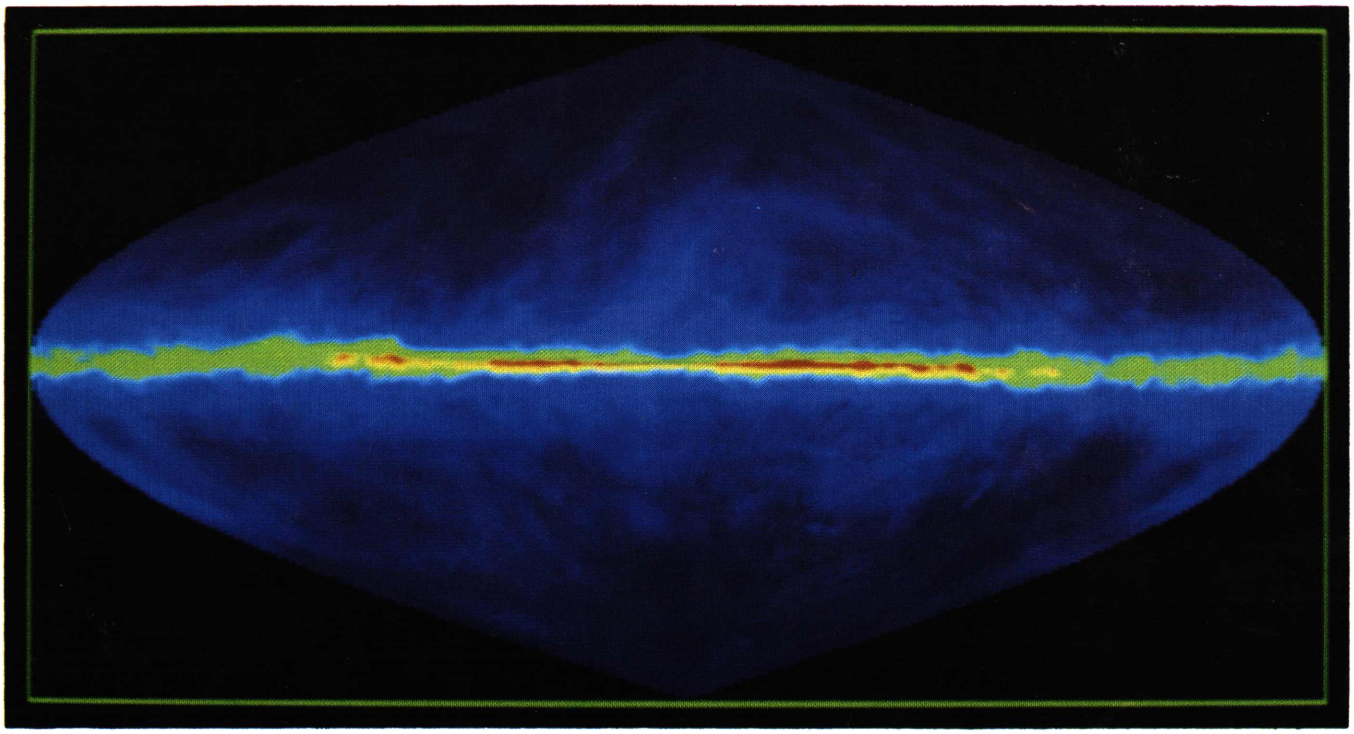
NATIONAL RADIO



ASTRONOMY OBSERVATORY

PROGRAM PLAN 1991

THE HYDROGEN SKY

This figure shows the amount of atomic hydrogen at all locations in the sky All of this hydrogen is in our galaxy Red indicates directions of high hydrogen density, blue and black show areas with little hydrogen. The figure is centered on the galactic center and galactic longitude increases to the left The data came from measurements of the 21cm line of hydrogen by radio telescopes. Some of the hydrogen loops outline old supernova remnants

This image is a composite from many 21cm surveys It includes data from the NRAO Green bank, West Virginia 140-foot and 300-foot telescopes, the 85-foot Hat Creek Telescope of the University of California at Berkeley, The AT&T Bell-Labs Horn-Reflector Telescope at Holmdel, New Jersey and the 60-foot Telescope at the Parkes Radio Observatory in Australia.

NATIONAL RADIO ASTRONOMY OBSERVATORY

CALENDAR YEAR 1991

PROVISIONAL PROGRAM PLAN

October 1, 1990

1991 PROGRAM PLAN

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APPENDICES

I. INTRODUCTION

The present NRAO Program Plan encompasses not only the material which has historically been part of the Program Plan but it also includes the projected plans, budgets, and personnel schedules that were formerly part of the NRAO Five-Year Long Range Plan. Presented in this way the relationship between current Observatory activities and the evolution planned for each of the Observatory's many roles can be seen with greater clarity.

In 1991 we expect more than 850 individual scientists from nearly 200 institutions to conduct their research with NRAO facilities. The three major telescope systems operated by the NRAO for scheduled astronomical observations are: the 27-element Very Large Array (VLA) synthesis telescope located on the Plains of San Agustin near Socorro, NM; the 12-meter millimeter-wave telescope on Kitt Peak in Arizona; and the 140-foot telescope in Green Bank, WV. Additionally, interim observations are conducted with the antennas of the Very Long Baseline Array (VLBA) as the antennas are completed in the construction phase of this instrument. Operation of the NRAO is funded by the National Science Foundation under the terms of Cooperative Agreement AST-8814515 with Associated Universities, Inc.

Many of the 850 scientists who will observe with NRAO facilities in 1991 will use more than one telescope; many will observe on several occasions during the year with a given telescope. Allocated observing time therefore remains at a premium and all the instruments are heavily oversubscribed. A representative sample of the kinds of research programs proposed for observations in 1991 is outlined in Section II. A description of each of the three major observing facilities is included in Section III, along with a brief mention of the immediate and long-term plans for enhancement or upgrade of the instrumental capabilities. The specifics of the plans are contained in later sections of the Program Plan.

Section IV of the Plan describes the continuing research instrumentation developments which will take place at the Observatory in the next five years. These include instruments which are used directly as integral elements of the telescope-receiver-computer data acquisition chain and those which are part of the subsequent signal and image processing and data analysis procedure. The instrumentation expenditures fall equally heavily on the electronics and computer hardware areas. In 1991 and subsequent years the emphasis will be on:

Improving the sensitivity of the VLA at all frequencies by replacing the multiband receiver with VLBA-style high electron mobility transistor (HEMT) amplifiers fed by short waveguide runs and cryogenically cooled polarizers;

- Implementing broadband photon-assisted tunneling (SIS) mixers at millimeter wavelengths;
- Developing software and the user interface for data analysis and imaging systems in a connected workstation environment.

Included in Section V is a specific section describing the arrangements made through the National Science Foundation for the NRAO support of that portion of the U.S. Naval Observatory (USNO) program in astronomy related to operation of the three-elements of the Interferometer in Green Bank. Several new initiatives involving work for others are also summarized in this section.

Section VI describes the status of the NRAO major construction projects, the Very Long Baseline Array and the Green Bank Telescope (GBT). Scheduled for completion in 1992, the VLBA will image with high fidelity the detailed physics of the particle acceleration and energy transport phenomena that ultimately find their manifestation in VLA images of such things as galactic nuclei and jets. The GBT, on the other hand, will provide us with a broad view of the interrelationship of the diverse objects which make up the radio sky and it will do so with data uncontaminated by the instrumental effects which have plagued conventional single dish radio telescopes.

Section VII highlights the two major new initiatives for the decade of the 1990's: the Millimeter Array (MMA), and connection of the VLA and VLBA. The MMA proposal, submitted to the National Science Foundation in 1990, represents the culmination of nearly ten years of design work on a high resolution synthesis imaging telescope for observations at short millimeter wavelengths where thermal processes illuminate the sky. The union of the VLA and VLBA into a single instrument will provide astronomers with uniform data on baselines from 40 meters to 8000 kilometers.

A plan to ameliorate the deferred maintenance needs of major NRAO facilities, together with the specifics of plans for expansion and enhancement of these facilities, is outlined in Section VIII. The highlights include:

- An emphasis on the accumulated maintenance needs at the Observatory so that users and staff can be assured that all equipment functions properly and safely. For the large structures, represented most particularly by the electrical power distribution system and 80 miles of rail track at the VLA, maintenance costs are substantial and the needs continuing;
- The computational resources, hardware and software, will be made commensurate with the needs of the VLA and VLBA through implementation of the NRAO Array Computing Plan;
- The VLA correlator and signal transmission system will be replaced by modern technology which will increase the bandwidth by a factor of twenty. Together with the new generation of VLA HEMT receivers, these improvements will enable research programs requiring twelve hours now to be completed in two hours or less.

The final sections of the NRAO Program Plan include the 1991 Preliminary Financial Plan and the Budget and Personnel Projections for the next five years. Appendices to the Plan include a summary of the 1991 scientific program planned by the NRAO staff, a list of the staff and their principal research interests, an organizational chart for the NRAO, and a list of various committees that provide advice and assistance.

II. SCIENTIFIC PROGRAM

1. VERY LARGE ARRAY

The number of research papers produced annually on the basis of observations carried out with the VLA easily exceeds that of any other radio telescope, worldwide, and its productivity continues to increase. This is in part due to an ever-expanding base of users and in part a result of ever more imaginative projects. Greater use of the VLA is also being directed toward the support and follow-up of fundamental surveys in other wavelength regions. Work connected with the Hubble Space Telescope (HST) and the ROSAT X-ray satellite have broadened the VLA's horizons significantly during the past year. As a consequence the proposal pressure remains high.

Solar physicists have demonstrated year after year the versatility of the VLA in addressing challenging research problems of the sun, and 1991 will be no exception. Simultaneous multi-wavelength studies of solar phenomena in conjunction with other ground-based telescopes or with coordinated space-based detectors continue to dominate the requests for VLA solar time. Observations from the far infrared region to centimeter wavelengths will be jointly acquired with the JCMT and the VLA in order to determine the sun's vertical temperature gradient low in the chromosphere over sunspots, plages, and quiet regions of the sun. A number of solar experiments will also be carried out with the VLA as part of the Max 91 campaign on Energetic Solar Phenomena (ESP-91). Broad wavelength coverage extending from gamma rays to optical and radio waves will study impulsive heating events and microflares spatially throughout the solar atmosphere as a fundamental attack on the classic problem of coronal heating mechanisms. The simultaneous VLA images will be crucial for isolating the compact solar features and tracing the accelerated particles created by the energy release process itself.

Mars will be observed near opposition to improve the spatial resolution of water vapor studies in the Martian atmosphere The pressure-broadened 1.3 cm water line will be used to probe the altitude distribution of water vapor toward the Martian limb. An investigation of the time variability of Jupiter's synchrotron radiation will continue in an attempt to determine the origin and mode of transport of the energetic particles.

Stellar observations with the VLA will again span a wide range of topics. Variable radio emission from a few radio detected Be stars will be monitored in coordination with optical and IR programs in an attempt to establish a link between surface activity and circumstellar disk structure. For two recently detected classic FU Orionis stars, further continuum observations will be used to differentiate competing radio models: free-free emission from ionized ejecta or circumstellar dust emission. The decay rate of supernova 1970G in M101, in the early stages of radio supernova evolution, will be tested with a search for its X-band emission.

Pulsar studies will divide between the detailed analyses of individual pulse profiles investigating the physics of pulsar emission mechanisms and the more general studies of pulsar statistics, detection, astrometry, and their astrophysical environment. The detection and investigation of the causes of unusual mode-switching pulsars will serve as a useful probe of pulsar magnetospheric phenomena. Polarization studies of these and other unusual pulsars will take advantage of the High Time Resolution Processor built especially for VLA pulsar observations. Fast pulsar timing experiments will prove useful for a wide variety of purposes, including astrometry, binary star evolution, cosmology, gravitation physics, and timekeeping metrology. The study of globular cluster pulsars will also be an important tool for understanding the formation of millisecond pulsars and comparing their evolution to that of low mass X-ray binaries.

Clues to the late stages of stellar evolution are found in VLA studies of supernova remnants. In a search for new supernova remnants, a number of small angular size, faint, and distant objects in the galactic plane will be studied more closely with the VLA to determine their morphology, polarization, and spectral index properties. Another group of candidates from a Clark Lake low frequency search for low surface brightness objects will be mapped with the VLA to confirm their likely SNR nature. An exploratory survey of eight shell supernova remnants will search for spatial trends in spectral index with the goal of understanding particle acceleration mechanisms in SNRs. Other remnants will be mapped in order to elucidate the nature of the interaction between SNR shells and their surrounding molecular gas clouds.

Numerous VLA studies will be undertaken in an attempt to further advance our understanding of the star formation process in specific regions of the Galaxy. Spectral line observations in the lines of ammonia show promise of identifying an actual contracting protostellar core toward the HII region W51. In the Rho Oph molecular cloud complex the star formation site in an unusually cold dense core will be observed in the lines of formaldehyde to determine the core structure, mass and density, while the dynamics of the region will be examined for evidence of a circumstellar disk. Another potential protostellar disk will be probed with ammonia emission around the infrared sources in NGC 2071. A survey of hot cores in a number of molecular clouds will be carried out using ammonia transitions in order to statistically search for a correlation between velocity width and clump size, and to study the spatial correlation between ammonia and OH masers and their relationship to molecular outflows.

VLA spectral line observations in a mosaic of fields around the galactic center will play a vital role in determining the complicated dynamics of the region in order to test the models which imply the existence of a central massive black hole. The kinematics of new structural features discovered with the VLA are consistent with velocity infall in a limited region to the south of the galactic center, but additional observations are required to determine if infall occurs from all directions.

The spatial resolution and sensitivity of the VLA offers an exceptional opportunity to investigate the magnetic fields of young star forming regions, where theory has shown that such fields may play a significant role in the star formation process. Regions such as the bipolar HII region S106, Orion A and B, and W3 will undergo VLA Zeeman observations and previous low resolution magnetic field detections will be fully imaged, and the relationship between the magnetic field and source morphology will be explored.

For investigations of normal galaxies with the VLA, a great deal of attention will be paid to low surface brightness galaxies and dwarf galaxies, neither of which have hitherto been studied as intensively as the major galaxies in nearby groups and clusters of galaxies. There are still many detailed characteristics of the morphology and kinematics of the neutral hydrogen of these optically fainter galaxies that remains to be learned. The VLA will be used to image Malin-1, for example, and other giant HI rich but optically faint galaxies to determine rotation curves, velocity dispersions, and HI surface densities. For ten of the most extreme dwarf galaxies known, the VLA will be used to compare the HI structure to the distribution of stellar populations determined from deep optical and infrared images. The star formation properties of such weak systems may be radically different from that in more luminous systems since rotational gas support is much less effective in the dwarf galaxy sample. In all cases the VLA will be instrumental in establishing the dark matter content of dwarf galaxies through the kinematical analysis of their HI content.

