications of the core infrastructure libraries of classes necessary to complete the implementations — mathematics, data management, graphics, and operating system support. Most of the effort during 1992 and 1993 went into the mathematics and management classes. We plan to release an initial version of the libraries in the last quarter of 1993. This release will contain support for mathematical operations on arrays (vectors, matrices, cubes, and hyper-cubes) and multi-dimensional images. In particular, we have implemented the FFT and CLEAN algorithms. We have completed an implementation of the table system, including the ability to create virtual tables containing data from other tables using a simple selection language. The library release will also contain a set of classes to support reading and writing of data in the FITS format. Included in the release are a suite of test programs, which are not yet suitable for release to astronomical researchers.

With funding included in the present Program Plan and Long Range Plan, we intend to continue the NRAO's contribution to the effort devoted to this product internationally and to participate in international workshops on AIPS++ design and development. As a result, we expect functional prototypes of significant parts of AIPS++ to be available in the first quarter of 1994, with more applications becoming available during the year. We expect major applications for VLBA and GBT data processing to become available from the first quarter of 1994. In addition, we plan to use AIPS++ to provide the basis for MMA routine data analysis and to be the main platform for algorithm research.

2. MMA Joint Development Group

Design of the Millimeter Array has been a cooperative venture between the NRAO and interested millimeter-wave astronomers for nearly a decade. The concept of the array as a fast imaging instrument capable of precision operation at frequencies as high as 360 GHz and capable of providing images of 0.1" angular resolution, equivalent to that achievable by the HST or SIRTF, was a result of a series of scientific workshops held at the NRAO. The realization of the concept — 40 transportable antennas of 8 meters diameter located on a high latitude site — was the instrument recommended by the 1991 report of the Astronomy and Astrophysics Survey Committee.

In September 1992, a plan for the research and development phase of the MMA was submitted to the NSF Astronomy Division. The program covers the years 1993-1996, inclusive. In conducting the design and development program for the MMA, we intend to work closely with university groups through the MMA Joint Development Group (JDG). In each of the areas of the plan the experience and expertise of these groups can be put to effective use. The primary contact between the NRAO and a particular university group is maintained at the working level, between the NRAO engineer and associate responsible for the development in an area and the individuals in a community group that are participating in the effort. Visits, exchanges of technical memoranda, and electronics mail are the means of communication. The current JDG membership and representatives are:

University of California, Berkeley	W. J. Welch
California Institute of Technology	J. E. Carlstrom
University of Illinois	L. E. Snyder
University of Maryland	L. Blitz
University of Massachusetts	[to be appointed]

In 1994, work under the auspices of the JDG will include a continuation of the studies of the thermal characteristics of antennas at BIMA and work on the design of sideband separating mixers at OVRO. In addition, in 1994 we will begin as a new JDG project the design of a radiometer to measure the water vapor along the line of sight to the source being observed by a millimeter telescope.

The JDG concept is new to the NRAO. It has the potential to provide an efficient way to "recruit" experienced millimeter-wave astronomers and instrument builders to the MMA project without disrupting their personal lives or professional careers. If the JDG model is successful, it has a natural extension to the operational phase of the instrument. Working together with the university groups, we expect, during the MMA development phase, to define the role and guide the fruitful evolution of the JDG.

IX. EDUCATION PROGRAM

1. Overview

Although the distinction between research and education is somewhat hazy and perhaps artificial, nevertheless it is possible to point to a number of programs at the NRAO specifically designed to broaden and enhance the scientific education of students and teachers. These include opportunities for undergraduate students to participate in on-going scientific, engineering, or computer science projects, opportunities for graduate students to conduct research under the direction of NRAO staff scientists, and opportunities for recent Ph.D. recipients to collaborate at the NRAO with scientists having mutual research interests. In addition, NRAO conducts institutes to enhance secondary education teaching of astronomy. The scope and purpose of such programs are briefly outlined in this section as are programs designed to reach the public.

2. Postdoctoral Fellows

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 postdoc 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.

At the end of 1993, we expect ten Jansky Postdoctorals at the Observatory. Nearly ten postdoctoral positions were lost in the budget reductions of the last six years. This represents an unfortunate loss to young astronomers and to radio astronomy. In 1993 we began the restoration of the postdoctoral program, and we will continue to give it emphasis in the period covered by the present Program Plan so that it may once again be at a level appropriate to a national observatory.

3. Resident Ph.D. Thesis Students

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

Presently there are eight resident Ph.D. thesis students at the NRAO 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.

4. Non-Resident Ph.D. Thesis Students

More than one hundred twenty-five Ph.D. thesis students use the NRAO facilities each year for their research. While these 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.

5. Summer Students

For thirty years the NRAO has offered summer appointments to students interested in broadening their exposure to radio astronomy. Many of the former NRAO summer students are now established researchers. In this sense the summer student program has been very successful indeed.

One of the strengths of the early program was its emphasis on students who had made a commitment to radio astronomy: the only students admitted to the program were graduate students in radio astronomy, engineering, or computing. One of its weaknesses was that it was funded out of contract funds and, when funding was tight, the program was constrained. In 1982 there was no summer student program at all.

In 1987 the NSF funded a program for summer student research opportunities called Research Experiences for Undergraduates (REU). The NRAO has applied for REU funds every year since 1987 and has annually supported eighteen to twenty summer students from these funds. All these students are, of course, undergraduates and as such have not made a commitment to radio astronomy nor do they, usually, have the research skills of graduate students. Many students are exploring radio astronomy as a career option; others are simply looking for summer employment.

Each year since 1987 we have supplemented the REU funds with funds from the Cooperative Agreement to support a few graduate students, bringing the total number of summer students to nearly thirty. Approximately half this number are astronomy students; the remainder are interested in the engineering and computing aspects of radio astronomy. Through exposure to hands-on research, we hope to persuade the summer students to strengthen their commitment to careers in science.

In addition to the REU summer students there are students working at the NRAO from other institutions. During the summer months, students not supported by the NRAO REU program come from other institutions at their own expense to work with the NRAO scientific staff and to participate in the NRAO student program.

6. Special Educational Programs

Special Education Programs

It is increasingly apparent that educational programs must reach young people at the high-school level or below in order to generate a continuing interest in science. NRAO has been involved in the past in a number of programs aimed at junior-high and high-school level students. We are actively evaluating these programs and investigating a wealth of new approaches to precollege science education that have arisen in recent years. We are considering several approaches to this type of education that will make use of our professional talent and the widespread appeal of astronomy among young people.

Secondary Science Teacher Institute

In cooperation with the University of West Virginia, the NRAO sponsors two week-long workshops for science teachers in secondary schools. The workshops are held in Green Bank, two sessions each summer. In addition to lectures on radio astronomy research and instrumentation, the teachers are also given access to a radio telescope and encouraged to create their own observing program. The teachers build their own radio telescope capable of monitoring emission from Jupiter and developing lab materials to go with it for use in their classrooms. Many teachers return with students on field trips to use the 40 Foot Telescope following their Institute experience. The hope is that they will appreciate research, and later pass along its excitement to their students, by being involved in all aspects of observational research. Fifty teachers and ten returning teacher/mentors are accommodated in the program each summer. This program is funded by the NSF Education and Human Resources (EHR) Division.

7. Workshops and Symposia

Green Bank Workshops

NRAO has traditionally hosted symposia and workshops on special topics of interest to research astronomers, those who develop new instrumentation, and their students. The series of Green Bank workshops are well-known: twenty workshops on topics from "Phases of the Interstellar Medium" to "Large Scale Surveys of the Sky" have been held to date. We anticipate a continuation of this series during the period of the present plan that will accompany bringing the GBT into operation.

Synthesis Imaging Workshops

One important measure of the success of the VLA is the number of scientists who use the telescope each year, that is, nearly 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, the most recent in June 1991. More than 115 students (mostly graduate students) attended the workshop, the third in six years. Thirty-one 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 1993 VLBI School

In 1993, it was twenty-six years since the technique of VLBI was first used in astronomy. Since the NRAO played a major role in the development of VLBI and that effort culminated also in 1993 with the completion of the VLBA, the NRAO commemorated this event by sponsoring a summer school on VLBI.

For over twenty-five years VLBI has been perceived as an arcane branch of radio astronomy capable of leading to considerable insight but the practice of which was limited to a few dedicated individuals. 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 hosted graduate students and others attending a summer school on the theory and practice of VLBI, with specific reference to the capabilities of the VLBA. Thirty one lectures were presented by 24 lecturers. About 100 graduate students and others attended for approximately ten days.

8. Public Education

Images of Radio Astronomy

The NRAO maintains a collection of slides illustrating the telescopes, techniques, and research images of radio astronomy. These slides are made available to students, classroom teachers, professional colleagues, and the media. In 1993 we expanded this outreach program by issuing a compact disk of more than 3500 astronomical images called "Images from the Radio Universe." These images can be displayed on a PC computer screen and manipulated by students seeking to explore radio astronomy from their classroom. Each of the images is fully documented and calibrated — they are not "toys" or illustrations. These are research quality images in every respect.

Work will continue in the next year on a similar collection of radio images made of the complete third Cambridge catalog of radio sources. This collection will include images from the VLA, MERLIN, and the Westerbork synthesis telescope. As a collection meant for students as well as professional colleagues, all these images will again be complete, documented, and available as a compact disk for personal computers and workstations.

Green Bank

Approximately 13,000 - 14,000 tourists visit the Green Bank site during the summer months, taking the hourly tours via bus and viewing the displays in the Visitors Center. A smaller group of people take self-conducted walking tours outside of the summer months; roughly 2000 sign the guest book. In addition, two special tours are given on average each week to organized groups of typical size 30 persons. The total is close to 20,000 public visitors per year.

Socorro

The VLA site has a visitors center built by the State of New Mexico and opened in 1983. NRAO maintains and operates the Center, which is attended by roughly 15,000 tourists each year. They take a self-guided walking tour of the central area of the VLA and view displays and a slide show in the Center. The VLA also hosts special tours, on average one per week, largely of student groups from junior high school through college.

Tucson

The 12 Meter Telescope is included in the special tours done by Kitt Peak National Observatory in connection with their monthly Public Nights. About 50 people visit the 12 Meter on each of these occasions. Special tours are arranged upon request throughout the year.

X. 1994 PRELIMINARY FINANCIAL PLAN

BY BUDGET CATEGORY

(NSF Funds, $ in Thousands)

	New Funds	Uncommitted Carryover of 1993 Funds	Total Available for Commitment	Commitments Carried Over From 1993 Funds	Total Available for Expenditures
Operations					
Personnel Compensation	$16,549		$16,549		$16,549
Personnel Benefits	5,129		5,129		5,129
Travel	657		657		657
Material & Supply	9,570		9,570		9,570
Management Fee	625		625		625
Common Cost Recovery/					
CDL Device Revenue	(830)		(830)		(830)
Total Operations	$31,700	$0	$31,700	$0	$31,700
Research & Operating Equipment	$1,180		$1,180		$1,180
Total NSF Operations	$32,880	$0	$32,880	$0	$32,880
Design & Construction					
GBT	$0	$8,000	$8,000	$30,000	$38,000
Total NSF Plan	$32,880	$8,000	$40,880	$30,000	$70,880

X. 1994 PRELIMINARY FINANCIAL PLAN

BY SITE/PROJECT

(NSF Funds, $ in Thousands)

	Personnel	Salaries Wages & Benefits	Materials Supplies & Services	Travel	Total
Operations					
General & Administrative	28	$1,718	$958	$117	$2,793
Research Support	53	4,141	768	238	5,147
Technical Development	22	1,349	90	20	1,459
Green Bank Operations	68	3,272	765	25	4,062
Tucson Operations	26	1,442	758	42	2,242
Socorro Operations	116	5,691	4,311	72	10,074
VLBA Operations	98	4,065	1,920	143	6,128
Management Fee			625		625
Common Cost Recovery/					
CDL Device Revenue			(830)		(830)
Research & Operating Equipment			1,180		1,180
Total NSF Operations	411	$21,678	$10,545	$657	$32,880

XI. LONG RANGE PLAN

(NSF Funds, $ in Thousands)

	1994	1995	1996	1997	1998	1999
OPERATIONS						
Base Operations	$31,700	$36,000	$37,150	$38,650	$40,200	$41,800
Research & Operating Equip.	1,180	1,200	1,400	1,400	1,500	1,500
VLA Upgrade	-	1,500	3,000	3,150	3,350	3,500
Total NSF Operations	$32,880	$38,700	$41,550	$43,200	$45,050	$46,800
New Initiative						
Millimeter Array ($120M)	-	$3,000	$3,000	$8,000	$9,000	$25,000
Total NSF Plan	$32,880	$41,700	$44,550	$51,200	$54,050	$71,800

Personnel Projection (Full-Time — Year End Ceiling)

Base Operations	411	426	437	440	440	445
GB Telescope Const.*	23	8	-	-	-	-
Millimeter Array	-	5	8	15	24	44
Non-NSF Research*	20	20	20	20	20	20
Personnel Total	454	459	465	475	484	509

*Separately funded and not included in the above budget.

APPENDIX A

NRAO SCIENTIFIC STAFF ACTIVITIES

In 1994 the NRAO scientific staff, individually and collaboratively, will conduct an active program of astronomical research studying objects as near as the sun and as distant as the quasars. Much of the staff research involves the use of the NRAO radio telescopes with the expectation that the staff scientists can, through their own proficiency with the instruments and the data analysis procedures, be in a better position to help visiting scientists at the NRAO. At the same time the staff scientists can and do experiment with observing techniques and research ideas that expand the horizons of radio astronomical research.

Astronomical research planned by the NRAO scientific staff in 1994 is summarized below by area of research.

1. Sun and the Solar System

Studies of solar flares at radio wavelengths provide information about where and when electrons are heated and accelerated in the solar corona, and how the energy contained in energetic electrons is subsequently transported within the flaring volume. Furthermore, they provide constraints on the magnetic field topology in the solar corona. Work in this area will proceed along several lines.

First, the details of energy release during the course of a solar flare remains controversial; the question being whether or not the release is "fragmentary," with a flare being nothing more than a superposition of hundreds or even thousands of elementary acceleration events. Two experiments are planned to explore this issue. The first will explore the smallest radio bursts detectable by the VLA, the so-called microbursts, in order to characterize their properties and their relation to hard X-ray microflares. The second experiment is to use the VLA simultaneously with a broadband optical spectrometer to obtain simultaneously radio and spectroscopic images of decimetric bursts.

The second avenue of solar research will explore the impulsive phase of solar flares. In the impulsive phase, within a matter of seconds, enormous amounts of energy are liberated, a large fraction of which goes into heating and accelerating electrons. High resolution imaging in microwaves offers a means of pin-pointing the energy release site and of following the evolution of the source in these critical early stages. Previously, the time resolution of available instrumentation was too low to accomplish this goal. However, recent improvements to the VLA allow us to obtain snapshot images of solar flares in two frequency bands five times per second. With this new capability, it is expected that the "magnetic footprint" of microwave flares can be localized.

The third question to be investigated is that of the processes by which energy is transported throughout the flaring volume. While nonthermal electrons most often appear to carry the bulk of the energy, and are ultimately responsible for the hard X-ray and microwave bursts observed, several flares have now been observed with the VLA which are dominated by thermal plasma. These results, to be pursued further, suggest that while some flares are characterized by a nonthermal distribution of electrons it is not these electrons that are transported effectively high in the solar photosphere.

Finally, one of the outstanding problems of solar physics has been a detailed understanding of the sun's outer atmosphere. The VLA will be used to attack this problem by imaging radio emission from the corona, from the transition region, and from the upper chromosphere. Of particular interest is the structure of solar active regions, the site of enhanced magnetic fields and of solar flares. A multiband VLA study of a solar active region will be used together with soft X-ray data from the Japanese satellite, Yohokoh, spanning half a solar rotation to construct a multi-thermal, inhomogeneous model for the outer solar atmosphere.

2. Stars and Stellar Evolution

Radio observations planned in 1994 will be used together with optical, infrared, and X-ray observations to investigate the nature of very young stars, to shed light on the physical processes that are responsible for nonthermal active stars, and to understand the details of the mass loss from evolved stars.

Early Evolution of Young Stars

Extremely young stars, such as VLA 1623-2418, IRAS 16293-2422A and B, NGC 1333-IRAS4A and B, and GSS 30, are all characterized by unusual radio continuum emission, presumably free-free emission powered by accretion. They also show compact strong dust emission, while molecular emission may not be most pronounced at the position where the dust emission is most intense. The new high frequency capability of the VLA will be used to survey cold cloud cores to identify other examples of the youngest known stars. One aim of the project is to compile a list of the youngest stars for examination by future space infrared telescopes.

Young stars are often surrounded by dusty gaseous disks. The interaction between the disk material and material expelled from the stellar atmosphere as the first light from the star begins to shine leads to pronounced shocks that can tell us about the energetics of the youngest self-luminous stars. Two approaches will be used to distinguish which observational phenomena are related to the disks and which to the stellar winds. The first is to search for CO band-heads in emission in a sample of young stars that show evidence for disks and winds via other diagnostics. A correlation of CO emission with an infrared continuum excess (indicative of a disk) or high-velocity forbidden line emission (originating in a wind) will provide a clue as to the location of the CO-emitting gas. The second approach is to extend the wavelength coverage of the high spectral resolution data to encompass lower rotational lines away from the v = 2-0 bandhead and to observe higher overtone bands (v = 3-1, 4-2, etc.). This will provide sufficient information for current models to constrain the conditions within the CO-emission regions.

Winds from the most massive stars, the Wolf-Rayet stars, are critical to recently constructed theories of the evolution of massive stars. Radio observations of the free-free continuum emission, which provide a measure of the mass outflow and gas density as a function of radius, will be used in conjunction with optical polarization observations to understand how the momentum is transferred from the radiation to the gaseous material of the wind. Preliminary indications from the combination of radio observations and optical polarization measurements suggest that many winds are aspherical. Verification of this intriguing result will be attempted in a large sample of stars in the next year.

Active and Main Sequence Stars: Radio observations of active and main sequence stars will be used to elucidate the physics of the emission processes; in addition the nearby-radio emitting stars will be used as astrometric standards and for parallax observations.