The VLA provides fundamental data for a large range of problems of importance in understanding the formation and evolution of normal galaxies. Work will continue which compares VLA HI observations of barred spiral galaxies to improved computer models that simultaneously treat both the gaseous and stellar components of the systems. Tidal interactions among galaxy partners will be observed with the VLA in order to assess the effects that binary interactions might have on star formation processes in different environments. Proof of direct tidal outflow and starburst activity can only come with the sensitive and detailed kinematical information that the VLA provides. Toward the starburst galaxy, M82, formaldehyde spectral line observations will be used to map the molecular material near the galactic nucleus and to determine how its distribution and kinematics have been influenced by the known starburst activity. Two spiral galaxies, selected because of their extreme high and low values of FIR/CO luminosity, will be imaged to study peculiarities in the cloud formation efficiency involving the relation between atomic and molecular gas. The detailed radio continuum morphology of four S0 galaxies which show various signs of star formation activity will be examined and compared with Hα and CO maps in order to evaluate both nuclear activity and extended star formation in producing the radio and far-infrared radiation. Accurate rotation curves will be determined for two one-armed spirals as a test of the swing-amplification theory of spiral arm formation. Interacting and merging galaxies will be studied with high resolution observations of the detailed features of the encounter phenomenon, such as rings, tails, and subsystems, in order to disentangle the system dynamics and to identify processes which differentiate the stars and gas in such encounters.

The VLA will be heavily used in support of large survey programs and space-based observations in the optical and X-ray portion of the electromagnetic spectrum. An attempt to substantially increase the number of known galaxies with $z > 2$ will critically depend on accurate source positions from the VLA so that optical follow-up can be made. VLA observations will be employed to expand the list of K-band calibration sources from candidates found in the MIT-Green Bank 5 GHz surveys. The brightest calibrators will likely require further observations with millimeter array telescopes as well. A sample of over 400 galaxies from the CFA deep redshift survey will be observed to very faint 21 cm flux limits in order to improve knowledge of the faint end of the radio luminosity function for galaxies. In support of the ROSAT mission, radio surveys will aim to study the dependence of the X-ray properties of active galaxies on radio luminosity and will also form the basis of a comprehensive radio database for follow-up studies of the primary X-ray survey.

Classical radio galaxies are the focus of renewed attention with the VLA as theoretical models and computer simulations of their features become more sophisticated. A new study of the closest radio galaxy, Cen A, is planned that will constrain supercomputer numerical simulations of the jets and improve our understanding of particle acceleration mechanisms responsible for producing X-ray emission from the jet knots. Extended HI emission in the outskirts of two powerful radio galaxies will be sought as a source of the required fuel that replenishes their nuclear activity and as a comparison with less powerful radio galaxies. A sample of giant radio galaxies will be monitored for core variability in order to test predictions of the beaming model of source energetics. For several recently discovered radio galaxies with $z > 3$, the VLA will test for high-z HI content in order to check the hypothesis that they may be high gas content protogalaxies.

Radio sources in the cluster and supercluster environment will continue to be studied as evolutionary probes of their surroundings.

Additional observations of the inner region of the Hydra I cluster will provide important comparisons with results from the Virgo cluster in terms of the distribution of gas-rich systems, the importance of galaxy interactions, and the effects of environment on star formation in the two clusters. A survey of all the dumb-bell galaxies found in Abell clusters will be carried out both optically and with the VLA in order to assess their importance to the dynamic histories of the clusters. A deep survey of Narrow-Angle Tail galaxies in rich clusters will be done in order to provide further information about the orbits of galaxies in clusters. A complete survey of 20 cm continuum sources in a very rich supercluster containing eight rich clusters will be obtained in order to statistically study the occurrence and luminosity of radio sources inside and outside of clusters vs. that in very empty regions. A search for more examples of radio halos in clusters of galaxies will attempt to improve our understanding of their origin.

The VLA will play a central role in the study of large samples of quasars. A sample of optically selected QSOs obtained from a large and complete machine-selected sample will be looked at with the VLA in order to assess the cosmic evolution of their radio properties and to determine how the probability that a quasar is an active radio source depends on epoch. The VLA will observe a comparable sample of optically selected quasars in Selected Area 94 in order to obtain statistical data on the radio characteristics of quasars brighter than $B = 19.4$ and $z \leq 3.3$. A background sample of bright QSOs selected for HST observations will be searched for Faraday rotation in metal-like absorption systems at large redshift in order to study the cosmic evolution of magnetic fields in galaxies.

2. VERY LONG BASELINE ARRAY

Although the VLBA is still under construction, several of the completed antennas are instrumented and tested to a sufficient degree as to be available for observations on a limited basis. Several programs will be carried out with these operational antennas both singly and in combination with other VLB Network antennas in order to exploit a growing national resource and to fully debug and exercise the new facilities. Unfortunately, the VLBA operations budget is not sufficient to provide for the manpower needed to fully operate all of the antennas as they become operable. Nevertheless, a number of excellent programs will be undertaken during the coming year.

Several one-day experiments for the Crustal Dynamics Project will be carried out in order to improve source positional accuracies and to evaluate and improve our ability to measure local vertical coordinates at each station. The improved source positions will define an astrometric coordinate system that will ultimately improve the relation between optical and radio coordinate frames. The Interim VLBA will be used to map the circumstellar structure of a mass-losing object which may be completing its evolution along the AGB to become a planetary nebula. OH and H_2O masers in the circumstellar shell will be used to determine the source morphology and velocity structure. Angular broadening measures toward several OH/IR stars in the galactic bulge are planned as part of a study of the turbulent electron layer in the galaxy. Another probe of the galactic interstellar medium will make use of a giant Cyg X-3 flare when available to check on the anisotropy and the variability of the scattering process.

The compact core of 3C 317 will be observed with a few of the VLBA antennas in order to provide a crucial check on the flow structure caused by the interaction of the radio source with the cluster cooling flow. In 3C 295 the VLBA will be capable of resolving hot spots in the radio source lobes and start to differentiate between competing acceleration mechanisms that have been proposed to fuel them. The Interim VLBA will also look at a complete sample of compact double sources in order to directly obtain accurate radio spectra for each individual component over parsec scales. The structural and spectral information will help identify energy flows over parsec scales in the compact regions and eventually check on the viability of relativistic beaming models of the emission. Additional instrumentation capabilities will augment the existing operational VLBA, manpower permitting, so that many more experiments can be undertaken before the end of 1991.

3. 12-METER TELESCOPE

Observations with millimeter-wave, single-dish telescopes address many fundamental astrophysical questions. Such telescopes are appropriate for the study of problems requiring sensitivity to low-brightness, extended emission, and to multi-species, multi-transition molecular line investigations. The Observatory has undertaken an aggressive program of technology development at the 12-meter to enhance the capabilities in two areas. First, to supply the frequency agility required for multi-line studies, sensitive receivers are under construction for all of the atmospheric bands between 68 and 360 GHz. These receivers will also provide improved capability for studies of weak emission. Second, to speed the observation of highly extended emission complexes, multibeam imaging receivers are being built. These will open up new areas of study that were previously blocked by slow data rates.

Millimeter-wave telescopes are sensitive to emission from cold, interstellar gas, to short wavelength bremsstrahlung radiation, and to long-wavelength emission from cold dust. Because of the sensitivity to cold material, millimeter-wave science is invaluable in the study of galactic structure, and unique in the study of star formation processes. Much of the research undertaken with the 12-meter will concentrate in these two areas.

In the area of star formation, researchers will combine millimeter-wave techniques with new infrared techniques to develop a more complete picture of the steps and chronology of the star formation process. For example, 12-meter observers will compare images of cloud density provided by emission from the CS molecule with wide field IR camera images. Such comparisons will show how sites of newly formed stars correlate with density clumps in molecular clouds. In a related study, the distribution of CO in a molecular cloud will be compared with the distribution of neutral hydrogen. The particular cloud to be studied is notable in that it has few if any signs of star formation. Neither OB stars nor IRAS sources have been identified. It is hoped that a comparison of this cloud with other clouds in which star formation is active will give information on the process that triggers star formation.

Making use of the frequency agility of 12-meter receiver systems, astronomers will use the emission from various molecules to determine the physical conditions of star forming regions. In one program, ratios of [DCO^+] to [$H^{13}CO^+$] will be used to estimate the temperatures of cold cores in clouds such as Rho Oph. For observations of warmer regions, astronomers will use emission from the CH_3CN molecule as an interstellar thermometer. Measurements of dense globules and "elephant-trunk" structures in the line of CO and HCO^+ will be used to search for evidence that the globules are being accelerated away from the parent HII region, and to search for gradients of velocity and density in the trunk features, since data on these gradients may distinguish between competing models of these curious regions.

It is now believed that bipolar-flow objects, which show features that are indicative of the expulsion of molecular material in two collimated flows on opposite sides of a forming star, are key to our understanding of the manner in which young stars separate from the cloud from which they formed. It is not surprising therefore that many investigations of these objects are planned for the next year. In a test of current theories of the development of a bipolar flow, observations will be made to confirm the existence of extended regions having anomalous velocities. Such regions can in principle permit a determination as to whether the protostar has experienced multiple stages of mass loss, and whether it is either precessing or rotating. It is also important to enlarge the sample of such objects, so that a new survey searching for outflow sources around B stars will be completed.

Studies of large-scale galactic structure can be extremely time-consuming when using the small beams of high-frequency radio telescopes. The 230 GHz, 8-beam receiver and future multibeam receivers will facilitate most studies of this sort, and make others feasible when they were heretofore practically impossible. These multibeam receivers are the millimeter-wave equivalent of imaging cameras used in the optical and infrared. For example, such systems will allow many globules, Barnard clouds, and Sharpless objects to be imaged quickly.

In addition to observations of galactic star forming regions, astronomers will use the 12-meter to study the cloud structure and interstellar medium of external galaxies. Because of the perspective offered by our view from afar, external galaxies can provide information on galactic structure that is not apparent by studies of our own galaxy. External galaxies including M31, M33, M83, and many others, are close enough to allow detailed structures to be resolved and studied. Here again, astronomers will make heavy use of the multibeam system to allow fast mapping even when high sensitivity is required.

Many specific problems in our understanding of external galaxies will be addressed by 12-meter research. For example, the existence of molecular gas and cooling flows in elliptical galaxies will receive considerable attention. Studies of spiral density waves and of star formation in dwarf irregular galaxies will also proceed. A key datum in this context is the ratio of the density of interstellar matter at the center of the spiral arm to that in the region between the arms. The instruments are now finally fast enough that good maps can be made to address this question.

Observations of CO also are now filling in the region of the rotation curve for certain galaxies showing a central hole in the neutral hydrogen distribution. Specifically, in M81 the rotation curve in the central region of radius 3 kpc is roughly as expected from extrapolation of the hydrogen rotation curve, but shows evidence for some asymmetries which will be explored with additional observations.

The 12-meter has a rich tradition in the study of astrochemistry, which should continue in the coming years. The high sensitivity and frequency agility of the new generation of SIS receivers will greatly aid in these studies. The emphasis in the coming years will likely be on refractory and light metallic compounds such as AlO and MgS. Studies of these and other second-row elements have been rejuvenated by recent laboratory work measuring the frequencies of favorable transitions. The alternative approach, which is to survey the spectrum and attempt to identify the numerous spectral features found, is being applied to the spectral region near a wavelength of 1 mm. The survey should be completed this year and the associated analysis will be well under way.

The 12-meter is a versatile instrument used for projects ranging beyond those described above. For example, each year the 12-meter is used for studies of continuum emission from quasars and galaxies, and sometimes from dust in our own galaxy. Each year the 12-meter supplies integral baselines in millimeter-wave VLBI experiments, which are now becoming routine and highly productive scientifically. The 12-meter will also be used for studies of planetary atmospheres, including that of the earth.

4. 140-FOOT TELESCOPE

A specific ongoing project using the spectral processor involves accurate timing of a distributed grid of pulsars. One goal is to discover, or place severe limits on, any gravitational radiation left over from the early moments of the universe. A background of gravity waves traversing the solar system could add a stochastic component limiting the accuracy of timing measurements. A second goal is achieved for those pulsars residing within globular clusters. These permit determination of the gravitational fields (hence mass distributions) within the clusters. For those pulsars that are members of binary systems, a third goal, testing general relativity, can be accomplished.

A second ongoing pulsar project lends support to the mission of the Gamma Ray Observatory (GRO). The GRO will search known radio pulsars for pulsed gamma rays. To bring the search within the realm of feasibility, only a portion of parameter space can be searched. The strategy is to fold all the gamma-ray data on the period of the radio pulsar. These periods are in the process of being accurately determined. Radio measurements will continue to be made throughout the lifetime of the satellite.

Very deep searches for rapid (periods ≤ few milliseconds) pulsars, for pulsars in binary systems and for pulsars in globular clusters will continue to be conducted. In addition, a new investigation using the 140 foot telescope and the spectral processor will be undertaken during 1991 and 1992. It will monitor pulsar signals three or four times per year for at least two years in search of interstellar electron density turbulence. If some lines of sight are particularly turbulent, multipaths from the pulsar to the telescope may interfere with each other, thereby providing < 0.1 microarcsecond angular resolution. Furthermore, if similar measurements are carried out at other telescopes, proper motions of some pulsars may be determined in just a few years.

The 140-foot telescope will continue in its role as a "redshift machine." One example of such an application is an HI survey of low surface brightness galaxies that are potential members of the Local Supercluster. A special focus will be on those southern galaxies to which few other radio telescopes provide access. An anticipated result is a better delineation of the organization of the Supercluster's matter into voids and clusters of galaxies.

Another investigation, begun in 1990 and yielding encouraging results, will conduct a blind search (i.e., without regard for optical galaxies) for intergalactic HI clouds within 15 degrees of the Supergalactic Plane. An initial survey suggests detections are likely in about one percent of the search locations. Each cloud thus found is intensely interesting, however, because it may be a protogalaxy in an early phase of collapse.

A major fraction of the available time on the 140-foot telescope is devoted to molecular spectroscopy. The centimeter-wavelength range the telescope covers is particularly well-suited for transitions of heavy molecules (atomic weights ≈ 20-50), most of which are organic. Therefore, the extension of the telescope's capability to cover the frequency range 25-32 GHz opens up a previously unexplored range of potentially great interest. To follow up on the interest in long carbon-chain molecules, one investigation will attempt to correlate the strengths of cyanopolyyne lines around carbon stars with the infrared light curves of the stars.