Sensitive VLA and VLBA observations of RS CVn stars will be used to investigate the following questions:

- What is the location of the radio emitting region in RS CVn binary systems?
- During non-thermal flares the radio spectra become optically thick. Are these emission regions confined to the photosphere of one (or both) of the binary stellar companions?
- What is the physical cause of the separation in properties between high luminosity (greater than 10^{16} erg/s) RS CVn stars and low luminosity stars?

The VLBA will be particularly important in answering all these questions. The combination of the resolution of the array, its sensitivity, especially that obtained by means of phase referencing techniques, and the multifrequency capability will permit answers to be obtained to these long vexing questions.

A comprehensive all-sky survey for radio emission from all known cataclysmic variables will be undertaken this year both at the VLA and with the Australia Telescope. Presently, only two stars in this class are known to be sources of radio emission. The detection of others is needed before we are in a position to draw conclusions about the role of radio processes in the physics of the cataclysmic variable phenomenon.

Stellar sources of radio emission, irrespective of their stellar type or the physics of the emission process, are important in establishing the fundamental reference frames of astronomy. In the next year observations with the VLBA will be made of all stellar sources near the sun in order to measure their parallax. The results will be compared with optical observations to determine systemic errors in the optical and/or radio measurements and to resolve the source of those errors should they become apparent.

In addition, observations with the VLBA of stellar radio sources will be used to inter-compare the fundamental radio and optical reference frames to an accuracy of a few milli-arcseconds.

Evolved Stars

The late stages of evolution of stars of mass between one and eight solar masses is characterized by a rapid phase of mass loss during which the bulk of the mass of the star is ejected, leaving behind a remnant star of mass a few tenths of a solar mass. Still later, the residual stellar remnant will ionize the expelled shell, giving rise to a planetary nebula. The details of the mass loss phase which occurs as stars traverse the so-called Asymptotic Giant Branch (AGB) will be investigated in a variety of ways at the NRAO in 1994.

Refractory molecules, especially SiO, are the first of the molecular species to form in a stellar outflow because their formation can occur at relatively high temperatures. High resolution VLBA observations will be used to study SiO emission and H_2O emission in the same stellar outflows. The water is representative of material much further out in the outflow than the SiO, so together the two species can tell us about the kinematics of the outflow and provide information as to whether the outflow is spherical or somehow confined.

The VLBA observations of SiO masers can also be used to establish whether or not the SiO is pumped by collisions or by the stellar infrared. Depending on how this question is answered, one learns, by observing SiO, either about the local density and density fluctuations in the outflow or we learn about the time evolution of the stellar infrared luminosity. Observations will be made of SiO in different vibrational states. If the ground rotational state of the three vibrationally excited states of SiO are found to be co-spatial, it would be a strong argument for an infrared pump.

VLBA observations of the polarization of OH masers will permit an assessment to be made of the magnitude of the magnetic field in the envelope of late-type stars. Observations will be made in a complete sample of stars so that the statistics of the prevalence of magnetic fields in stellar outflows can be assessed.

Single dish millimeter-wave observations will be important in obtaining a census of the molecular and isotopic composition of the AGB outflow envelopes. Such an understanding is important because moderate mass stars replenish the interstellar medium with molecules rich in processed material. Large molecules formed in AGB envelopes may proceed undestroyed into the interstellar medium with their isotopically distinct signature. Maps of a large number of molecular species will be made with the 12 Meter Telescope. Preliminary work indicates that complex cyanopolyynes form from fragments of smaller molecules photo-dissociated in the shell. The larger molecules effectively channel ultraviolet energy into infrared energy through their many vibrational modes, with the large molecules surviving in the process to large distances from the progenitor star. Smaller molecules cannot degrade the UV energy, having few bonds, and are dissociated deep in the shell to provide the material for formation of the larger species. Attempts will be made to understand the details of these processes in the next year.

Isotopic abundances, even for so simple a species as CO, are poorly understood in AGB outflows. Both atmospheric and circumstellar isotopic ratios are available to date for only a handful of carbon stars. These values, atmospheric compared to circumstellar, do not show agreement within a factor of two or more. Mapping the ^{12}C and ^{13}C isotopes will give us insight into the evolutionary history of the stars's experience on the AGB, since the carbon isotope ratio in evolved stars is a reflection of nuclear processes going on in the stellar interior. The hope is to obtain a synthesis of atmospheric isotopic abundances and kinematics with the structure and composition of the much larger circumstellar envelope and thereby achieve a unified picture of the stars that are so important to the isotopic evolution of the interstellar medium.

Somewhat past the AGB phase, a star of moderate mass evolves to the planetary nebula stage. This transition is one of the more poorly understood processes in stellar evolution. Briefly, it is thought that an extended envelope is deposited around the star during a heavy mass-loss phase and because of the high densities and low temperatures in the stellar atmosphere this envelope is predominately molecular. As the star evolves off the AGB and the stellar core is exposed a secondary wind — the "fast wind", which has much less mass but comparable momentum to the red giant wind — develops and begins to plow into the slower red giant wind. It has been proposed that the interaction of these winds is partly responsible for the shaping of planetary nebulae. As the central star and nebula evolve, a photodissociation front moves through the gas and the circumstellar envelope changes from molecular to atomic to ionized. In the coming year this transition resulting from the passage of the photodissociation front will be modelled theoretically. The work will involve the integration of a complex chemical network throughout the lifetime of a model nebula. Photo processes will be studied in detail and the results will be compared to observations in progress.

3. Supernovae and Supernova Remnants

In only a few years the enormous sensitivity of the VLA has changed the nature of radio astronomical research in supernovae from a study of their remnant's radiation in the Galaxy to studies of distant extragalactic supernovae immediately as they are seen to occur and even to using extragalactic supernovae as probes of their environment. This exciting field is still in its infancy; its potential continues to increase.

In 1994 the recent supernova in the galaxy M81, SN1993J, will be used as an *in-situ* probe of the nature of the neutral hydrogen in the disk of M81. Here the goal will be to compare the properties of the hydrogen disk in M81 with that in the Milky Way. This year, the HI absorption spectrum of SN1993J will be studied over as wide a range of velocities as possible so that the temperature and kinematics of the HI in M81, or in any of the group of galaxies associated witl M81 found along the line of sight to SN1993J, can be investigated.

More generally, studies of extragalactic radio supernovae at the VLA will concentrate on two areas: (1) observations of starburst galaxies and (2) the detection and monitoring of individual radio supernovae.

In starburst galaxies numerous supernovae and supernova remnants contribute to and even dominate the radio emission from a galactic nucleus. In nearby galaxies like M82 and NGC 253, dozens of individual supernovae can be distinguished in VLA images. In these very dusty environments, the radio images provide a unique means of studying the spatial distribution of supernova and supernova rate in a starburst galaxy.

The study of individual radio supernovae leads to a greater understanding of the supernova process. VLA observations have established radio light curves for nearly a dozen supernovae. These detailed light curves provide constraints on the mass loss rate and thus on the nature of the supernova progenitor star. Details in some light curves suggest variations in the stellar wind during the final stages of the evolution of the supernova progenitor. As the list of detected radio supernovae grows, it will be possible to establish the radio luminosity function for supernovae.

Important radio images will also be made of supernova remnants in the Galaxy. Among the most well-studied such remnants, the Crab Nebula is the remnant of a supernova in the year 1054. This supernova is thought to be typical of the phenomenon with one important exception: the swept-up shell of interstellar gas indicating the presence of the supernova blast wave has never been seen at any wavelength. A more sensitive attempt will be made to find the shell this year with the VLA at 327 MHz. Finding the shell is not only important for settling the heritage of this supernova, but it allows us to put important constraints on the progenitor star mass and mass loss history from the observed properties of the shell.

Searches will also be made for the radiative HI shells around several young pulsars which do not have a known supernova remnant. We suspect that the lack of the radio remnant is suggestive about the density of the interstellar medium into which the supernova remnant expanded. This can be checked against the timing and dynamic age of the pulsar. Discovery of an HI shell will show that supernova remnants are younger than is thought and that the simple-minded evolutionary theory is inadequate. Modifications may need to be made in our understanding of the Galactic supernova rate, the supernova remnant birthrate and the pulsar birthrate.

4. Pulsars

Pulsar research involves not only the study of individual objects in an attempt to understand the physics of the radio emission mechanism, but it is also possible to use ensembles of pulsars to investigate phenomena associated with the passage of large-scale gravitational waves through the solar system and to investigate the proper motions of pulsars with astrometric precision. The NRAO research program in 1994 incorporates aspects of all these studies.

Theoretical estimates of the masses of neutron stars range from 0.1 $M_\odot$ to 3.0 $M_\odot$, depending on the equation of state used in the calculation. These estimates can be verified observationally by timing pulsars in "relativistic" binary systems. Measurements to date indicate that neutron star masses are amazingly close to the Chandrasekhar limit of 1.4 $M_\odot$.

One method of estimating pulsar mass involves the measurement of both its mass function in a binary orbit and the rate of advance of the longitude of periastron. The mass function relates the masses of the two objects in the binary to the orbit inclination. The advance of periastron is the same effect as the perihelion advance of Mercury, well-known from studies of relativity, and its magnitude is directly proportional to the total mass of the binary system. With measurements of these two parameters, one can set limits on the masses of the pulsar and its companion with a reasonable estimate of the orbit inclination. Such timing measurements will be made on the binary pulsar system PSR B1820-11 at the VLA.