A new program shows promise of explaining many mysteries of interstellar chemistry. The 140-foot telescope will survey the frequency spectrum from about 6 to 9 GHz for absorption lines revealed against strong galactic continuum sources. The supposition is that several lines will be detected, and that their origin will be large molecules. If so, these, rather than a solid-state component of interstellar grains, may be responsible for the mysterious optical diffuse bands.

The search for $^3He^+$ in galactic HII regions and in planetary nebulae will continue. As detections are secured in more regions, the abundance distribution in the Galaxy can be determined. If variations with Galactic location are found, there are important implications for the chemical evolution of galaxies. In addition, the abundance ratio of helium to hydrogen has profound cosmological implications.

Another new cosmological investigation will exploit the 24-32 GHz capability of the 140-foot telescope. The investigation will search for anisotropies in the Cosmic Microwave Background Radiation on angular scales 5-10 arcminutes. To date only a few dozen patches of sky have been searched to a limit of a few times 10^{-5} in $\Delta T/T$ on these angular scales. Theoretical predications warrant continued searches.

The 140-foot telescope will continue as a major station in the international Very Long Baseline Interferometry network. Its collecting area and low-noise receivers make it particularly valuable for the special experiments requiring the greatest sensitivity. Two examples of experiments the 140-foot and only a few other telescopes can participate in are distance measurements to external galaxies using water-vapor masers, and proper motion of Sco X-1. The former measurement uses Doppler-shifted frequencies to determine line-of-sight velocities of individual maser features and measures transverse angular rates of expansion via VLBI. The combination of the two pieces of evidence yields directly distances to the masers and therefore to the galaxy in which they reside. The proper motion study of Sco X-1 utilizes phase referencing to nearby point sources to maintain phase stability. Nevertheless, at the level of signal involved, very few telescopes supply the necessary sensitivity.

A study important to galactic structure uses the formaldehyde molecule as a probe for the existence of dense cores in translucent, high-latitude clouds. By mapping large cloud areas in the formaldehyde line radiation, several high density regions have been found. Future studies will focus on the star-forming capabilities of these cloud cores.

One of the most speculative experiments will search high redshift ($z \geq 4$) quasars for CO emission redshifted to the K-band region, where the 140-foot telescope has an excellent receiver.

III. MAJOR USER FACILITIES

1. VERY LARGE ARRAY

Status of Present System

The Very Large Array is the ultimate radio astronomical tool for acquiring radio "pictures" across the full diversity of the radio sky with a resolution similar to or better than that obtained by the world's major telescopes at other wavelengths. Multiwavelength investigations of the broad range of astronomical objects from the sun and planets to stars, galaxies, and quasars are now no longer hindered by inferior resolution at radio frequencies. The combination of VLA sensitivity, angular resolution, frequency flexibility, and adjustable baseline configuration has propelled the instrument to the forefront of many non-traditional radio astronomical investigations in a way that was totally unpredicted by its designers. A full decade after its completion the size of the VLA user community and the annual publication rate continue to increase. Ground support follow-up radio observations for the Hubble Space Telescope and the NASA "Great Observatories" promise an even stronger user base in the future. Future joint VLA/VLBA observations offer prospects of a further increase in the quality of radio images and thus in our understanding of the physics of cosmic sources of radio emission.

Present Instrumentation

The VLA consists of twenty-seven 25-meter antennas arranged in a wye-configuration, 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, respectively. Reconfigurability provides the VLA with variable resolution at fixed frequency.

The VLA supports six frequency bands, remotely selectable; the five upper bands by means of subreflector rotation. When the VLA became fully operational in 1981, receiving systems were supported at 1.4, 5.0, 14.4, and 22.5 GHz, with the fundamental amplification at all four frequencies occurring via a 5 GHz parametric amplifier--1.4 GHz was preceded by a parametric-upconversion to 5 GHz, whereas both 14.4 and 23 GHz were mixed down to 5 GHz for amplification. Since 1981, most of these systems have undergone major improvements. Presently,

- 1.4 GHz amplification is done at the signal frequency with a cryogenic GaAsFET developed at the NRAO Central Development Laboratory (CDL);
- 5.0 GHz amplifiers are nearly all CDL GaAsFETs;
- 14.4 GHz amplification is done at the signal frequency with CDL GaAsFET amplifiers;
- 23 GHz amplifiers are CDL HEMT units.

In addition, two new frequency bands have been installed.

- 8 GHz HEMT amplifiers have been added to all antennas. This X-band system was constructed with funding provided by NASA/JPL in support of the Voyager 2 encounter with Neptune.
- 327 MHz prime focus FET receivers were installed.

The table below summarizes the parameters of the VLA receiver system.

VLA Receiving System

Frequency (GHz)	T_{sys}(K)	Amplifier
0.308 - 0.343	150	GaAsFET
1.34 - 1.73	60	Cooled GaAsFET
4.5 - 5.0	60	Cooled GaAsFET
8.0 - 8.8	35	Cooled HEMT
14.4 - 15.4	110	Cooled GaAsFET
22.0 - 24.0	180	Cooled HEMT

The VLA receives two IFs with full polarization capability in continuum 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, 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 is seriously out of date. Major replacement and upgrading of the instrumentation is needed to keep the VLA at its current leading position among the world's radio astronomy facilities.

When designed in the mid 1970's, 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 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 optic 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 scheduled completion of the VLBA in 1992 will give a milli-arcsecond imaging capability to complement the arcsecond capability of the VLA. There still remains, however, a gap in the range between the largest spacings of the VLA (up to 35 km) and the smallest spacings of the VLBA (about 200 km). The baselines between Pie Town and the VLA and between Los Alamos and the VLA lie in this gap. The location of these VLBA antennas was chosen in part to partially cover this range of spacings. However, the addition of four new antennas is needed to give good image quality, with a resolution about an order of magnitude greater than that of the VLA. This will permit scaled observations at a fixed resolution between about 0.01 arcseconds to 0.1 arcseconds over a wide range of frequencies. The planned VLA/VLBA connection is discussed further in Section VII.

Receiver Upgrade and Addition Program

The receiver upgrade and addition program will be described here. The program to expand the bandwidth of the VLA by replacing the correlator and substituting fiber optics for the waveguide is described in a later section.

Completion of 327/75 MHz Capability. The P-band (327 MHz) system is "complete" only in the sense that all 28 antennas have P band receivers installed and operational. However, only four antennas have RFI shielding installed on their B-racks. Without this shielding the self-generated RFI environment provides a strict limit of 3 MHz on the useful P-band bandwidth and hence on the array sensitivity at this frequency. As a result the basic sensitivity of the VLA at 327 MHz compares unfavorably to that at 20 cm, for example, even when account is taken of the steep spectrum of many cosmic non-thermal sources. RFI shielding must be installed on all antennas before P-band observations can reach their potential sensitivity and fidelity using bandwidths of 12.5 and perhaps even 25 MHz.

Eight VLA antennas have been outfitted with simple dipole feeds to explore the feasibility of VLA observing at 75 MHz. Initial tests with this system have been encouraging. A 100:1 dynamic range image of the radio galaxy Cyg A at a resolution of 20 arcseconds has been made. Future research programs will include the studies of steep-spectrum components of radio galaxies and quasars, the haloes of normal galaxies, the spectra of more compact sources, imaging of supernova remnants, searches for steep-spectrum galactic sources such as millisecond pulsars, studies of diffuse

HII in absorption against the nonthermal background, flare stars, interstellar propagation effects, and solar system objects.

Receiver Upgrades and Additional Bands. New receivers based on cooled low noise HEMT amplifiers are needed to lower the system temperature at all bands except 3.6 cm where these devices already exist. The proposed receivers are based on designs already implemented at the VLBA. With the current VLA design, there is a large contribution to the system temperature from the uncooled polarizer located at the base of each feed, plus the waveguide runs to the common cryogenically cooled first-stage amplifier. Advances in cryogenics now allow each polarizer to be individually cooled, together with the first stage amplification within the same dewar. The required cryogenic capacity is already in place. This approach has been taken with the VLBA receivers and with the VLA's new 3.6 cm system where these devices are already installed as a result of the VLA's participation in the Voyager Neptune encounter. The resulting system temperature at this band of 35 K makes this by far the most sensitive of all the VLA's observing bands. Implementing both the above items will improve the sensitivity of the VLA by over a factor of two at the 2, 3, and 18-21 cm bands and by nearly a factor of three at 1.3 cm.

L-Band Sensitivity Improvements. Spectroscopic observations with the VLA at 21 cm are limited in sensitivity by the ten year old frontend design, which provides 50-60 K system temperatures with all of the frontends in the same dewar. Twenty centimeter sensitivity is the most important commodity to the nearly 15 percent of VLA users who study extragalactic HI; the high system temperature is the greatest impediment to their research. The solution to this situation is replacement of all the L-band receivers with HEMT amplifiers in independent dewars as is done on the VLBA antennas. Currently one VLA antenna is equipped with a VLBA style L-band receiver. A program is in progress to completely equip the VLA with these receivers by the end of 1993. In 1991, we hope to have twelve antennas finished.

C, Ku, and K-Band Improvements. The improvement to the L-band system sensitivity that can be achieved by the installation of VLBA-style receivers applies equally well to the C, Ku, and K-band systems (6, 2, 1.3 cm, respectively). These three bands must be upgraded simultaneously as there is insufficient space to allow the present large four-frequency dewar to remain in place while each of its frequencies is upgraded to a separate VLBA-style receiver. (The L-band feed location is sufficiently far from the dewar to allow separate replacement of that frequency, as outlined above.)

The following table shows the expected improvements.

Potential VLA Receiver Improvements

System Temperature (K)

Frequency (GHz)	Present VLA	Achieved VLBA	Integration Time Ratios (fixed B.W.)
1.3 - 1.8	60	25	5.8
4.5 - 5.0	60	25	5.8
14 - 15	110	48	5.3
22 - 25	180	85	4.5

The improvement in observing efficiency is dramatic. Alternatively, the limiting flux density sensitivity that can be achieved in long but reasonable integration times improves; we expect this to produce new kinds of science.

Receiver Upgrade - New Bands. For observing programs that combine VLA and VLBA data, or even include both arrays simultaneously, having the same frequency bands available on both arrays is highly desirable. That means adding 2.3 GHz, 43 GHz, and 610 MHz to the VLA. 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 all important for continuum studies of spectral shape 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 observation are determined by the spectra and dispersion; and for unique spectral lines such as SiO at 43 GHz. A schedule for doing so, together with estimated costs, is given in the following table, both for these new bands and the improvements to existing bands already discussed.

VLA Receiver Upgrade Schedule (M$)

Frequency (GHz)	1990	1991	1992	1993	1994	1995
1.3-1.8	0.2	0.4	0.2			
4.5-5.0 14-15 22-25			1.2	1.1		
2.3				1.2		
43					2.0	
0.61						1.2

Increased Angular Resolution. Many types of radio sources have physically interesting structures that are barely resolved with the VLA but which do not require VLBI resolution. These include galactic circumstellar sources, compact HII regions, bipolar outflow sources, filaments and knots in supernova shells, filaments and knots in extragalactic jets, and "hot spots" in the lobes of radio galaxies and quasars. For nonthermal sources one cannot simply increase the resolution by increasing the frequency, as brightness sensitivity is also essential. Studies of Faraday depth or of radio spectra must also be done at given frequencies to address given physical questions. The ability to vary the VLA's configuration to obtain "scaled arrays" has been vital to its success as an astrophysical instrument--but this capability is restricted to resolutions of 1 arcsecond or lower at 20 cm and to 5 arcseconds or lower at 90 cm. We can increase the angular resolution of the VLA by linking it to the Pie Town VLBA antenna. This has recently become more feasible as a result of the installation of an AT&T commercial optical fiber west along U.S. 60 from Socorro that passes both the VLA and Pie Town. We will investigate use of this link To complete the system, the delay, fringe-rotation, and control systems for the VLA must also be expanded. In so doing, we will double the resolution of the VLA for northern sources, but the imaging quality at this resolution will be of low fidelity. True imaging requires additional antennas, as discussed in the description of the VLA-VLBA connection program.

2. 12-METER TELESCOPE

The NRAO 12-meter telescope began as the 36-foot telescope, the telescope responsible for the birth of millimeter-wavelength molecular astronomy. Following a period of explosive growth in this new area of astronomical research, during which most of the dozens of molecular species known to exist in the interstellar medium were first detected at the 36-foot, the telescope's reflecting surface and surface support structure were replaced and the 36-foot was re-christened in 1984 as the 12-meter. Subsequently, the scientific program has evolved from one dominated by observing programs in astrochemistry to one with concentrations on studies of molecular clouds and galactic star formation, evolved stars, and, more recently, studies of external galaxies. The 12-meter is the only millimeter-wavelength telescope 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 are maintained and operational reliability throughout is emphasized. 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.

Present Instrumentation

The basic specifications of the 12-meter telescope, its site, receivers, and spectrometers are given below:

Telescope Specifications

Diameter: 12 m
Astrodome with slit
Pointing accuracy 5"
Effective surface accuracy: 50-60 μm rms
Aperture efficiency: 49% at 70 GHz
45% at 115 GHz
25% at 230 GHz
15% at 345 GHz

As many as four receivers are mounted simultaneously at offset Cassegrain foci on the telescope. Receiver selection is by means of a rotating central mirror and can be accomplished in minutes.

Receiver List

Frequency Range (GHz)	Mixer	SSB Receiver Temperature (K) (per polarization channel)
70-115	SIS	80-150
200-240	SIS	200-260
240-270	Schottky	1200
270-310	Schottky	1200-1500
330-360	Schottky	1800-2200
Eight-beam Receiver		
220-240	8-Schottky	500-700

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

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

Filter Bank List

Resolution (kHz) Per Channel	Number of Channels	Number of Filter Banks
25	256	1
30	128	1
100	256	1
250	256	1
500	256	1
1000	256	2
2000	256	2

Note: All filter banks except the 25 and 30 kHz units can be divided into two 128-channel sections to accept two independent IF channels. The 25 kHz filters use the spectrum expander.

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

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

  1 x 2400 MHz

  2 x 1200 MHz

  4 x 600 MHz

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

Future Instrumentation Plans

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

All the developments described here are of immediate relevance to the 12-meter telescope, and most are equally relevant to the MMA.

One-Millimeter Imaging SIS System

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

To this end, we have already developed an 8-feed Schottky mixer system. This has been interfaced to our new 1536 channel hybrid spectrometer, and was made available to observers during the 1989-90 season. At this stage the full versatility of the hybrid spectrometer is not yet available--budget considerations have caused us to implement a cut-down compromise design. We hope that funding will enable us to complete this project according to the original specifications.

During 1991-92, we will upgrade the eight Schottky mixers to use SIS devices, thereby giving us state-of-the-art sensitivity in all feeds. We plan to have a 32-feed SIS system operational during 1994. The key to this development is the backend electronics. We have developed a prototype acousto-optic spectrometer, which will eventually become an 8-spectrometer system to extend the usefulness of the 8-feed system. In addition, we will initiate shortly a project for a new 32-section digital spectrometer for the full imaging system planned with the 32-beam SIS system. The digital system will provide the full resolution and bandwidth versatility required for both galactic and extragalactic observations. Of course this puts severe demands on the computer hardware and software. We are in the process of updating our real-time telescope control system (both hardware and software) to allow support of these future developments. Planning has begun for a multi-workstation environment at the telescope to support data analysis of the 8-beam imaging system. The data acquisition rate will have increased by between 1 and 2 orders of magnitude. A great deal of new computer hardware and software development will be required in the next three to four years.

Single-Beam Systems

Receivers. NRAO has traditionally provided receivers equalling or bettering any others in the world, and this is particularly true at mm wavelengths. A prototype closed cycle 4.2 K system capable of holding several SIS receivers sharing the same dewar has been completed. This will enable, by the early 1990's, a complete set of state-of-the-art dual-channel SIS receivers to be operational over the entire range 70-360 GHz.

The arrangement of several receivers sharing the same dewar is extremely effective in terms of cost, manpower, and in operational demands. These will equal or better the sensitivity of any existing receivers in the world.

To enhance further the flexibility and data acquisition efficiency, we are exploring the possibilities of simultaneous observations in different frequency bands through the use of beam splitters. This would be an important development for the future MMA.

Antenna Improvements

Pointing. Especially with the new 12-meter shaped subreflector (a project carried out in cooperation with the University of Texas), operation of the 12-meter telescope at the highest frequencies (360 GHz) is becoming more feasible. This puts a more critical demand on the pointing characteristics of the telescope. In order to improve the pointing, we have implemented the following in the past year: real-time monitoring of movements of the focus assembly using a laser and quadrant detector and an improved focus (Sterling) mount offering more freedom of movement and more precise control. We expect to implement additional instrumentation (inclinometers, strain gauges, temperature sensors), replacement of feed legs with a carbon-fiber design giving less temperature dependence and less aperture blockage, and a sun screen to reduce thermal distortions of the telescope during daytime operation. We have conducted successful experiments with an auxiliary optical pointing system, observing stars optically as an aid to better understanding of the pointing characteristics of the telescope. We intend to explore a higher level of automation, with the possibility of offset guiding on optical stars to give accurate tracking of weak radio sources.

Active Secondary Optics. Further improvements in the aperture efficiency of the 12-meter can only be accomplished through active, correcting optics. The primary reflector has been "tweaked" to the extent possible and the shaped subreflector has made further substantial improvements. However, the 12-meter exhibits significant gain-elevation defects owing to the distortion of the primary reflector and backup structure under the force of gravity as the telescope moves through its range of elevation angles. Since the shaped subreflector must be configured for a given elevation angle, active optics are required to remove the gain-elevation effects. Two options are available: active adjustment of the primary reflector (such as with the GBT and Keck optical telescope), or active adjustment of the secondary (or tertiary) optics. Adjustment of the primary may produce the overall best results, but it is costly and would require significant down-time for the 12-meter. Active secondary optics (e.g., a deformable subreflector) is the best option for the 12-meter. It is technically feasible, economical, and would result in no telescope down-time (i.e., it could be developed totally in the laboratory). Considerable expertise in this area exists among the 12-meter staff and in the Tucson astronomical community.

Future Plans

In addition to continued improvements in the 12-meter, the Tucson staff expects to 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. The Tucson staff is essential to this aspect of the MMA development work.

3. 140-FOOT TELESCOPE

The period 1991-95 represents an extremely important transition era for the 140-foot telescope. The major goals for it during this period are (1) to build momentum toward the Green Bank Telescope in the centimeter-wavelength, single-dish research community and (2) to stay at the forefront of telescope instrumentation so the move to the GBT proceeds smoothly.

Major Research Goals

The goal of strengthening the single-dish research community, will be achieved by relying on the unique versatility of the 140-foot telescope. Some of the characteristics that make it distinctive and therefore in demand by astronomers are:

- Frequency coverage. With very few gaps, sensitive receivers are available throughout the frequency range 100 MHz to 25 GHz. Often the Green Bank receivers define the state-of-the-art in radio astronomy.
- Stable spectral baselines. Detection of broad, weak, spectral features may be limited by instabilities in the RF/IF systems to a greater extent than by receiver noise. Exceptional care is taken to minimize these effects.

- The telescope is accessible. The 140-foot telescope is dedicated full-time to radio astronomical research. Astronomers are encouraged to bring their own instrumentation and/or to experiment with nonconventional observing techniques. The now "standard" spectroscopic observing procedures at the 140 foot e g total power, and nutating dual-beam--all resulted from users experiments and experience.
- Simultaneous dual-frequency operation. Between 8 and 25 GHz astronomers can observe at two different frequencies simultaneously This permits reliable comparison of two molecular species or two lines of a single species.
- High-time resolution. The spectral processor provides a unique combination of large bandwidth and number of channels for detailed study of pulsars. It also provides interference rejection, essential to observations at frequencies below 1 GHz.
- National Radio Quiet Zone (NRQZ). The 140-foot telescope enjoys the unique protection of the NRQZ. Green Bank remains one of the few sites where observations over the range 25-250 MHz remain possible. Frequencies > 250 MHz are also interference-free by comparison with the RFI environments of other radio observatories.

The major areas of scientific research envisioned for the 140-foot telescope during 1991-95 are pulsars, large scale structure of the universe, spectroscopy, and very long baseline interferometry (VLBI). The focus of pulsar research has shifted to the search for and study of millisecond and binary pulsars. The 140-foot telescope's sensitive receivers, relatively interference-free environment, spectral processor, and full-sky coverage (particularly to the Galactic Center) make it competitive with any existing radio telescope. The figure (Fig. 1) shows a one-hour integration at 1.67 GHz of PSR1745-24, an eclipsing binary pulsar in the globular cluster Terzan 5. This is the highest frequency at which the pulsar has been detected. The plasma causing the eclipse is therefore probed to a greater depth than at lower frequencies.

Some of the same advantages that enable world-class pulsar research also equip the 140-foot telescope to make HI redshift measurements of galaxies necessary to map supergalactic structures in all three dimensions. Spectroscopic research has shifted toward studying particular objects--circumstellar shells, HII regions, dark molecular clouds, etc.--over as broad a frequency range as possible, i.e., surveying in frequency space. In this way, new spectroscopic features are discovered that require laboratory studies to identify, a reversal of the early years of astrochemical research. As one example of new discoveries, various ^{13}C isotopes of HC_5N have been detected. VLBI also continues to rely on the sensitivity of the 140-foot telescope.

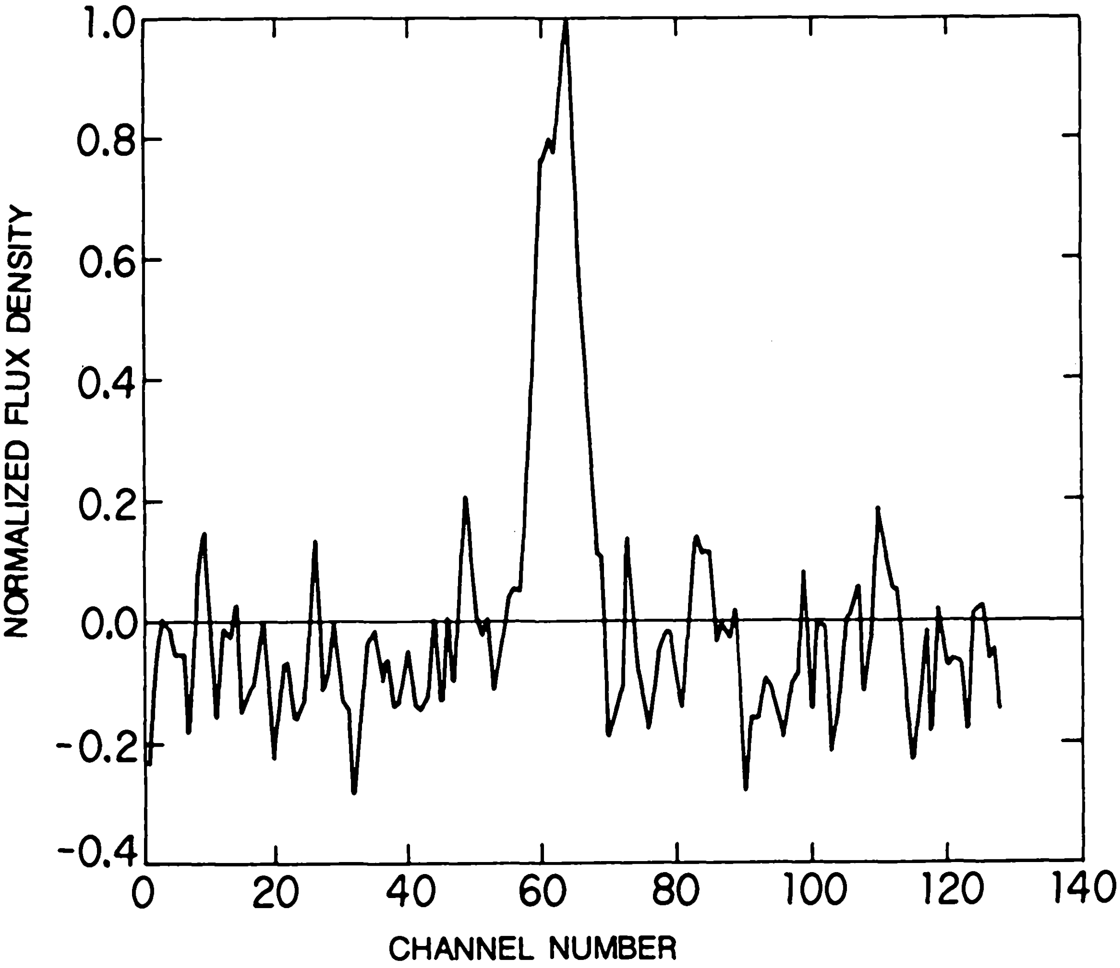


Figure 1. Pulsar 1745-24 at 1.67 GHz. The peak flux density is about 5 mJy. The period is approximately 11 msec. Eclipsing occurs at slightly different phases in the period than at lower frequencies, using a plasma diagnostic.

Present Instrumentation

Telescope Specifications

Diameter:	140 feet (43 meters)
Pointing Accuracy:	7"
Sky Coverage:	-46° to 90° declination
Fully steerable. Tracking time is 3 hours at d - -45°, 7 hours at -30°, 10 hours at 0°, and 13 hours at all d > 20°.	
Sensitivity:	0.26 K Jy^{-1}
Surface Accuracy:	0.7 mm (rms)

Receivers at frequencies lower than 5 GHz are mounted at prime focus. Two high frequency maser/upconverter receivers are mounted at the Cassegrain focus. Both Cassegrain receivers cover the entire range 5-25 GHz and may be used simultaneously at frequencies above 8 GHz by a polarization splitter mounted on the optical axis at the Cassegrain focus. When both Cassegrain receivers are used simultaneously, they can be tuned independently throughout the range 8-25 GHz. In this way true simultaneous dual-frequency observations may be conducted.

Receiver List

Frequency Range (GHz)	Amplifier Type	System Temperature (K)
0.025 - 0.088	Transistor	300
0.110 - 0.250	Transistor	250
0.250 - 1.0	Cooled upconverter/GaAsFET	45-70
1.0 - 1.45	Cooled GaAsFET	35
1.30 - 1.80	Cooled HEMT	18-23
2.90 - 3.50	Cooled HEMT	25-35
4.47 - 5.05	Cooled HEMT	25-35
4.70 - 7.20	Upconverter/Maser	30-50
7.60 - 11.20	Upconverter/Maser	35-80
12.0 - 16.2	Upconverter/Maser	50-80
18.2 - 25.2	Maser	35-60

Note: All receivers are dual polarization.

Future Instrumentation

As mentioned for the 140-foot telescope at the outset, the second major goal is to continue instrumental development. Electronics instrumentation proceeds incrementally. Engineers must work through every stage to stay at the forefront. It is therefore critical, if the GBT is to enjoy state-of-the-art instrumentation, to prevent any gaps in development between now and the time when the GBT starts operation. It is also true that instruments built henceforth, while initially for the 140-foot telescope, should be done in such a way that they can be transferred to the GBT. Planned developments consistent with these goals include:

Cassegrain Receiver. New receivers for the 140-foot Cassegrain system are currently under development. Cooled HEMT amplifiers have been constructed by the Central Development Lab to cover the 25-35 GHz frequency range (Ka band) and to replace the upconverter series over 5-18 GHz. The

18-25 GHz (K band) masers will not be altered. Two independent receivers are being built to receive orthogonal polarizations. We expect more uniform gain response and improved noise temperature vs. frequency using transistor amplifiers, as well as better stability and reliability. A few gaps in frequency coverage will be eliminated.

The Ka band capability will be new for the astronomical community. We plan to install one such receiver for winter 1990/91 observing. The 5-18 GHz capacity will be implemented in 1991.

Spectral Processor. The spectral processor is in use for pulsar observations at the 140-foot telescope. Previously pulsar observers had supplied their own specialized equipment for on-line data processing. The spectral processor makes this capability available to the general community Its second 1024 channels will be added by fall 1991. Software enabling spectral-line observations should be available by the end of 1990. For spectral line observations, the main advantage of the spectral processor over the Model IV autocorrelator will be higher tolerance to interference and twice as many IF inputs (8 instead of 4). A few comparative specifications are given in the following table.

	Model IV Autocorrelator	Spectral Processor
IF Inputs x Bandwidth	4 x 80 MHz 4 x 40 4 x 20 4 x 10 4 x 5 etc.	2 x 40 MHz 4 x 20 8 x 10 8 x 5 etc.
Total Number of Channels	512 @ 80 MHz 1024 < = 40 MHz	2 x 1024
Relative Sensitivity	0.81	~ 0.7 with 2048 channels > 0.9 with effectively 1024 channels
Time Resolution	10 seconds	25 μs @ 4 x 512 12.5 μs @ 4 x 256 Depends on bandwidth
Interference Sidelobes (narrowband)	20 dB	-40 dB Depends on Taper Fn
Integration Modes	Total Power Switched Power Pulsar Synchronous Spectral	Total Power Switched Power Pulsar Synchronous Time or Spectral Time/Frequency Matrix Dedispersed Time

<u>800-MHz Receiver</u>. The oldest receivers for the 140-foot telescope are those for frequencies less than 1 GHz. With the intensified interest in pulsar research, which is definitely signal-to-noise limited, the need for improved sensitivity is apparent. The same receiver could be used for

HI absorption-line searches in highly redshifted quasars. We plan to construct a cooled HEMT amplifier receiver with a feed designed to minimize spillover for the band 800-840 MHz. This band has little interference at Green Bank. The receiver will use fiber optics throughout. This will enable the rf signal to be transmitted to the control room before a local oscillator signal is mixed with it to produce an IF signal. Other innovations will be full computer control of receiver functions.