The masses of the objects in the binary can be determined unambiguously with the measurement of one additional orbit parameter. If the pulsar's companion is also a detectable pulsar, its mass function can be measured to provide this additional piece of information. The ratio of the mass functions varies as the ratio of the individual masses and the orbit inclination. Due to the orbital properties of the PSR B1820-11 binary, we suspect that its companion is a neutron star. Searches will be made to see if it is also a pulsar.

Of the 558 pulsars now known, 19 exhibit the phenomenon of "glitches," which are sudden, almost discontinuous, increases in the pulsar's rotation frequency. A glitch is thought to be the sudden coupling of the star's crust to its faster-spinning, neutron-rich, superfluid core. Eventually, the star's pre-glitch rotational properties are restored. The characteristic time scale for this exponential recovery is proportional to the star's internal temperature. Adequate data for this type of measurement exist for only three pulsars, and estimates of their internal temperatures range from 1×10^7 to 4×10^8 K.

PSR B1823-13 was discovered in a recent pulsar search, and subsequent timing of it revealed glitching behavior. Although the details of its glitch are poorly documented, its glitch activity is claimed to be second only to Vela, the glitch prototype. PSR B1823-13 is a promising candidate for studying the glitch phenomenon because its glitches appear to occur frequently and they are of large magnitude. Observations will be made in Green Bank to monitor the glitch activity of PSR B1823-13.

Millisecond pulsars represent a particularly extreme population of pulsars since they rotate hundreds of times a second yet remain incredibly stable. There are only a few millisecond pulsars, and several projects will seek to increase that number. There are numerous motivations for searching for millisecond pulsars. They can be used as probes of a variety of astrophysical phenomena, and they exhibit a wide range of intrinsic and orbital properties. It has become clear from recent surveys that readily observable millisecond pulsars are relatively near the sun in a distribution that appears isotropic. Most of the Northern sky has not yet been searched for these objects. To rectify this situation a search program will begin in Green Bank using newly developed search algorithms and observing procedure. The program should uncover several new, high luminosity, millisecond pulsars. The search will be extended at high frequencies in the direction of the galactic center in an attempt to reveal young, Crab-like pulsars, which could be missed at low frequencies owing to interstellar scattering.

Despite twenty-five years of observations, the details of the mechanism by which pulsars emit radio signals has remained elusive. One potential source of information on the nature of the mechanism is high-energy gamma-ray and X-ray emission patterns of radio pulsars. The high-energy emission carries a relatively high fraction of the pulsar spin-down energy and as such should be particularly discriminating for the various emission mechanism models. Radio observations will be used in conjunction with observations made with the Gamma Ray Observatory in an attempt to model simultaneously the microwave and gamma ray pulse spectrum.

Several studies of pulsar proper motions are planned in 1994. These are difficult observations, either with the VLA or the VLBA, and the optimal observational technique is not yet established. Exploratory observations are planned with both instruments. Once the technique is better refined the plan is to search for the proper motion of the pulsar PSR 1757-23 associated with the supernova remnant W28. It is thought that this pulsar is the stellar remnant from the supernova explosion that gave rise to W28, and if so its proper motion vector should lead us back to the site of the explosion. A second study will be made of the motions of pulsars that could have been the companions of runaway OB stars prior to the disruption of the stellar binary orbit by a supernova event. Finally, it appears as if a small number of pulsars leave a "wake" of diffuse emission as they move through the interstellar medium. Accurate proper motion measurements of these objects will be made to see if the pulsar motion is consistent with the wake being the direct result of the passage of the pulsar.

5. Molecular Clouds and Star Formation

Investigations of the star formation phenomenon involve studies of the chemistry of the molecular environment in which stars form, an understanding of the density fluctuations in molecular clouds that may grow or lead to gravitational collapse, and finally to the study of newly luminous stars that may, through their radiation, illuminate for us to study the material in their immediate surroundings from which they formed. Star formation appears to be a complicated chemical and physical process that nevertheless is capable of proceeding efficiently in a variety of astrophysical environments. This simple statement raises a number of questions that will be addressed observationally and through theoretical studies in the next year.

The structure and dynamics of the regions of molecular clouds where star formation is likely to occur is known in a theoretical context, but only recently have sufficient spatial resolution and sensitivity been achieved to allow us to test the ideas observationally. However, in the closest cloud complexes (D $\sim$ 150 pc), millimeter interferometers and the VLA can now probe scales 10-1000 AU that directly test theoretical ideas of star formation: circumstellar disks with Keplerian rotation should occur inside radii of approximately 100 AU, and infalling cloud material should have a density distribution intermediate between free-fall and hydrostatic equilibrium. Observations are planned with the OVRO millimeter array and the VLA to study several embedded young sources. It is hoped that these observations will reveal the rotation rates, density profiles, and outflow/infall velocities. Since each molecular species has a different excitation requirement, observations will be made of several molecular species so that one can trace out the variety of density components that may co-exist in the star formation region.

In the earliest stages of low mass star formation the molecular cloud core which nourishes the nascent young star has not yet warmed. The molecules which emit strongly are those whose abundance has been enhanced by low temperature chemistry, such as the light deuterated molecules DCO^+, HDO and NH_2D. Many strongly polar molecules may be depleted onto grains in such clouds, making recognition of the cold core and measurement of its properties difficult. In the L1689N cold core near the low mass protobinary IRAS 16293-2422, one of the deuterated "signposts" of star formation, NH_2D, has been mapped with the OVRO millimeter array. This cloud is devoid of either dust or gas structures on scales smaller than a few thousand AU, hence it represents the class of cold 8 K cores that have not yet formed stars. Low level gas and dust emission, however, connects this core with the protostellar core IRAS 16293-2422: Why is one core forming stars and its neighbor not? Preliminary VLA observations, to be pursued further this year, indicate that the ammonia emission vanishes near the IRAS 16293 star, presumably owing to freezeout onto grains in the cold protostellar core. But if molecular emission diminishes where molecules freeze onto grains, why is the L1689N core so prominent in line emission? Is this the clue as to whether a cold core will or will not form stars?

The VLA 1623-2418 core lies at the southern extremity of the massive Oph A condensation near a peak of DCO^+ emission. A compact dust structure harbors a protostar identified through free-free emission. Sensitive maps of ammonia and water emission made with the VLA have revealed no molecular emission associated with the dust core except that of the water masers. Both dust and gas temperatures show the region about this protostar to be the coldest in the core. The fact that it is nearly invisible in gas emission may result from freezing out of the molecules onto grains in this cold core. Here again prominent dust condensation accompanied by little gas emission guides us to the youngest stars. This phenomenon, and its implication, will be investigated further in several additional cold cores in the coming year.

It is unclear what differences in dense molecular gas properties give rise to massive star formation versus those that favor low mass star formation. As part of a study of high mass dense cores to understand these differences, a study of the cores in the Serpens region will be completed. In 1994 maps will be made of the CO(J=3-2) emission which traces the outflows in the region. The existing maps show that studying the outflows is vital for our understanding of the observed properties of the dense cores. The Serpens results, and similar studies of the outflows from young stars in the Perseus cloud, will be compared with the outflows in the Taurus cloud which result from low mass stars. This will permit an investigation of how outflow properties are related to stellar properties.

Still later phases of stellar formation may be investigated with observations designed to study warmer molecular environments, those that have had time to be heated by the newly formed stars. Methanol masers are a particularly good probe of the warm environment, because it is thought that methanol freezes out onto grains in a cold environment and then requires the heat of a newly formed star to release it back into the gas phase. A good place to search for methanol masers, therefore, is where molecular outflows encounter ambient cloud gas. The VLBA resolution of the methanol masers will be used to study the kinematics and excitation of the gas in the immediate environment of protostellar sources.

Somewhat more speculatively, the VLBA will be used to monitor the proper motion of water masers near low luminosity, young, stellar objects. One current idea to be evaluated is that the water masers arise at the points where the stellar outflowing wind interacts with a local density concentration. Since we expect to find "protoplanets" encircling young protostars, it could be that it is the protoplanets that are concentrations that the wind "ignites" as sources of water maser emission. If so, the VLBA observations will reveal the orbit of the putative planets and confirm or deny this intriguing suggestion.

Finally, the composition of molecular clouds continues to be a fruitful field for more detailed investigation. Several mysteries may be cleared up in the coming year. For example, no sodium compounds have yet been detected in interstellar clouds, but NaNC has been predicted as the most abundant one in the dense innermost cores of circumstellar envelopes. The recent detection of MgNC in the IRC 10216 circumstellar envelope makes detection of NaNC promising. This will tell us how much sodium escapes in the gas phase to the interstellar medium, and it will also indicate to us how such a refractory species as MgNC can be expelled ("desorbed") from very cold grains.

Searches will also be made for CaNC, the laboratory microwave spectrum of which has recently been established. Since Ca is among the most refractory of refractory elements, and since CaNC can be argued to be the dominant molecular form in IRC 10216, the results will be a good test of the "layered" picture of grain formation in inner circumstellar envelopes.

The role of shock chemistry in regions of star formation will be assessed by means of a large-scale survey for SO^+ emission in known regions of star formation. The strength of shocks in massive star-forming regions is important in understanding how massive accreted gas clumps collapse to form massive stars without fragmenting into only many smaller clumps and hence smaller stars. The SO+ survey will define a starting point for these investigations.

6. Emission Nebulae

Radio observations of gas excited by a luminous central star, HII regions, novae, and planetary nebulae, provide important information as to the gas density, the density distribution and the temperature of the nebulae. Since the radio observations are unaffected by dust extinction, they are complementary to optical observations of these same objects. For distant nebulae in the disk of the Milky Way, nebulae that are wholly obscured at visible wavelengths, the radio observations are the sole probes available to ground-based astronomers and used to study emission nebulae. In 1994 several new avenues of research will be pursued.

Recent radio light curves and images of several novae — Nova Cyg 1986, Nova Her 1987, Nova Her 1991, Nova Pup 1991, and Nova Cyg 1992 — have provided data with a level of detail that permits systematic modelling and analysis of the kinematics and mass of the nova shell ejecta. These new data, together with the similar but less complete data on historical novae, will be sufficient to construct a realistic "representative" model of nova evolution. Departures from this model noted in specific novae can then be interpreted and understood. Moreover, completion of light curves and imaging for Pup 1991 and Cyg 1992 should be possible in the next year. Model fitting with the standard model that fits previous novae will provide information on the nova ionization structure, energy balance, and evolution of the soft X-ray emission.

HII regions will be probed with high angular resolution by means of their radio recombination line emission, water vapor and hydroxyl maser emission, and radio continuum radiation. The recombination line observations from ultracompact HII regions will allow a determination to be made of the kinematics and dynamics of the ionized gas, thus leading to models for the evolution of these very young (less than 1000 years) HII regions and their young ionizing stars. Water masers and OH masers provide a probe of the interaction of the ionized gas with the natal molecular cloud gas. Finally, high-resolution observations of the radio continuum emission reveal the details of the ionized gas very close to the (proto)star and help establish the source of the ionization. Observations this year will focus on the bright, compact HII regions G34.3+0.2, W3(Main), Sgr B2, and Sgr E.

7. The Galaxy

Observations of the large-scale structure of the Milky Way galaxy provide the point of reference for all observations of galaxies beyond the Milky Way. If we can understand the distribution and composition of gas and stars in the Milky Way, we can begin to understand the reasons for departures from these properties in other galaxies we may study. Since the composition of the Milky Way is diverse, the probes used to study it are themselves diverse. The radio observations which are unaffected by dust obscuration even in the plane of the Galaxy are a unique source of information and understanding. In 1994 observations will be made of neutral hydrogen, free electrons, and molecules in the Galaxy.

Observations of the Zeeman effect in neutral atomic hydrogen will be used in an attempt to measure the magnetic field in Galactic HI clouds. It is quite plausible that the magnetic field limits the ability of an HI cloud to be compressed in collisions with other gas, e.g., a supernova remnant. This can modulate the ability of supernovae to rearrange the interstellar medium, it can reduce the effect of cloud-cloud collisions, and so on. Unfortunately, relatively little is known about the field strength because of the great difficulty of making 21 cm measurements of the Zeeman effect. In 1994 measurements will begin of a new set of Zeeman measurements in an attempt to make progress in this most important, but observationally difficult, area.

HI observations will also be used to elucidate the nature of high velocity clouds in the Galaxy. It has been known for some time that HI concentrations with apparently anomalous velocities of more than 100 km/s cover about 10 percent of the sky, but this result has been derived from observations of rather limited sensitivity. It has been an open question whether the number of high velocity clouds continues to increase to ever lower column density, or if there is a turnover in their luminosity function due, perhaps, to ionization of the smallest clouds by the ultraviolet background from quasars. In 1994 a systematic search will be made in the directions of high galactic latitude using the 140 Foot Telescope. The results of this work will be combined with UV spectra from the Hubble Space Telescope to study the population statistics, abundances, and ionization state of halo gas in our galaxy.

The kinetic energy in the interstellar medium is shared by cold HI, molecules and ionized gas. But by far the dominant component is the warm interstellar medium. The electron temperature, density, and distribution of the warm interstellar medium are crucial in understanding the energetics of the interstellar medium. While we know its local properties, we do not know its global properties in the disk of the Galaxy. One way to explore this is to look for stimulated recombination lines of hydrogen in the warm interstellar medium against strong extragalactic radio sources. The lines should be strongest at low frequencies, and observations will be made with the VLA in 1994 to search for the lines and to understand the properties of the warm interstellar medium.

Work also continues on a program at the VLA to probe the ionized gas layer in the Galaxy using HI absorption measurements toward pulsars. These observations will enhance the current space sampling from previous pulsar observations, and it will allow an improvement to be made in our understanding of the electron density at low galactocentric radii. In addition, the HI absorption data will be used to model the global properties of the layer of cold atomic hydrogen in the Galaxy in much the same way as the electron layer was modelled.

Work on gas well out of the disk of the Milky Way will proceed in several ways including observations of the molecular content of Galactic cirrus clouds. Essentially all cirrus clouds, which are not subject to disruptive collisions in the disk of the Galaxy, can be modelled as polytropes in hydrostatic equilibrium. Multi-transitions observations of CS, C_3H_2, and HC_3N will be made in a sample of cirrus cores in an attempt to delineate the degree to which grains and gas-phase processes are relevant to the chemistry in diffuse and translucent clouds.

Galactic molecular clouds will also be studied in detail by means of absorption line observations made against extragalactic sources of continuum emission. In one such observation made toward the QSO 3C 454.3, weak CO emission has been detected as has HCO^+ in absorption. Apparently the CO is optically thin; this is probably the first demonstrable instance of genuinely optically thin CO seen in the Galaxy.

The central region of the Galaxy, Sgr A, is the single unique part of the Galaxy and as such receives special observational attention. CO(J=3-2) observations made recently will be analyzed to investigate the very strong emission at v = -140 km/s seen some 3 arcminutes from Sgr A*; in addition, the interaction between Sgr A West and the ambient molecular gas will be studied. Preliminary analysis suggests that Sgr A West is actually embedded in the 50 km/s cloud, which may account for the unusual velocity of OI gas recently detected in the cavity of the 2 pc circumnuclear disk. Analysis to be done in the next year should shed further light on these possibilities.

It is widely speculated that the compact radio source at the center of the Galaxy known as Sgr A* is similar in nature to the compact radio sources found in distant more luminous quasars and AGNs. Previous radio observations of Sgr A* indicate that the observed angular size at centimeter wavelengths is affected by interstellar scattering. Preliminary observations with the partially completed VLBA at 7 mm place an upper limit to the angular size of 0.4 mas or 3 AU linear size. New measurements planned using the VLBA at 7 and 13 mm and VLBA instrumentation at 3 mm should refine this result and improve the resolution by up to a factor of 4, define the degree of variability including correlation of the variability with the X-ray emission, determine the spectral shape of Sgr A*, as well as better define the properties, particularly the asymmetry in the interstellar scattering medium.

8. Normal Galaxies

Galaxies, such as the Milky Way, without a dominant nuclear radio source can be studied by means of the emission from their gaseous HI disks, by means of their molecular line emission from molecular clouds in the disk of the galaxies, and by their radio continuum emission. In 1994 all these probes will be used in attempts to understand the distribution of matter in the galaxies, their kinematics, and the extent to which their dynamics and evolution are controlled by the presence of dark matter associated with the galaxies.

Recently it has been shown that the amount of cool gas in early-type galaxies increases monotonically from the earliest Sa galaxies to the latest Sa galaxies. The ratio of the mass of the cool component to the total optical luminosity is about 0.15. In the early Sa's, and most SO galaxies, the surface density of cool matter is lower than that required to support star formation.

There are two details of the distribution that will be studied in 1994. First, if the sample is extended to include Sc galaxies, it is seen that the total mass of atomic hydrogen, normalized by luminosity, rises with galaxy type from Sa to Sc, whereas the mass of molecular hydrogen as inferred from CO data appears to be independent of type, at least for the Sc galaxies. It is important to explore whether this apparent dearth of molecular material arises because of incomplete information. The data may be incomplete because most of the galaxies were sampled only along the major axis, and the CO signal was integrated assuming the CO followed the optical isophotes. This assumption can be checked by making a more complete map of two or three carefully selected galaxies. Also, the estimate of the amount of CO may be uncertain because the bulk of the observations were made using the J = 1-0 transition of CO. Questions about the optical depth and excitation effects will be explored using the extensive new published observations.

Second, it is found that there is an extremely large dispersion in the intrinsic properties of galaxies of the SO type, be it the total HI mass, the X-ray luminosity, or the cold matter content. There is rising interest in the question as to the existence of two separate populations of SO galaxies which are indistinguishable by their optical morphology, but which have important differences in their physical characteristics, such as the degree of flattening or the nature of the rotation. These questions will be explored with new data from ROSAT since the X-ray flux should be stronger in those objects dominated by a central stellar bulge; with an analysis of the two-dimensional optical isophotes, since the gas content is expected to be a sensitive function of the bulge-to-disk ratio; and by new HI mapping, if an examination of the maps now available for several of these objects suggests that the rotation curve is useful in separating types of SO galaxies.