Present Computing Capability

NRAO-Green Bank is presently served by a Local Area Network (LAN), using Ethernet connections to distribute computing power across the site. Observers, for instance, can analyze data being acquired at the 140-foot telescope with equal ease from the telescope's control room, the Jansky Lab, or, if they have a PC and modem, from their residence hall room. The same data set can be accessed by more than one observer in a team. Different observers time-sharing the 140-foot telescope in the course of a single day can simultaneously analyze their separate data sets. In addition, an Internet connection has been installed that connects the Green Bank LAN to other computers in any locale. Evolution toward completely remote access is well underway.

Data analysis software is currently an advanced version of POPS. It runs on SUN workstations and Masscomp computers at the Observatory. There is also a PC version that observers can use and maintain at their home institutions.

Future Computing Capability

The transition to accessibility must be completed during 1991-95. Instructions to control computers on site, e.g., observing schedules, and file transfers of data from the site must be easily interchanged over national networks. This work will require additional workstations in Green Bank to assure complete network reliability, greater data storage capacity, and high-bandpass communications lines. These improvements are ongoing throughout the period as available technology evolves.

The data analysis software will be upgraded to UNIPOPS, providing greater functionality and compatibility at all NRAO sites. This installation will take place in 1991. Simultaneously, a new FITS reader and writer will be installed, consonant with recently defined international standards. In 1991 work will begin on the more powerful packages needed for the high-volume output of multibeam receivers and spectrometers with > 10,000 channels anticipated for the Green Bank Telescope. This development work will include an examination of both commercially available software and analysis packages in use at other observatories. It, too, will be an ongoing activity throughout 1991-95.

IV. EQUIPMENT PLANS

1. RESEARCH INSTRUMENTS

As a purely observational science, progress in radio astronomy is dependent on technological advances in all those areas that contribute to a successful observation. The experience at the NRAO and elsewhere has been that qualitative technical developments are soon reflected in qualitative, not incremental, scientific advances. The image of the emission from neutral atomic hydrogen in the Milky Way galaxy shown on the cover of this Program Plan is an appropriate illustration of this point. An enormous quantity of data went into the construction of this image, hundreds of thousands of spectra each with many hundreds of spectral points. The ability to acquire, manipulate, and display that information provides the astronomer with the opportunity to discover and investigate the highly nonuniform distribution of gas in the Galaxy. The superposition of the large-scale loops and filaments so prominent in this image can be directly related to the distribution and frequency of supernova events in the Galaxy. Fundamental knowledge such as this is unobtainable without a concerted and continuous program of instrumental construction, evolution, and improvement.

Each of the three major telescopes operated by the NRAO as well as the partially completed VLBA provides a unique service to astronomers and each benefits by a scientifically considered and prioritized plan for improvements to its capabilities as enumerated below. To this end an NRAO research and development program in electronics, instrumentation, and/or computing techniques is maintained at each observing site as well as at the

Central Development Laboratory in Charlottesville. Each of these locations is involved in design, development, and construction of auxiliary instrumentation for augmenting the research capabilities of the NRAO telescope systems. However, it is a mistake to think of these instruments solely in terms of steel reflectors and cryogenic radiometers--as research instruments one must consider not only instrumentation but also data-handling and the user-interface. The purpose of the NRAO is to provide unique facilities to the researcher which he/she can use to maximum scientific profit. The typical user, in residence at the NRAO but a few times a year, thus needs to be provided with hardware and software interfaces to the instrumentation that are logical and comprehensible, yet which provide ready access to the full flexibility available from the instrument. The need for a suitable user-interface has a considerable impact on NRAO plans for the design and utilization of astronomical instrumentation which can be seen reflected in demands on the research equipment and budget.

One of the most significant advances in radio astronomy in the last few years was spawned from the recognition that the quality of radio astronomical data could be markedly improved by more sophisticated data manipulation software. Here the most striking example is the use of self-calibration algorithms on VLA and VLBI data to correct the incoming wave-front for atmospheric (and instrumental) effects. This radio analog of the optical "adaptive optics" technique allows the VLA to achieve theoretical angular resolution unencumbered by atmospheric smearing while at the same time reaching a dynamic range 100 times higher than expected in the design of the VLA. For the specific case of VLA data, the price of this improvement is an enormous computing burden that requires the astronomer to seek the resources of faster computers and greater data storage capacity. The NRAO, cognizant of these escalating demands, has sought additional computing facilities and personnel for algorithm development and user support through the proposed "Array Telescope Computing Plan." An addendum to the plan was submitted to the NSF in 1990. However, the single-dish telescopes, as well as the VLA, have also benefitted by access to rapid data-handling and data-manipulation hardware and software. The multi-feed receivers on the 140-foot telescope and on the 12-meter telescope have led to a remarkable improvement in the capacity to map large regions of the sky and to study more numerous astronomical objects. But again the direct ramification is a need for faster, more flexible, and distributed computer power together with more sophisticated software in order to exploit properly these additional scientific opportunities.

The Research Equipment (RE) plan is designed to realize these opportunities. This plan has been under-funded in the past few years and while our 1991 planned expenditures are $825k, it is not possible to budget new NSF funds for RE within the limits of even the request-level budget.

The following table shows the planned distribution of funds for the RE account, were funding to be made available, and it reflects established scientific priorities in each of the NRAO operating divisions. The NRAO, in consultation with its users, continually updates this table as scientific priorities change. A brief narrative describing the various items in the RE plan follows the table. It is important to note that most of the RE projects extend over several years; those high priority activities in 1991 are not necessarily planned for completion in 1991.

RESEARCH EQUIPMENT

($ in thousands)

	Expenditure			
	1990 (est)	1991 (plan)	Add'l Cost	Completion Date
1. Laboratory and Test Equipment	$ 50	$ 50*	$100/yr	continuing
2. Miscellaneous Projects	90	75*	200/yr	continuing
3. Very Large Array				
1.3-1.7 GHz Improvements	200	200*	200/yr	1993
Imaging Computer Additions	70	50*		continuing
4. 12-m Telescope				
Multibeam 230 GHz Receiver	10	25*	10	1992
Multiband SIS Receiver	30	30*	60	1993
Hybrid Spectrometer	30	60*	30	1992
Telescope Control Upgrade	30	30*	60	1992
5. 140-ft Telescope				
LAN/Computer Development	5	45*	50	1992
5-32 GHz HEMT Receiver	20	20*	40	1991
6. Common Development				
Millimeter Device Development	140	150*	150/yr	continuing
HEMT Amplifier Development	25	25*	20/yr	continuing
Computational Imaging	70	50*	50/yr	continuing
Single Dish Support		15*	15/yr	continuing
TOTAL	$770	$ 0		

*Note: No NSF funding available in 1991.

1. Laboratory Test Equipment

In order to improve existing and to develop new telescope instrumentation, it is essential that NRAO upgrades its Laboratory Test Equipment. This area has been neglected in recent years due to very low RE budgets. There is a need to correct this as soon as possible. This budget line covers equipment for all sites and includes the Central Development Lab and also some computer diagnostic equipment. Included also are enhancements to existing test equipment.

2. Miscellaneous Projects

Numerous electronic and computer projects, limited in scope, are continually in progress throughout the Observatory. Although the budget for each project is generally considerably less than $20k, collectively the projects are vital to the ability of the Observatory to respond quickly to evolving technology and to the specific needs of visiting astronomers. Improvements to cryogenic systems, data record capacity or speed, and so forth are accounted for as miscellaneous projects.

3. Very Large Array: Electronics

1.3-1.7 GHz Tsys Improvement - HI imaging is the most important class of spectral line project at the VLA. The observation of HI in emission (either galactic or extragalactic) is almost always sensitivity limited, either because the HI has to be followed to the faint outermost regions of galaxies, or because more angular or frequency resolution is desirable.

The current VLA 18-21 cm receiver has a system temperature of approximately 50-60 K. A significant fraction of this system temperature results from the arrangement of all front-ends in the same cryogenic dewar.

This results in longer input waveguide runs than would usually be required and prevents the polarization splitters from being cooled.

An improved 18-21 cm receiver, using cryogenically-cooled HEMT amplifiers and a cooled polarizer, was designed for the VLBA. These systems are now being retrofit to the VLA. We expect an L-band system temperature of 35 K. Six VLA antennas will be equipped with the new receiving system in 1991, making a total of twelve antennas so equipped by the end of the year.

Many other VLA electronics projects are planned, but none can be funded in 1991.

Imaging Computer Additions - Access to the full data rate of the VLA provided by the new on-line computers is a mixed blessing. Scientifically, it permits true spectro-polarimetry for the first time since the VLA was constructed; polarization images of OH masers (and similar science) are at last possible. But the price one pays for this information is a sustained data rate greater than can be accommodated by the downstream imaging computers. A very substantial enhancement in computing resources is needed and, indeed, such has been requested in the proposal "Array Telescope Computing Plan" submitted to the NSF. In the interim, and prior to the expected start of funding for this plan, we acquired a second CONVEX C-1 computer for calibration and imaging at the AOC, and in 1991 we plan some modest enhancement of the disk storage capacity, tape handling, and interactive display for both CONVEX imaging computers. We also intend to enhance the system of distributed workstations as precursor to implementation of the Array Telescope Computing Plan.

4. The 12-Meter Telescope

The increased emphasis on higher frequencies puts greater demands on the pointing accuracy. A major program has commenced which attacks this problem through continuous laser measurement of the focal point, an optical pointing capability, and thermal stabilization of the feedlegs Replacement of the steel feedlegs with carbon fiber feedlegs is being investigated.

Multibeam 230 GHz Receiver - The 8-beam Schottky receiver for 230 GHz, which has been in scheduled operation for two seasons, will be rebuilt with more sensitive superconducting tunnel (SIS) junctions. This receiver, the only multibeam receiver on any millimeter-wave telescope, is particularly useful for large-scale mapping programs.

Multiband SIS Receiver - A long-term goal of the 12-meter telescope is to achieve complete frequency coverage at all usable wavebands between 70 and 360 GHz with highly sensitive, state-of-the-art, SIS receivers. Complete frequency coverage allows observers total flexibility in choosing the spectral-line transition that is most appropriate for their astrophysical research.

The present 90-115 GHz SIS receiver has been highly successful and has produced some of the world's most sensitive millimeter-wave detections. This receiver uses a hybrid cryostat that must be filled with liquid helium twice a week. This operation is expensive, both in helium costs and in manpower, and takes about one hour away from the observing schedule for each fill. This problem will be avoided in the next generation of SIS receiver, which will make use of 4.2 K niobium junctions cooled with a closed-cycle (i.e. low maintenance) refrigerator system.

Construction has begun on a 4.2 K system that can handle eight inserts which include SIS mixer/feed/amplifier assemblies. The telescope version of the system, with coverage of the 1 mm, 2 mm, and 3 mm windows, will be scheduled for observations on the 12-meter in the 1990-1991 observing season. The objective is to have complete coverage of all the windows between 70 and 360 GHz with this receiver in the near future.

Hybrid Spectrometer - In order to provide the greater instantaneous bandwidth needed by the higher frequency 12-meter telescope receivers, as well as to improve the spectral resolution at lower frequencies, a hybrid filter-bank autocorrelator has been constructed. The 2.4 GHz total bandwidth and 1536 spectral channels incorporated in this device will benefit the present single-beam receivers but, in addition, the spectrometer can be divided into as many as eight separate spectrometers for use with the existing 8-beam receiver. An interim system without the full frequency versatility is now operational. The full system will be completed in 1991.

Telescope Control Upgrade - The existing control system for the 12-meter telescope has been stretched to the limit in supporting the current generation of instrumentation, and already imposes a severe limitation on the potential of the telescope and new data-acquisition equipment. It is long overdue for replacement. The implementation of a new system must not necessitate any prolonged shutdown of the whole telescope, so the approach adopted involves a gradual transfer of control tasks to a loosely coupled network of microprocessors, based upon a standard bus system. This greatly simplifies the eventual replacement of the control computer itself. During 1991, most of the CPU-intensive control tasks will be implemented in satellite microprocessors. The main control computer itself was replaced in 1990 with modern hardware and a user-friendly software interface was installed on the telescope, thereby benefiting both operators and astronomers. The new control system is being designed with a remote observing capability in mind.

5. The 140-Foot Telescope

The 140-foot, fully steerable, radio telescope incorporates great frequency flexibility through dual-polarization maser/upconverter receivers that provide exceptional sensitivity from 4.8 to 26 GHz. Longer wavelengths are observed with receivers mounted at the prime focus. With very few gaps, system temperatures lower than 50 K are available on the 140-foot telescope from 1 to 26 GHz. It is no surprise, therefore, that so many recent successful searches for molecular spectral lines in this frequency range have been made on the 140-foot telescope and not elsewhere.

During the last two years significant improvements have been made in the high-frequency sensitivity of the 140-foot. The sensitivity at most frequencies was improved by $\sqrt{2}$ by installation of a polarization beam splitter at the Cassegrain focus which allows both maser/upconverter receivers to be used simultaneously. One can choose either to observe at one frequency in two orthogonal polarizations or to observe with two receivers tuned independently anywhere in the range 4.8-25 GHz A tilting, lateral focus mechanism for the subreflector was installed, resulting in an increase of a factor of two or more in K-band aperture efficiency at large hour angles. Finally, the surface panels were adjusted based on holographic surface maps, reducing the rms error from 1.0 mm to approximately 0.6 mm. The aperture efficiency at 33 GHz is now in the range of 10 percent to 15 percent, depending on declination. These successful improvements have encouraged us to continue our program to instrument the 140-foot at higher frequencies.

5-35 GHz Receiver: The accuracy of the individual surface panels of the 140-foot telescope is sufficient for useful observations to be made at frequencies as high as 35 GHz. There is considerable scientific motivation to observe at higher frequencies, driven principally by (a) spectroscopy, (b) cosmic background radiation studies, and (c) VLBI. Although there are many molecular lines between 25 and 35 GHz, the following species have transitions important for astrochemistry in this frequency band: methanol (maser lines), formaldehyde, silicon monoxide, cyanoacetylene, and cyclopropenylidene. A frequency band near 32 GHz is particularly interesting because the atmospheric transparency is greater than that at any frequency above the resonant water line at 22 GHz. Significant continuum research, especially on the microwave background, can take advantage of this window.