It has long been recognized that the cool gas component of isolated galaxies extends beyond the standard and very faint outer optical isophote of these systems. This has been the basis for concluding that dark matter exists in the outer parts of galaxies: mass is inferred from the HI rotation curve, but there is no optically visible material. A long-standing puzzle regarding this outer HI is that its extent varies from galaxy to galaxy. It can range from radii of 1.3 R_{opt} to 5 R_{opt}. This range in HI radius appears to be unrelated to any other parameter of the galaxies.

Attempts will be made to understand the physical cause of the extended HI by examining the shape of the HI velocity profile. For all but the lowest mass systems the profile must have sharply defined boundaries. Any deviation from such a situation implies that the basic assumptions of an isolated, rotating, quiescent, flat disk does not apply. Optically faint companion galaxies that fall within the antenna beam will distort the HI line profile either through gravitational effects or from the HI residing in the companion.

In either case the search for faint companions is important in this context, and it will be conducted in a systematic manner next year for all the galaxies that show anomalous HI profiles.

Sensitive VLA HI observations will be made of the nearby spiral galaxy M81. The sensitivity and spatial resolution provided by these new observations will allow a test to be made of density wave theories by determining the arm-to-interarm density contrast and velocity streaming motions in the arms. It will also be possible to confirm or deny the possible detection of leading spiral arms in the disk of M81 which were found in previous VLA data. The leading arms are a prediction of the "modal" spiral arm density wave theory and their identification would be a seminal achievement in reconciling theory and observation.

VLA observations of the gaseous content and kinematics will be made in several types of "unusual" galaxies — ring galaxies, HII galaxies, dwarf galaxies — in an attempt to discover the reason why these galaxies differ so markedly from the Milky Way in morphology, mass, or dynamics.

— A sensitive search will be made for isolated HI clouds in the vicinity of HII galaxies. The hypothesis that interactions with HI clouds triggers violent star formation in the HII galaxies will be investigated quantitatively.

— A systematic search will be made for high velocity clouds at forbidden velocities in the disk of nearly face-on spiral galaxies. Here the goal is to understand whether the high velocity cloud phenomenon is a phenomenon unique to the Milky Way or a phenomenon shared by other spiral galaxies.

— Star formation in ring galaxies presents special problems the solution to which has been the hyp thesis that galaxy collisions give rise to expanding ring-shaped regions of high gas density inside a galaxy disk. These regions are often the sites of very intense, massive, star formation. As the rings propagate outward through a galaxy they become very extended with sustained starbursts. Because they are extended one can now study the starburst regions in detail over a wide range of wavelengths. The questions to be be addressed next year include: Why are some rings apparently effective triggers of massive star formation but not others? How do they compare with spiral arms in this regard? The regions of the galaxy enclosed by the expanding ring is almost always completely free of massive star formation. How does this come about? Is there a reduction in the amount of gas in this region? The propagating starburst will leave in its wake progressively older groups of stars resulting in strong optical-infrared radial color gradients. It may be possible to use these color gradients to constrain basic quantities in the ring starburst like the initial mass function.

— It has been recognized that galaxies in the cores of clusters differ from those in the field in their morphological type, stellar population, and gaseous content. By studying galaxies in clusters over a moderate range of redshifts, it might be possible to observe the galaxies transformed. With this in mind, a comprehensive HI study of a rich cluster will be undertaken to determine the evolution of galaxies between redshifts of approximately 0.1 and the present epoch. The expectation is that this study will provide a crucial datε ɔoint typing in the present-day clusters to those at redshifts of 0.2 to 0.4.

— X-ray observations of clusters of galaxies have implied that there may be large quantities of cold HI gas in the cores of clusters of galaxies. If the cold gas exists in the form of HI, then we should expect to see it in absorption against strong continuum sources that usually harbor these clusters. Sensitive HI observations will be made of three extreme cooling flow clusters. The observations are sensitive to a wide range of spin temperatures and to HI masses about three orders of magnitude lower than that believed to be present in these clusters.

— VLA HI observations will also be made of the interacting galaxies Arp 143. The velocity field, including the unusual HI plume, will be compared with dynamical collision models to study whether gravitational interaction can explain the observed morphology and velocity field.

Radio continuum observations will be used in several cases as probes of the effect the non-thermal energetics of galaxies has on the galaxies morphology, evolution, and kinematics. For example, VLA multi-configuration, multi-frequency observations will be made of the Einstein Ring MG1654+1346. This gravitational lens is the first lens for which the mass of the lensing galaxy has been reliably determined. These observations will determine the mass distribution of the galaxy as a function of distance from the galaxy center.

The elliptical galaxy M84 hosts an FR-I radio continuum so
initially asymmetric, but become symmetric about 1 kpc from t
relativistic turbulent-jet model can describe the brightness and spreading-rate evolution of individual jets in FR-I sources, but cannot account for the trends in the symmetry properties of the jets seen in the VLA image of M84. Is the VLBI pc-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 VLBI and VLA scales that can be studied with the VLBA. Observations of M84 on the VLBA should answer this question.

Finally, observations are planned of Seyfert I galaxies to determine whether their energy source is accretion onto a massive central object (the "monster model") or by the evolution of a massive young cluster of coeval stars in the high metal abundance of galactic nuclei (the "starburst model"). A powerful way to discriminate between these two models is to use the VLBA to image the milliarcsecond structure and to monitor changes in the structure over time. First epoch VLBA observations will begin this year.

9. Radio Galaxies, Active Galaxies, and QSOs

The VLA changed our perception of radio galaxies. Not only do we know now that the origin of the luminous radio emission from distant radio galaxies is a result of processes occurring in the nuclear regions of the galaxies but we also know that the energy is efficiently transported from the galactic nucleus thousands of kiloparsecs in confined relativistic beams or jets. The detailed physics of both the energy production process, and the energy transport, remain a mystery. Observations this year and in the future with both the VLA and the VLBA should begin to clarify our understanding of the astrophysics of these energetic and unusual galaxies.

Powerful radio galaxies and quasars exhibit radio emission on both sides of the galactic nucleus but there are significant asymmetries on the kiloparsec scale. It is important to understand whether any, or all, of these asymmetries can be explained by coupling the relativistic jet model that are required to explain the parsec-scale phenomena in such objects with the orientation-dependence suggested by optical spectropolarimetry and apparent emission-line anisotropies. Two studies will be made to test different aspects of this "unified model."

First, an analysis of the relative prominence of jet and counterjet features in samples of radio galaxies and quasars will be extended to include nuclear features and hot spots in the radio lobes. Preliminary work, to be extended this year, on the prominence statistics show (a) that the prominence of straight kiloparsec-scale jet segments correlates well with the prominence of parsec-scale features, but not with the slope expected if the jets reach kiloparsec-scales with typical Lorentz factors as high as those on parsec scales, and (b) that increased bending of jets both increases the detectability of counterjets and decreases the prominence of hot spots. These results suggest that the jets are strongly decelerated between the parsec-scale and the kiloparsec-scale. These ideas will be tested this year.

Second, the spectral index asymmetries of a sample of powerful radio galaxies and quasars will be imaged using the VLA and MERLIN. In sources without prominent jets, the shorter arm of the radio source usually exhibits greater depolarization and a steeper radio spectrum (as well as brighter optical emission lines). By contrast, in sources with prominent jets, the depolarization asymmetry correlates not with arm length but with the jet brightness asymmetry — the lobe fed by the brighter jet shows less Faraday depolarization than the other regardless of arm length. This effect is frequently cited as evidence for the orientation bias required by the standard relativistic-jet models of quasar asymmetries. Low-resolution studies of the spectral index asymmetry have recently claimed that it too is governed by the jet brightness asymmetry in sources with prominent jets. It is important to examine the spectral index asymmetry of the most extended lobe emission at higher resolution to avoid contamination by potentially beamed components of the sources. The relationships between spectral asymmetries, arm length, jet sidedness, and depolarization may then become an important testing-ground for models of all of them.

The synthesis of observations of thousands of radio sources has also led to construction of a radio H-R diagram, a test of the idea that all radio jets are beamed and the relationship of quasars to radio galaxies. The radio H-R diagram is three dimensional and consists of radio luminosity, optical luminosity, and radio size for radio galaxies in rich clusters. All the observations and data reduction needed for this program are complete. In the next year analysis of the radio images to extract size parameters will be the focus of activity, thereby completing the observational phase of the project.

The idea that FR-I radio galaxies are the parent (unbeamed) population of BL LAC objects (beamed) can be evaluated in a straightforward manner by measuring the size of the 4000 Å break in radio galaxies. In elliptical galaxies in clusters the magnitude of the break is constant. Therefore, any departure from this amplitude measured in other sources is an indication of the presence of a non-thermal nuclear source. The observational data have been acquired and analysis is in progress.

VLA observations of optically selected quasars from the Palomar Bright Quasar Survey shows that the radio structure in some radio quiet objects appears to be remarkably similar to that in radio loud quasars and FR II radio galaxies. Five of the quasars will be observed at 20 cm, with an order of magnitude improvement in surface brightness sensitivity to trace the low surface brightness features a greater distance from the quasar. In a separate study, new high sensitivity observations of four of the quasars not previously detected by the VLA will be made in order to see if there is indeed a population of truly radio silent quasars.

In 1994 observations will also be made of particular radio galaxies and quasars selected as being capable of providing answers to specific astrophysical questions.

— 3C 119 is a compact source with complex, steep-spectrum radio structure. It has been hypothesized that this structure results from the interaction of the radio-emitting plasma with a dense external medium. It has an unusually high rotation measure, 1728 radians/m^2, and it depolarizes at short wavelength. There are two possible explanations for the observed depolarization: it may be due to an external Faraday screen or to a high free electron density in the emitting matter. Multi-frequency observations will be made with the VLBA this year to map the rotation measure variation across the source. If the Faraday screen exists, then a high degree of linear polarization should be observable. If the depolarization is internal, then no significant linear polarization should be detectable.

— The VLA radio images of Cygnus A and Pictor A will be compared with new high resolution X-ray ROSAT images. Preliminary indications are that the X-ray emission exhibits an excess toward the radio hot spots as well as an overall deficiency of emission from the radio lobes. The X-ray excess is probably due to inverse Compton scattering off the relativistic electrons of radio photons produced by those same electrons. The observed X-ray and radio intensities, combined with information on the extent of the spectra, will give an accurate estimate of the magnetic field of the hotspots.

— The extraordinary radio galaxy Pictor A comprises a possibly unique combination: it has extremely bright radio hotspots with extremely dim lobes. Its low redshift makes it a good candidate for careful multiband imaging. New observations will be made this year in an attempt to understand the spectral aging and depolarization in the source and to see if these properties are consistent with recent trends discovered in large samples of radio galaxies at low spatial and frequency resolution.

— The low luminosity radio galaxy 3C 449 has bright symmetric jets with peculiar polarization properties. New multi-frequency observations are being used in a cooperative effort to try and understand spectral peculiarities in the radio jets and lobes similar to those identified in Cygnus A that suggest the existence of a "universal" radio spectrum.

— The nearby, bright radio galaxy 3C 120 has been observed with VLBI for many years, and it has become the prototypical active galaxy because its distance is not in dispute (in contrast to the situation with the quasars). Superluminal motions have been detected on parsec-scales in the VLBI observations, and initial VLA observations gave the indication that the superluminal motion continued to kiloparsec-scales. This latter result was not confirmed in MERLIN observations. In 1994 further observations will be made to clear up this important question so that, at a minimum, we have a better of understanding of our "prototypical" active galaxy!

10. Radio Surveys and Cosmology

In 1994 the VLA will be used in a major undertaking to survey the entire northern sky at 1.4 GHz. This task, comparable in scale to construction of the Palomar sky survey, will require 2500 hours of VLA observing time covering all the sky north of -40 degrees declination with a grid of about 200,000 individual and overlapping images. New software is being developed to help in scheduling the observations, analyzing the data, and distributing the results to the astronomical community as rapidly as possible. For example, AIPS tasks requiring little hands-on intervention now edit, self-calibrate, and map the uv-data. They also correct for a number of small distortions and errors resulting from the wide fractional bandwidth, large map size, and limited uv-coverage.

The final "product" of the VLA sky survey will be (1) a set of 2326 large (4 degree by 4 degree) sky images with nearly uniform sensitivity (rms noise less than 0.4 mJy per beam) and resolution (54") obtained by mosaicing the corrected snapshot maps; and (2) a catalog of more than 2 million discrete radio sources with rms position uncertainties ranging from < 1" for flux densities greater than 10 mJy to approximately 5" at the survey limiting flux density of approximately 2 mJy. Since nearly all faint extragalactic sources have angular sizes smaller than 54", these relatively low-resolution maps and the source catalog derived from them should be complete and photometrically accurate. In particular, their noise limited sensitivity to low brightness sources is within a factor of four of the limit set by confusion. This VLA survey will have about the same sensitivity as IRAS for galaxies that obey the remarkably tight far-infrared/radio correlation. The radio emission from these galaxies is ultimately powered by massive short-lived stars. The cumulative counts of sources found at 1.4 GHz predict that approximately 100,000 such "normal" and "starburst" galaxies will be detected, two orders of magnitude more than in all earlier radio surveys combined. Accurate radio positions from the VLA maps will be used to identify many optically faint ultra-luminous galaxies and protogalaxies in the IRAS Faint Source Catalog.

All other survey work pales in comparison with the VLA all-sky survey, but nevertheless there are three surveys with far more focussed goals in progress in 1994.

— A survey is being conducted at 330 MHz on the VLA for "dying" radio sources. Synchrotron aging, which is energy dependent, suggests that radio galaxies and quasars that have long since ceased to produce high frequency emission may radiate for very long times at very low frequencies. If such sources exist, that is if our understanding of the physics of radio sources is correct, surveys at the lowest frequencies will reveal a different and very old population of once active objects. Bright sources detected at Kharkov at 10-26 MHz will be surveyed at 330 MHz with the VLA to see if some fraction of these objects display the spectral signature of dead or dying radio sources.

— An exceptionally deep survey will be made with the VLA at 3.6 cm to search for fluctuations in the cosmic microwave background. Using 100 hours of VLA time in a single field, it will be possible to determine the properties of the weakest radio sources. Complementary X-ray images and Hubble Space Telescope images have also been made of this same field as an aid to source identification. In addition, the observations will be used to determine the cosmic background fluctuations in the radio field at an angular scale of one arcminute to a sensitivity of one part in 100,000.

— The 14.5 m antenna to be used for space VLBI will be used as part of the shake-down process next year to survey the northern sky at 15 GHz. These observations will produce a catalog of bright sources in the northern sky, and they will be used to search for short-term fluctuations of the brightest sources. More speculatively, it will be interesting to compare changes in the 15 GHz survey prior to and immediately after the report of a gamma ray burst in order to seek the radio counterparts of such events.

Large samples of radio sources, compiled by the surveys mentioned above and others, will be used for cosmological investigations. In 1994 there are several revealing cosmological projects in progress.

- Standard Friedmann cosmological models make specific predictions about how the angular size of a linear rod should vary with redshift. Previous attempts to measure this effect, or indeed any other prediction of Friedmann cosmologies, using extended double lobed radio sources or optical measurements have been inconclusive owing to the apparent evolution of the population with cosmic epoch. VLBI observations suggest that compact radio galaxies and quasars, which are both very young and very small, may be free of these evolutionary effects. The VLBA will be used to relate the angular size and internal velocity with redshift for a large sample of radio galaxies and quasars to determine the value of omega, the mean density of the universe, and to study the morphology of compact radio sources and the dynamics of superluminal motion.
- The Butcher-Oemler effect will be investigated with radio observations. The Butcher-Oemler effect is the occurrence of a higher proportion of blue galaxies in clusters as the redshift increases from the present epoch to values at least as high as 0.5. It is believed that these blue galaxies in high redshift clusters probably contain large amounts of gas and may be undergoing enhanced star formation. A completely independent way of testing this is to look for enhanced radio emission from the blue galaxies. This will resolve some of the difficulties associated with interpreting the Butcher-Oemler effect as due to evolution. An Abell cluster at a redshift of 0.25 will be observed with the VLA. The sensitivity will be such as to detect the thermal radio emission from the putative population of young blue stars if it indeed exists in the galaxy.
- Gravitational theories will be tested to precision higher than was previously possible by means of observations of the gravitational bending of radio waves passing by the limb of the sun. Using VLBI phase referencing, observations will be made of the deflection of radio waves from distant quasars by the solar gravitational potential. By measuring the relative changes in separation between nearby sources, it is hoped that significant improvements can be made on current estimates of departures from the predictions of general relativity, the "gamma" parameter, that will rule out certain theories of gravity.

Finally, fundamental cosmological observations will be made of the Sunyaev-Zel'dovich effect in galaxy clusters that have the potential to establish the value of the Hubble constant to a precision better than 10 percent. The Sunyaev-Zel'dovich effect is a distortion of the spectrum of the cosmic microwave background due to inverse Compton scattering with the hot electrons that are present in dense clusters of galaxies. At a frequency of 20 GHz, the effect is a decrement in the temperature of the background radiation of about one milli-kelvin in the direction of the densest and hottest clusters of galaxies. Due to the beam-switching schemes that must be used with single dish telescopes at these levels of sensitivity, the measured decrements are about -0.4 mK as the reference beams are affected by the Sunyaev-Zel'dovich distortion. Such small signals have to be confirmed by observations at other frequencies. In 1994 observations will be made with the Berkeley-Illinois-Maryland-Association array at 86 GHz of the cluster 0016+16. The observations will be made using a tessellating technique to measure the necessary short spacings. The resulting radio image, together with a high resolution X-ray image, will be used to map out the electron concentration in the cluster environment and to solve for the Hubble constant.