The present Cassegrain receiver systems use parametric upconverters to convert signals from 5 to 16 GHz into the 18-25 GHz frequency range of the ruby maser amplifiers. State-of-the-art HEMT amplifiers are now competitive or superior to the noise performance of the upconverter/maser system below 16 GHz. Conceptual work has been completed on a project to re-work the Cassegrain receivers to incorporate HEMT amplifiers for the 5-18 GHz range, and also above 25 GHz, but retaining the masers for the 18-25 GHz range. In 1991 we expect to have this HEMT receiver ready for use over the 5-35 GHz frequency range.

Local Area Network - The Green Bank LAN creates an integrated computing system, one that has been essential to the many recent improvements in the Observatory's single dish analysis software. The existence of the LAN allows users at the telescope, in the Jansky Lab and, in principle, at their home institution, to access data as it is taken, or as it has been archived, at the telescope. In 1991 the flexibility and utility of the LAN will be increased by the addition of additional transceiver ports, robust connection to wide-area computer networks (Internet), and the addition of peripheral equipment such as tape/disk media.

6. Common Development

Although the NRAO is distributed over the four operating sites, there nevertheless exist technical research programs that benefit all sites and which are carried out using the resources, where appropriate, of two or more sites. These programs often involve technical experimentation in innovative or even speculative technical areas. As such, they are not properly representative of any one particular site but rather they are the developments that may most rapidly improve the technical base of the whole Observatory.

Millimeter Device Development - Virtually all astrophysics done at millimeter wavelengths is sensitivity limited, because the emitting gas is both cold and spatially extended in most objects of interest. Thus, the spectral lines involved are both of low intensity and of narrow width, containing very little energy. There is accordingly a greater scientific need for continued improvements in receiver sensitivity at millimeter wavelengths than exists at centimeter wavelengths. To this end, millimeter-wave device development at the NRAO emphasizes both in-house work and a subcontract with the University of Virginia to supply superconducting circuits specialized to our millimeter-wave applications.

HEMT Amplifier Development Development of cryogenic FET/HEMT (Field Effect Transistor/High-Electron-Mobility Transistor) devices represents a second important activity. This type of amplifier has become widely used for centimeter-wave radio astronomy receivers largely through the development work done at NRAO. The amplifiers are more reliable, stable, and have lower noise than parametric amplifiers. They are also used as IF amplifiers for millimeter-wave receivers. Hence, the sensitivity of almost all observations performed at the NRAO is improved with the development of these amplifiers.

GaAs FET and HEMT amplifiers have been designed at 0.3, 1.5, 5.0, 8.3, 10.7, 15, 23, and 43 GHz. Several hundred units have been constructed. Work in 1991 will focus on development of broader band amplifiers for various applications at all sites. We will also start work on a prototype amplifier at 86 GHz for the VLBA project.

Computational Imaging - This includes the support and development of the Charlottesville data-processing facility, the AIPS development project and associated projects as, for example, hardware evaluation. It also includes the support of the network infrastructure which provides the backbone of the Observatory's intersite digital communications.

Single Dish Support Experimentation with hardware and software for analysis of single dish data takes place at all the Observatory sites. Algorithm development and the interface of the algorithms to new display hardware is given emphasis.

2. OPERATING EQUIPMENT

For the past several years, funding of operating equipment has been almost nonexistent. In an effort to meet the minimum budgetary needs in research equipment and regular operations, it has been necessary to postpone indefinitely the purchase of operating equipment. In addition, we have had to delay the replacement of existing obsolete equipment. This approach to funding leads to higher maintenance costs, more frequent "down" time and inconvenient and inefficient use of our personnel resources. the plan presented below attempts to reverse this trend in operating equipment funding. Over the next several years, with adequate funding, we will be able to provide the infrastructure to meet the increasing demands of our users. The distribution of funds (shown in thousands of dollars) for the various equipment accounts is as follows:

	1991*	1992 - 1996
1. Maintenance and Shop Equipment	$134	$915
2. Office and Library Equipment	217	535
3. Living Quarters Furnishings	5	40
4. Building Equipment	15	35
5. Observatory Services	15	55

*Note: No NSF funding is available for this plan in 1991.

1. Maintenance and Shop Equipment

Funds included in this category provide for the replacement and acquisition of new items for the shops and maintenance divisions. Major purchases for 1991 include replacement of a Bridgeport mill, motors, engine generators, dump truck, and other machine shop equipment. During the period 1992-1996 major planned equipment purchases include replacement of the dome cover in Tucson in 1992, installation of new above-ground fuel tanks in Tucson and Socorro to meet new EPA requirements, engine generators, backhoes, forklifts, and tractors. In Green Bank there are plans to replace the old Checker diesel vehicles being used around the antenna sites. A new dump truck and tractors are also needed to replace old equipment for which parts are continually harder to locate.

2. Office and Library Equipment

Funds for the purchase of office and library equipment have lagged behind virtually all other equipment purchases over the past several years. These funds normally provide for the replacement, updating, and acquisition of communications equipment, business data and word processing equipment, copying machines, and related library equipment. Since these purchases have been postponed over the years, a major investment in 1991 is planned to replace several old and unreliable copying machines and computers. Major purchases from 1992 to 1996 include updating the telephone system in Tucson, implementing an indepth safety program by purchasing the necessary training equipment and supplies for a structured, Observatory-wide program.

3. Living Quarters Furnishings

These funds provide for the purchase of household appliances and furnishings used in the site living quarters.

4. Building Equipment

These funds provide for items that are generally attached to and become a part of the buildings. The coming years will require more emphasis on building security since computers and other related equipment are becoming more expensive and considered an easy target for potential theft. In addition to security, routine improvements to the Charlottesville trailer offices, such as replacement of heating and cooling units, will be required. The cafeteria equipment in Green Bank is approaching thirty years of age. In the out years there are also plans to install air conditioning in the Jansky Lab

5. Observatory Services

Funds are required for this category in order to replace and improve the graphic arts and information services divisions. Items such as cameras, darkroom equipment, projectors, and measuring equipment are included in this figure.

V. WORK FOR OTHERS

1. USNO OPERATIONS

In 1991 NRAO will continue to operate two telescope systems for the USNO. The primary system uses one 85-foot antenna as a VLBI station permanently involved in the NAVNET of stations. NAVNET determines the earth's (variable) rotation rate and, with less accuracy, the position of the pole. It uses 1-3 antennas in addition to the 85-foot in Green Bank, all equipped to operate simultaneously at 2.3 and 8.4 GHz. Several upgrades to the VLBI station in Green Bank are in progress. The recording terminal will be replaced by a VLBA terminal in 1991. The wider bandwidths this terminal is able to record will necessitate modifications to the receiver as well. In addition, the IF frequency entering the VLBA terminal's baseband converters must be modified.

The geodetic observations so far do not use all hours of every day. The time not used for VLBI is devoted to pulsar timing observations. Some 100 pulsars are observed as often as possible at 610 MHz. A 327 MHz receiver will be added in 1991. The goal is to monitor for changes in their periods, especially for "glitches" or discontinuous jumps in period.

Two other 85-foot antennas are linked by fiber optics as a single baseline interferometer. This interferometer also operates at 2.3 and 8.4 GHz simultaneously. It observes a few hundred compact radio sources daily, monitoring changes in their flux densities. Changes may be either intrinsic to the source or they may be attributed to changes in the path the radiation travels through the interstellar plasma of our own galaxy.

The funding plan for USNO operations is shown in Table V-1.

2. NEW INITIATIVES

In collaboration with West Virginia University, the NRAO has proposed to the NSF Division of Education for support of a program to train Secondary Science Teachers. The thrust of this program is to expose classroom science teachers to hands-on scientific research using the research instruments in Green Bank, giving them a first-hand knowledge of research techniques they can pass on to their students. Such a summer science institute was sponsored by the NSF at Green Bank in 1988 and 1989, but was unfunded in 1990. The current proposal, pending before the NSF, seeks support in 1991 and 1992 as shown in Table V-1.

In anticipation of a flood of astronomical data from the "Great Observatories," NASA has begun to create a National Data Archive which astronomers may access remotely. The plan is to make the data easily available to those wishing to analyze or interpret it, both now and in the future. NASA also recognizes that the space data is of greater value when it is combined with complementary ground-based data; they have proposed a plan whereby data from the VLA (and other telescopes) would be incorporated into this same archive. The NRAO has proposed to translate archived VLA data into the form and medium appropriate to the NASA archive NASA support would be required in an amount shown in Table V-1 This proposal is pending with NASA.

NASA has also begun a program to support Orbiting Very Long Baseline Interferometry (OVLBI) that has ramifications for the NRAO. While the U.S. will not launch an orbiting radio telescope, both the Japanese and the Soviets intend to do so. The two space missions, known respectively as

VSOP and Radioastron, are both scheduled for launch about 1995. Both require support from the ground to be effective scientific missions. Ground radio telescopes must be involved in interferometry with an orbiting spacecraft, and the dedicated VLBA is well-equipped to provide such support. Second, the space-ground data needs to be recorded correlated, and processed into images, the facilities for which exist with the NRAO. For these reasons NASA is negotiating with the NSF for access to the VLBA for OVLBI science support. The approximate costs are shown in Table V-1. At the present time there is no signed agreement between NSF and NASA. This entire schedule is fluid as it is dependent on the plans of NASA and foreign space agencies.

In addition to the "OVLBI-Science" support mentioned in Table V-1, we also show construction of a "OVLBI Earth Station" in the same table. The earth station is a response to the need for the spacecraft to be in communication with the ground whenever scientific data are being taken. Negotiations are in progress between NASA and NSF to construct an earth station for OVLBI in Green Bank using some NSF equipment. If this project is approved by both agencies, the schedule for NASA funding is expected to be that shown in the table.

V. Work for Others - Budget Projections
Table 1
($ in Thousands)

	1991	1992	1993	1994	1995	1996
Operations & Equipment						
USNO - Interferometer	$848.0 *	$900.0	$950.0	$1,010.0	$1,070.0	$1,135.0
NSF - SSTI Grant	795.0	965.0	0.0	0.0	0.0	0.0
NASA - Archiving	200.0	0.0	0.0	0.0	0.0	0.0
NASA - OVLBI - Science	300.0	1,600.0	1,800.0	1,385.0	1,650.0	1,450.0
Other Misc. Projects	50.0	50.0	50.0	50.0	50.0	50.0
Total Operations	$2,193.0	$3,515.0	$2,800.0	$2,445.0	$2,770.0	$2,635.0
Construction						
NASA - OVLBI Earth Station	$1,000.0	$2,000.0	$1,000.0	$0.0	$0.0	$0.0
Total Construction	$1,000.0	$2,000.0	$1,000.0	$0.0	$0.0	$0.0
Total - Operations & Construction	$3,193.0	$5,515.0	$3,800.0	$2,445.0	$2,770.0	$2,635.0

* These are the only funds which have been committed to NRAO.
All other funding requests are under consideration by the agencies involved.

VI. MAJOR CONSTRUCTION PROJECTS

1 VERY LONG BASELINE ARRAY

Revised Construction Plan and Budget for the VLBA

The 1991 budget plan for VLBA construction, BD76N01, and associated overview schedule is presented below. This budget reflects $10M of new funds for 1991. This budget also reflects a decrease in estimated program contingency of $900k, due to increased expenses divided almost equally between the higher cost of the Hawaii construction, costs of an increased supply of recording tape, and the costs of future reliability retrofits (discussed under Monitor and Control) at the ten sites. Funds for the final NRAO-fabricated recorders, and approximately $300k of expected additional antenna and previous site outfitting cost increases were shifted from the spares budget to the relevant divisional budgets. The remaining $600k contingency is needed for possible contractor claims and any unforseen technical problems that might arise during outfitting and initial testing and operation.

As detailed in the 1991 VLBA budget plan submitted earlier, prior authorization of certain funds will be necessary at the beginning of the Foundation's 1991 fiscal year, October 1990, to continue orderly progress in the VLBA construction program. An advanced authorization of $3M is requested. This advanced funding allows:

1. Authorization of the third production run of eleven recorders to Haystack Observatory and Honeywell Test Instruments Division this year. Up to six months lead time is required for parts procurement to keep

production from being interrupted and incurring extra costs. Estimated costs for these orders are $1.6M.

2. Authorization of $1M for AOC capital repayment to save an additional quarter-year's interest payment.

3. Authorization of $0.4M for purchase of long lead electronic components, for quantity procurement savings and more efficient assembly schedules.

For the 1991 budget, there is also the necessity of advanced authorizations from 1992 funds. A $4M total advanced authorization process is likely to be requested from the NSF next year for the following:

1. Authorization of the fourth recorder production run at Haystack Observatory; $1M of 1992 funds required in October 1991.

2. Authorization of the purchase of the VLBA data processing mini-supercomputers; of 1992 funds required in October 1991.

Antennas and Sites

The schedule for manufacture and erection of antennas indicates that the tenth and last antenna is scheduled for erection by December 1991. Site acquisition for all locations is complete. With "first light" observed in May, 1990 at the fifth antenna of the VLBA (North Liberty, IA), half of the array is now operable to at least some limited degree. The construction status of the individual sites follow.

Pie Town, NM - This site has been operational since April 1988, and has participated routinely in VLBI Network observations since then, as well as frequent NASA/GSFC Crustal Dynamics observations. It will continue such observations in 1991, as well as serving as a test bed for upgrades and improvements.

Kitt Peak, AZ - This site was made operational in June 1989. The antenna will continue routine VLBI Network and *ad hoc* observing in 1991.

Los Alamos, NM - This antenna is complete and operable. However full-time staffing to support all Network observing was delayed until October 1990 because of operation budget constraints. It is used to support occasional observing where it can be supported by one on-site technician. Routine operation and debug are scheduled for 1991.

Fort Davis, TX - This antenna is complete except for network communications hardware. Staffing for operation is scheduled for October 1990 and routine operation is scheduled for 1991.

North Liberty, IA - This latest operable antenna is undergoing test and debug. It is scheduled to be staffed for operations in October 1991 (requires advance funding from 1992 VLBA operations funds)

Owens Valley, CA - This antenna is undergoing electronic outfitting, to be completed October 1990 Testing and debugging will proceed in 1991. Staffing for operation is scheduled for October 1991 (requires advanced funding from 1992 VLBA operations funds.)

Brewster, WA - Antenna erection was completed in July 1990, except for punch list items. Electronic outfitting is scheduled to start in November 1990 and continue through March 1991. Operational staffing is scheduled for January 1992.