APPENDIX B

SCIENTIFIC STAFF

(Does not include Visiting Appointments)

D. S. Adler - Interstellar medium in the Milky Way and external galaxies; molecular clouds; observations and computational studies of the dynamics of spiral galaxies; star clusters; star formation

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

T. S. Bastian - Solar/stellar radiophysics; radiative processes; plasma astrophysics; particle acceleratrion; 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

W. R. Burns - Information theory and signal processing

B. G. Clark - VLBA control; software development

M. J. Claussen -Interstellar masers; circumstellar masers; interferometry; young stellar objects; compact and ultracompact HII regions; centimeter and millimeter-wave molecular spectroscopy; spectropolarimetry; radio recombination lines

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

J. E. Conway - Extragalactic radio sources; jets in radio sources; VLBI observing techniques; extragalactic radio supernova and supernova remnants

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; superconducting electronics; millimeter wavelength receivers; radio astronomy from space

V. Dhawan - Extragalactic radio sources; VLBI; instrumentation

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

K. S. Dwarakanath - Clusters of galaxies; interstellar medium; aperture synthesis at low frequencies

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

G. A. Fuller - Star formation; galactic molecular clouds

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. Glendenning - Starburst galaxies; scientific visualization

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

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

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

J. L. Higdon - Multi-wavelength studies of star formation in intracting galaxies; primaeval galaxies; galaxy kinematics

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 - Circumstellar shells; interstellar molecules; cometary line emission

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

A. R. Kerr - Millimeter-wave 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

W. B. Latter - Astrochemistry; interstellar medium; mass loss processes; planetary nebulae; magnetic white dwarfs

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

P. J. Napier - Antenna and instrumentation systems for 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

M. P. Rupen - Interstellar medium of early type galaxies; galaxy dynamics through radio/millimeter observations; radio supernovae; steep spectrum radio sources

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; methods and techniques for astronomical image analysis

C. M. Wade - Astrometry; stellar radio emission; minor planets; extragalactic radio sources; VLBA development

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

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

E. M. Wilcots -HII regions in the Magellanic clouds; HI and the intrstellar medium in nearby galaxies; extragalactic star formation; structure and evolution of barred Magellanic irregular galaxies

D. S. Wood - Star formation; HII regions and the interstellar medium; radio and infrared astronomy; interferometry and infrared arrays; atomic and molecular spectroscopy

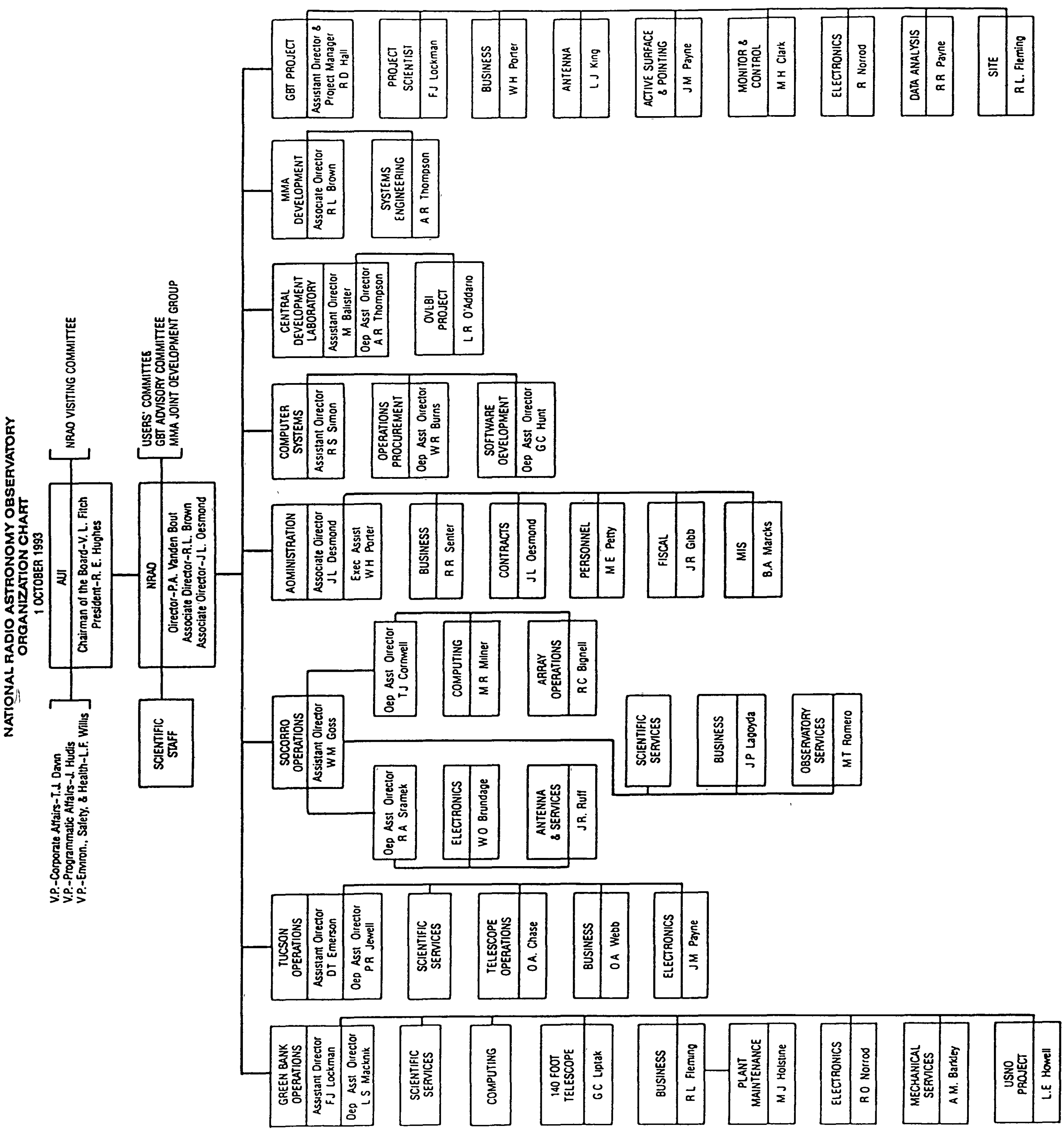
A. H. Wootten - Star formation; structure, spectroscopy and chemistry of the interstellar medium in galaxies; circumstellar material

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

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

A. Zensus - VLBI observations of quasars and active galactic nuclei; compact radio jets and superluminal motion in compact radio sources

APPENDIX C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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:

E. C. Churchwell	University of Wisconsin - Madison
J. N. Hewitt	Massachusetts Institute of Technology
R. Hills	Cavendish Laboratory
A. P. Marscher	Boston University
A. I. Sargent	California Institute of Technology
P. Thaddeus	Center for Astrophysics

Two additional members to be appointed.

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, which is appointed by the Director, meets annually in May or June.

Current membership is:

M. A. Barsony	Center for Astrophysics
F. H. Briggs	University of Pittsburgh
E. B. Churchwell	University of Wisconsin
J. M. Cordes	Cornell University
R. J. Dewey	Jet Propulsion Laboratory
J. M. Dickey	University of Minnesota
N. Duric	University of New Mexico
D. M. Elmegreen	Vassar College Observatory
A. S. Fruchter	University of California, Berkeley
R. A. Gaume	Naval Research Laboratory
C. R. Gwinn	University of California, Santa Barbara
C. J. Lonsdale	Haystack Observatory
C. R. Masson	Center for Astrophysics
K. M. Menten	Center for Astrophysics
L. G. Mundy	University of Maryland
M. J. Reid	Center for Astrophysics
F. P. Schloerb	University of Massachusetts
R. Taylor	University of Calgary
J. Turner	University of California, Los Angeles
S. C. Unwin	California Institute of Technology
A. E. Wehrle	California Institute of Technology
R. A. Windhorst	Arizona State University
D. Woody	California Institute of Technology
L. M. Ziurys	Arizona State University

3. Green Bank Telescope Advisory Committee

Appointed at the inception of the Green Bank Telescope (GBT) project in 1989, this committee reviews periodically the design planning for the GBT. Initially the committee advised the Director on critical design issues facing the GBT project: staffing, decisions, and decision-making process of the GBT design team. The committee may identify alternative design techniques or suggest specific tasks. Construction review and proposed instrumentation are future areas of concern to the Committee.

The committee is appointed by the Director. It is composed of scientists and engineers representing the range of skills — structural, mechanical, electrical, computational, and scientific — needed for the telescope design and construction.

Current membership is:

M. P. Haynes	Cornell University
C. Heiles	University of California, Berkeley
R. A. Jennings	University of Virginia
J. D. Nelson	University of California, Berkeley
V. Radhakrishnan	Raman Research Institute
S. von Hoerner	Independent Telescope Consultant
S. Weinreb	Martin Marietta Laboratories
R. W. Wilson	Bell Laboratories

4. Millimeter Array Advisory Committee

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

Current membership is:

J. H. Bieging	University of Arizona
J. E. Carlstrom	California Institute of Technology
N. Erickson	University of Massachusetts

N. J. Evans	University of Texas
R. Hills	Cavendish Laboratory, UK
G. R. Knapp	Princeton University
K. Y. Lo	University of Illinois
C. R. Masson	Center for Astrophysics
L. G. Mundy	University of Maryland
A. I. Sargent	California Institute of Technology
W. J. Welch	University of California
R. W. Wilson	Bell Laboratories
C. G. Wynn-Williams	University of Hawaii