Hancock, NH - Antenna erection started in April 1990 and is scheduled for completion in December 1990. Outfitting is scheduled to begin in April

1991, followed by test and debug. Staffing for this site is planned for January 1992.

St. Croix, VI - Antenna foundation and control building construction resumed in June 1990. Antenna erection is scheduled to start in January 1991. Staffing of this site is scheduled for October 1992.

Mauna Kea, HI - Construction of the antenna foundation and control building begins in September 1990. Antenna erection is scheduled to start in mid 1991. The Mauna Kea antenna is scheduled to be staffed for operation in October, 1992.

Electronics

Construction of a number of major items of the electronic receiving system will be completed by the end of 1990. These include the racks (racks A, B, and C), and the front ends for 4.8, 8.4, and 23 GHz. The front ends for 1.5 GHz were completed last year. Eleven of each of the racks and front ends are being constructed, to allow one system for testing and maintenance in the laboratory as well as one at each antenna. The first 43 GHz front end has also just been constructed, and will have been tested on the antenna at Pie Town by the end of 1990. During 1991, front ends for 330/610 MHz, 2.3 GHz, 15 GHz, and 43 GHz will be largely completed.

Construction of Data Acquisition Racks (Rack D) through serial No. 10 will be completed by the end of 1990, and further units of this type will be constructed in 1991. Also during 1991 a number of spare modules will be constructed to use for maintenance of the array. For example, in the case of modules for which there is just one of a given type at each antenna, 14 units will be constructed to provide four spares.

The outfitting plan calls for completion of installation of all electronics during the third quarter of 1992. Construction continues to remain sufficiently well ahead that outfitting and testing plans are not impacted. Over the past year, however, the availability of baseband converter modules has provided some constraints on preliminary operation for programs that require a large number of baseband channels; for example those which include non-VLBA antennas using Mark III recording. Increased manpower has been assigned to these modules, and by mid-1991 they should no longer be a limiting item. Hydrogen masers 10 and 11 are expected to be delivered by Sigma-Tau Standards Corporation during the final quarter of 1990.

Data Recording

VLBA recorders through serial No. 13 have been shipped from Haystack Observatory to the first five antenna sites, NRAO development laboratories, USNO at Green Bank, and the VLA. Deliveries from a second production (of eight) through serial No. 21 are expected to start in October 1990, with shipment intervals of approximately two weeks. One of these is scheduled for a one year loan starting in early 1991 to the Astro Space Center in the USSR to allow their staff to develop the necessary interfaces to ground stations for the Radioastron satellite, as well as earth based VLBI antennas in the Soviet Union. A change order to Haystack for another 11 recorders is expected to be placed in October 1990 and again in October

1991. Three recorders are scheduled to be assembled at the AOC in 1991 and again in 1992

Orders were placed in 1990 for significant field test quantities of thin-base recording tape with each of three competing vendors: Sony, Maxell, and Ampex. Shipments began in August 1990. Field and laboratory tests will start in the fall 1990, and continue for at least a year. Among other tests, it is expected that they will be mixed into VLBI and JPL/GSFC Network tape supplies for participating observatories and processing sites. Durability, magnetic, and mechanical performance will be carefully monitored and analyzed before deciding in late 1991 on the supplier of the larger, operational quantities of tape.

Monitor and Control

The initial monitor and control software was converted to run on the VxWorks operating system during 1989 and the first half of 1990. This conversion is nearly complete, although there remain problems with reliability. The VLBA stations are scheduled to be entirely converted to VxWorks by the end of September, 1990. The plans for the eventual communication network for the array have been completed, although much work remains to implement the plan in late 1990 through 1991.

It has been decided to replace the CPU boards of the site computers, currently Motorola MVME121 boards having a 68010 chip, with the more modern and faster MVME147 board having 68030 CPU and 68882 floating point units.

The station system currently returns real-time monitor data to the SUN computer in Socorro, but little software has yet been written for array-wide display of these data streams. This work will have very high priority in late 1990 and early 1991.

There remain several enhancements to be added to the on-line system in 1991, as well as rewriting a couple of modest sized areas in which the initial design has proved inadequate. The latter includes improvements in the handling of station dependent data (e.g., collimation offsets, tape recorder parameters). The former includes security features, handling the greater flexibility available with the VLBA tape format, automatic diagnostic routines, and real-time fringes via the 4 Mb data buffer.

All of the hardware for the monitor and control system has now been purchased, except for items pertaining to the network communications, spares, and the CPU upgrades (this last should be ordered in September 1990).

The monitor and control hardware and firmware are now operating at the first five antenna stations. These include the standard interface boards for the receiving system, data acquisition system, and antenna control system; the utility monitoring system of the control building; the focus/rotation control for the subreflector mount; the weather station; and the station monitor and control computer hardware and software. These systems allowed the unattended remote control of antennas during observation and test runs.

Assembly of serial versions of these systems will be mostly completed in 1990. However, additions and modifications in firmware and hardware will continue to be added in 1991 to correct bugs, to improve safety during FRM maintenance, to improve weather and lightning resistance, and to improve computer reliability as evidenced by observational, test, and maintenance experience at the sites. Upgrades are planned for backup methods for vital functions such as computer reboot, monitor and control bus reboot, alarm monitoring, and improving station immunity to commercial power fluctuations.

Correlator

Work continues on the VLBA correlator. A major milestone was completed in July 1990 when NRAO authorized production of the "FX" chip after extensive tests of a modified prototype chip more than a year after receiving initial, and defective, sets of prototype chips from the manufacturer. Most board fabrication by vendors is nearing completion. Other electronic parts procurement is well underway. During the remainder of 1990 and all of 1991, the two channel, seven station subset of the VLBA correlator will be assembled and tested at NRAO's Charlottesville laboratory. Correlator software development and testing continues apace. The subset correlator is scheduled for delivery in December 1991 to the Array Operations Center. Expansion of the correlator to the full VLBA eight channel, 20 station configuration will be implemented in Socorro during 1992.

Post Processing

Programming work continues to add to the AIPS package the programs necessary to process VLBA data. Purchase commitment for mini-supercomputers is scheduled for October 1991.

BD76N01 K Stetten
14-Sep-90 09:52 AM
VLBA BUDGET AND COST ESTIMATE (Constant $)

	1983,4	1985	1986	1987	1988	1989	1990	1991	1992	TOTALS
ANT STARTS/INSTLS		1/1	3/1	2/2	2/2	3/2	0/3			
SITES	32	194	2,204	1,605	1,171	2,036	2,754	174	190	10,360
ARRAY OPNS CTR			33	19	41	1,414	100	2,130	345	4,082
ANTENNAS	1,088	2,460	6,540	5,180	5,090	5,734	1,111	893	205	28,301
ELECTRONICS	533	1,573	1,652	2,045	1,277	2,201	1,678	1,682	1,046	13,687
DATA RECORDING	298	424	4	906	1,242	1,092	687	2,446	2,405	9,504
MONITOR CONTROL	63	94	316	549	376	596	459	108	9	2,570
CORRELATOR	322	133	196	370	895	619	814	523	272	4,144
POST PROCESSING	0	0	0	75	61	97	149	275	3,070	3,727
SYST ENGINEERING	54	86	76	24	0	0	0	0	0	240
MISC & SPARES	0	0	0	16	122	560	538	701	0	1,937
PROJ MGT& SUPPORT	272	374	606	657	590	510	496	456	328	4,289
OPNS TRAINING	0	12	49	26	0	0	0	0	0	87
EXPENDITURES	2,663	5,350	11,676	11,472	10,865	14,859	8,786	9,388	7,870	82,928
CONTINGENCY	N/A	N/A	N/A	N/A	N/A	N/A	188	227	187	602
PERCENT CONT.	0.0	0.0	0.0	0.0	0.0	0.0	2.1	2.4	2.4	0.7
NEW FUNDS (1990 $)	2,806	9,000	8,552	11,400	11,600	11,800	10,700	9,615	8,057	83,530
CARRYOVER from prior years							(1,726)			
PROJECTED carryover from prior years										

BD76N01
14-Sep-90
VLBA BUDGET AND COST ESTIMATE (Current $)

	1983,4	1985	1986	1987	1988	1989	1990	1991	1992	TOTALS
INFLATION (%)	0	0	0	0	0	0	0	4	4	4
ANT STARTS/INSTLS		1/1	3/1	2/2	2/2	2/2	0/3			
SITES	32	194	2,204	1,605	1,171	2,036	2,754	181	206	10,382
ARRAY OPNS CTR	0	0	33	19	41	1,414	100	2,215	373	4,195
ANTENNAS	1,088	2,460	6,540	5,180	5,090	5,734	1,111	929	222	28,354
ELECTRONICS	533	1,573	1,652	2,045	1,277	2,201	1,678	1,749	1,131	13,840
DATA RECORDING	298	424	4	906	1,242	1,092	687	2,544	2,601	9,798
MONITOR, CONTROL	63	94	316	549	376	596	459	112	10	2,575
CORRELATOR	322	133	196	370	895	619	814	544	294	4,187
POST PROCESSING	0	0	0	75	61	97	149	286	3,321	3,989
SYST ENGINEERING	54	86	76	24	0	0	0	0	0	240
MISC & SPARES	0	0	0	16	122	560	538	729	0	1,965
PROJ MGT& SUPPORT	272	374	606	657	590	510	496	474	355	4,334
OPNS TRAINING	0	12	49	26	0	0	0	0	0	87
EXPENDITURES	2,663	5,350	11,676	11,472	10,865	14,859	8,786	9,764	8,512	83,946
CONTINGENCY	N/A	N/A	N/A	N/A	N/A	N/A	188	236	202	626
PERCENT CONT.	0.0	0.0	0.0	0.0	0.0	0.0	2.1	2.4	2.4	0.7
NEW FUNDS, Current $	2,806	9,000	8,552	11,400	11,600	11,800	10,700	10,000	8,714	84,572
CARRYOVER from prior years							(1,726)			
PROJECTED carryover from prior years										

File: FIN74N02 JChavez
17-Sep-90

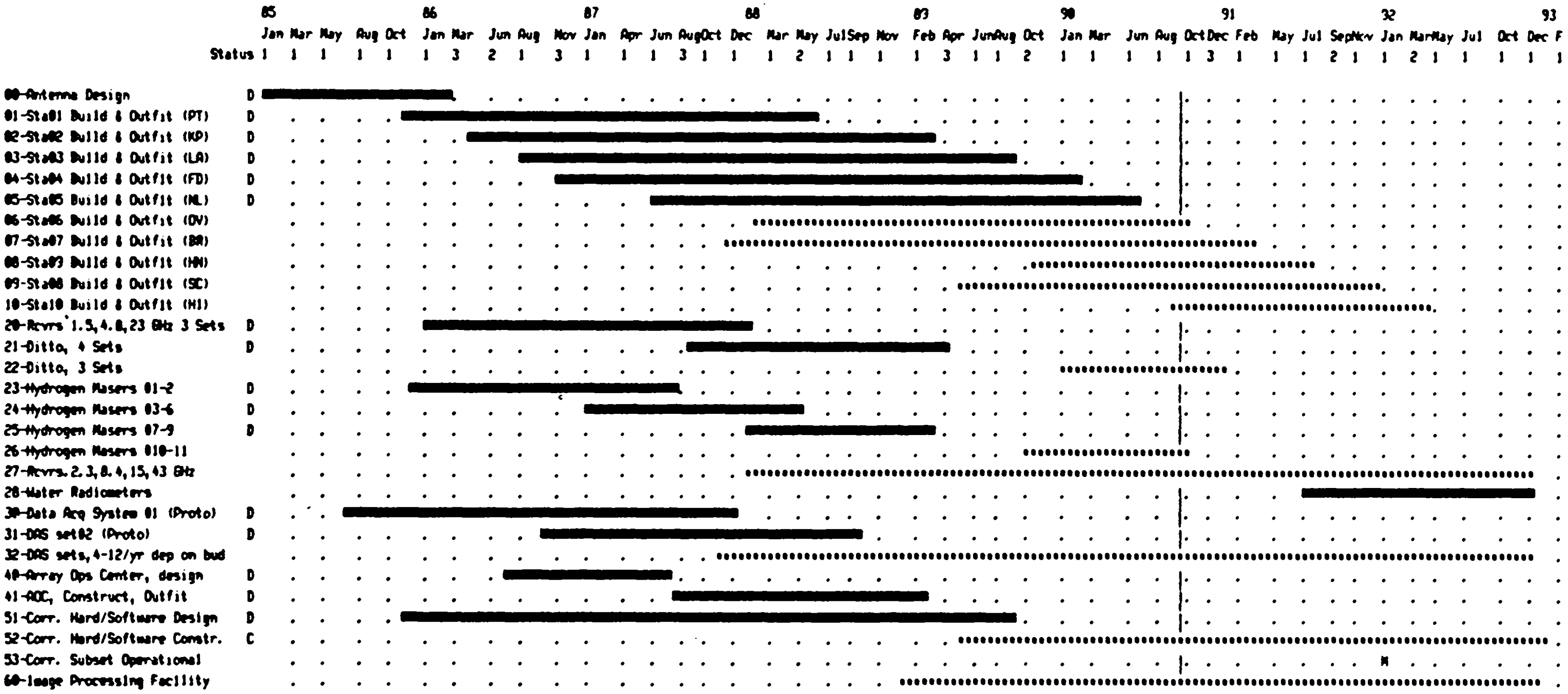
1991 Financial Plan VLBA Constant'90	Effort	Salaries & Wages	Benefits (@ 27.5%)	Materials & Services	Travel	Contract Charges	Total
Sub-project	Man-months	$k	$k	$k	$k	$k	$k
Sites	6	29	8	137	0	0	174
Antennas	96	289	79	45	90	390	893
Electronics	252	526	145	971	40	0	1682
Data Recording	24	97	27	1092	5	1225	2446
Monitor & Control	12	13	4	81	10	0	108
Correlator	108	406	112	0	5	0	523
Data Processing	24	75	21	169	10	0	275
System Engineering	0	0	0	0	0	0	0
Array Oper. Center	0	0	0	2130	0	0	2130
Spares	0	0	0	701	0	0	701
Project Management	90	268	74	94	20	0	456
Operations Training	0	0	0	0	0	0	0
Planned Commitments	612	1703	470	5420	180	1615	9388
New Funds, 1991							9615
Carryover from prior years							0
Net Contingency, $K							227

File: FIN74N02
17-Sep-90

1991 Financial Plan VLBA Current '91	Effort	Salaries & Wages	Benefits (@ 27.5%)	Materials Services	Travel	Contract Charges	Totals
Sub-project	Man-months	$k	$k	$k	$k	$K	$K
Sites	6	30	8	142	0	0	180
Antennas	96	301	82	47	94	406	930
Electronics	252	547	151	1010	42	0	1750
Data Recording	24	101	28	1136	5	1274	2544
Monitor & Control	12	14	4	84	10	0	112
Correlator	108	422	116	0	5	0	543
Data Processing	24	78	22	176	10	0	286
System Engineering	0	0	0	0	0	0	0.
Array Oper. Center	0	0	0	2215	0	0	2215
Spares	0	0	0	729	0	0	729
Project Management	90	279	77	98	21	0	475
Operations Training	0	0	0	0	0	0	0
Planned Expenditures	612	1772	488	5637	187	1680	9764
New Funds, 1991							10000
Carryover from prior years							0
Net Contingency, $K							236

Schedule Name: VLBA SCHEDULE OVERVIEW
Project Manager: Peter Napier
As of date: 18-Sep-90 7:33am Schedule File: C:\TLDATA\VLBAOV11

An approximate bar chart keyed to Budget RD70N01



D Done ▬ Task - Slack time (▬—), or
C Critical ••• Started task Resource delay (—▬)
R Resource conflict M Milestone) Conflict
r Rescheduled to avoid resource conflict p Partial dependency
Scale: Each character equals 12 days

TIME LINE Gantt Chart Report Strip 1

2. GREEN BANK TELESCOPE

The process of evaluating the several proposals for the design and fabrication of the Green Bank Telescope (GBT) will occupy the project staff during the last quarter of CY 1990. It is anticipated that an acceptable proposal will be identified and that a mutually satisfactory contract will be negotiated by the end of the quarter.

This Program Plan assumes that final approval of the contract will be obtained early in 1991, and that funds will be committed under the contract. The most urgent aspect then is the design of the foundation. The contractor will be authorized to proceed with the design of the foundation using the concept of the telescope as the basis. After approval by the NRAO of the design, the construction of the foundation will be started, probably in early summer. The bulk of the concrete, an estimated 5000 cubic yards, will be poured before the onset of cold weather in the late fall. The foundation and the other associated site work will be completed in the first quarter of 1992. The project engineering staff will monitor this work, the first tangible sign of the telescope at Green Bank.

Once the design of the foundation has been completed, the contractor will devote the bulk of his resources to the design of the telescope itself. It is anticipated that this will require close coordination with the NRAO design engineers, especially if the final design closely follows the original NRAO/JPL concept. As the design proceeds, every effort will be made to identify long-lead items, and procurement or fabrication of such items will be authorized at the earliest time possible, consistent with prudent management. Thus, it is planned that at the end of this program year the engineering staff will be occupied in the supervision of the final stages of the foundation and site preparation, in the review of the intermediate phases of the antenna design, and in the approval of the initial stages of antenna procurement and fabrication. Undoubtedly some members of the project staff will be temporarily resident at the contractor's manufacturing facility to provide oversight.

The surface of the GBT will have the capability to be adjusted. Initially the adjustment will provide only for compensation of the gravitational deformation. Actuators from five manufacturers have been ordered, and in the early part of 1991 will be evaluated under conditions appropriate to the anticipated use on the GBT. A final selection of the actuator system will be made on the basis of these tests, and the procurement of the systems will be initiated.

In a second stage, still under development, it is envisioned that the surface figure will be measured by an infrared laser, and the results used to correct the figure for slowly varying deformations arising, for example, because of thermal gradients in the structure. Tests on a prototype laser ranging device will be continued in this program year. The device will be equipped with a computer-controlled mirror to permit measurement to several targets. A test panel will be erected, complete with retroreflectors and actuators. The laser ranger will be used to position this panel remotely, in a manner similar to its intended operation on the GBT.

As delivered from the contractor, the GBT will point with an rms accuracy of 14 arcsec, using traditional techniques. While this is satisfactory for operation at decimeter and long centimeter wavelengths, it is not sufficient to support observations at long millimeter wavelengths. It is the intention of the NRAO to provide an accurate pointing system which will be added to the telescope. During the next year, evaluation of a number of possible fine-pointing methods will continue. The fine pointing performance that is required will likely be achieved in two stages. The first stage--a scheme to detect distortions in the structure beneath the elevation axis--will be pursued by the purchase and evaluation of various commercially available optical instruments. The second stage, a more ambitious scheme using a system of laser rangers to reference the surface and feed structure to points on the ground, will be developed and evaluated. Installation of a prototype system on an existing telescope, such as the 140 foot, is a possibility that is being discussed.

In the period covered by the Program Plan the GBT Electronics group will concentrate on four main areas. With the antenna geometry now fairly well understood, it is possible to begin the design and manufacture of the several different prototype feeds that are representative of the feeds that will eventually be required. The design of the local oscillator system will be started, and the synthesizers that are at the heart of the system will be selected. This work will proceed in tandem with the study of the problem of the distribution of both the LO and the Intermediate Frequency signals. It appears that a useful first step in exploring new techniques that might be applied to the LO/IF distribution is to install a fiber optic transmission system on the 140 foot telescope, where it can be used for routine operation. Such a test will provide an excellent environment for establishing the performance of optic cables in this application, and for identifying any problems which might arise. Finally, a start will be made on the receiving systems of the GBT. At this early stage the concentration will be on system design, on the specification of components which will be common to all receivers, and on research into wide-band polarizers. Fabrication of actual receivers will be deferred to later years.

Activity in the area of Monitor and Control will increase sharply, as staff are hired. The overall concept of the system will be developed, and the specification of the various protocols needed to facilitate communication among the many pieces of computer-controlled equipment will be completed. The principal tasks that the group will focus on include the basic telescope drive, the control of the actuators which set the surface of the telescope, the precision pointing system, and the interfaces with the various receivers and telescope monitor points. Some work will also be done on the data analysis system, but the effort on the Monitor and Control will dominate.

To successfully complete the heavy program of NRAO design and development, while monitoring the progress of design and fabrication under the antenna contract, it is necessary to increase the personnel over the twelve now working for the project. Of the eight new persons to be assigned to the GBT in 1991, four will be electronics engineers or technicians, and three will be computer programmers or software designers. A secretary will be added to the Project Management.

Project Plans CY 1992-1994

The design of the GBT will be completed early in 1992, and the necessary detailed drawings will be available by the middle of the year.

Fabrication of the telescope, starting with the long-lead items in 1991, will continue throughout the entire year. After the foundation and related site work have been finished, in the spring of 1992, the contractor will begin staging the material and fabricated pieces at the Green Bank site.

Project engineering staff will be responsible for the Quality Assurance at the contractor's plants, and for the supervision and monitoring of the fabrication and assembly work on the site. The increased activity will require the addition of a field engineering supervisor. The acquisition of the actuators for the active surface will continue, and the design of the surface position monitoring system will be finished. The effort on receivers will accelerate, with the addition of another engineer. Ongoing activities include work on the LO/IF system, the monitor and control system, and the data reduction system.

The GBT will begin to take shape in 1993, when the first major components are lifted into place. Fabrication of telescope parts will be continuing throughout the year, but by the end of 1993 most of the contractor's activities will be centered at the site in Green Bank.

The project staff will remain at the same level as in the previous year. All electronics development will be in full swing. The software development will have progressed to the point at which some of the interfaces with the computer-controlled devices must be tested. Examples include the actuator control, certain of the electronics controls, and possibly even a preliminary interface with the telescope drive control.

The GBT erection will be finished in the middle of 1994. At that point outfitting of the antenna will begin, as will the various acceptance tests. By the end of the year it is hoped that the telescope tests will have been completed, the GBT will be accepted and the contract completed, and that the electronics and software will be ready. The project itself will be completed early in 1995 when the first astronomical observations are made.

GBT Project

($ in thousands)

	1989	1990	1991	1992	1993	1994
Authorization	500	4410	69580	0	0	0
Expenditures	263	1500	25000*	21000*	16080*	10647*

* These are preliminary estimates which are subject to change depending upon the antenna contract procurement schedule.

VII. MAJOR NEW INITIATIVES

1. MILLIMETER ARRAY

The Millimeter Array (MMA) is a fast-imaging telescope situated on a high-altitude site and optimized so as to provide high-fidelity images in the λ 1 mm (200-360 GHz) spectral region. The MMA features flexible spectral-line and continuum capabilities in the atmospheric windows between 9 mm and 0.9 mm. The expected MMA sensitivity results from a combined collecting area of 2000 m^2 achieved with forty antennas of 8-m diameter. The antennas are transportable, and the MMA is reconfigurable into any of four configurations, whose dimensions are set by the need to match the Array's angular resolution to a wide range of astrophysical investigations. Imaging resolution at λ 1 mm will range from $0\overset{''}{.}07$, for the largest 3 km configuration, to 3" for the compact, 70-meter configuration (with the latter configuration providing essentially complete u-v sampling).

The MMA is a unique instrument. It is the only synthesis telescope conceived and designed as a complete imaging instrument capable of measuring accurately all spatial frequency components, from zero to the maximum array baseline. Partially, the motivation for such a complete instrument comes from the spatial complexity of the sky at millimeter wavelengths and the interrelationship of astrophysical phenomena on a wide range of spatial scales. (For example, do sites of nascent star formation--cold cores--within extended GMCs evolve from, or initiate, specific local changes in the cloud chemistry?) And partially, the motivation derives from the experience of imaging with existing synthesis array telescopes, all of which have identifiable limitations. The design of the MMA incorporates remedies for the deficiencies recognized in existing synthesis arrays. Thus the MMA provides those capabilities that will be essential for continuing progress in millimeter wavelength astronomy during the next decade and beyond.

The MMA is a versatile imaging instrument which emphasizes the following capabilities.

- Sub-arcsecond imaging at 115 GHz and higher frequencies;
- Wide-field imaging (mosaicing);
- Rapid imaging "snapshots" of high fidelity;
- Sensitive imaging at high frequency (≤ 350 GHz);
- Simultaneous multi-band operation;
- Comprehensive single dish observing.

High sensitivity implies that the total collecting area of all the individual elements in the array should be made as large as possible, while fast imaging is achieved by distributing the collecting area over many elements. The precise requirements of how many elements and the size of the individual antennas is then decided by minimizing the total array cost. Sub-arcsecond imaging places a constraint on the array dimension: 0".1 at 230 GHz, for example, requires an array that includes baselines extending to 3 km. Finally, sensitive imaging at high frequency demands that the MMA be located on a high altitude site with excellent atmospheric transparency. Considerations such as these have defined the design of the MMA. The unique imaging capabilities of the MMA are amplified below.

<u>Rapid Imaging Capability</u>. The MMA will be of special value for observations which must be completed quickly. Here "quickly" can mean

within a few seconds, or perhaps a few minutes, or it may mean within a day or two. But, in any case, many vital projects must necessarily be finished in a time short compared with the time needed to physically move antennas. For this class of research it is not feasible to improve the u-v coverage by repositioning antennas--the phenomenon to be studied, the requisite atmospheric transparency, or the scale of the investigation requires short integrations.

The need for rapid imaging is most crucial for the construction of wide field mosaic images. One must be able to observe rapidly a raster of adjacent fields with sufficient instrumental stability and reliable enough calibration to enable one not only to image each field but also to combine all separate images into a coherent whole. Since the u-v coverage in each separate field must be good enough to produce a well sampled image even though the data extends over one or a few hour angle ranges, the "snapshot" capability of the array must be nearly complete. Excellent instantaneous u-v coverage is a prerequisite for an array to image wide fields.

Mosaics of wide fields are needed to address many questions regarding:

- the kinematics and chemical evolution of giant molecular clouds through the star formation stage;
- the gas content and distribution in galaxies; and
- the pressure of the hot (10^7-10^8 K) gas within clusters of galaxies.

<u>Sensitive Imaging Capability at 230 and 345 GHz</u>. A cornerstone for the science proposed for the MMA is its capacity to provide well-sampled, high resolution images at frequencies corresponding to the J = 3-2 and J =

2-1 transitions of the common molecular tracer CO and its isotopomers at the appropriate Doppler shifts. Spectroscopically, many important questions involve the spatial distribution and kinematics of molecular material. Such questions are best addressed by observations of strong lines of an abundant, and widely distributed, constituent. Carbon monoxide fulfills these requirements. In the continuum, observations at 250 and 350 GHz provide a high resolution, uncontaminated, view of the emission from thermal dust grains and solid surfaces. Owing to the steep spectral dependence of thermal emission, one can obtain this particular insight only by observing at wavelengths of one millimeter and shorter. A wealth of scientific opportunities is opened to astronomers given access to an imaging instrument at these wavelengths.

Wideband/Multiband Capability. The ultimate goal of astrophysical research is to reach an understanding about the nature and evolution of objects in the universe. Rarely is such an understanding reached with observations at only one particular wavelength. So it is perhaps not surprising that the scientific demands placed on the millimeter array emphasize wideband and multi-band capabilities. Wide bandwidths increase continuum sensitivity, while a true multiband facility allows the astronomer to explore the relation of information in one band to that in another. Both capabilities are important to the scientific value of the MMA; together they make it unique.

The MMA Proposal - The instrument to realize these scientific capabilities has been defined by the NRAO in consultation with the user community and other technical experts. A summary of the MMA specifications is given below:

Array --	
Number of Antennas	40
Total Collecting Area	2010 m^2
Total Resolution	0″07 λ (mm)
Antennas --	
Diameter	8.0 m
Precision	$\lambda/40$ at 1 mm
Pointing	1/20 beamwidth
Transportable	
Configurations	
Compact	70 m
Intermediate (2)	250, 900 m
High Resolution	3 km
Frequencies --	
Emphasis on	200-350 GHz
Capability at	70-115 GHz; 9 mm
Desirable	Simultaneous multi-band
Site	
High Altitude--suitable for precision imaging at 1 mm	

A proposal to the National Science Foundation, that such an instrument be constructed, was submitted in July of 1990 Major construction is planned to begin in 1994 following two to three years of detailed design work. The total cost is expected to be approximately \$120M. Operations could begin in 1998.

2. VLA-VLBA CONNECTION

The proposed VLA-VLBA connection will close the "intermediate resolution gap" which will make possible for the first time "scaled array" observations with the same angular resolution at different frequencies. The interpretation of radio observations depends on measuring how all the Stokes parameters vary with frequency over a wide band at a fixed resolution. These observations lie on a vertical line in Figure 2, and without filling in the "intermediate resolution gap," are possible only at a resolution of about 3 arcsec.

The doubling of the VLA resolution made possible by the use of the Pie Town antenna, and of the VLBA resolution by the addition of 3 mm receivers appears modest compared with the very large increase in resolution which these instruments already have over other instruments. However, a factor of two in resolution can be critically important to many types of observations. For example, it reflects the difference between a site with "good" optical seeing (~ 1 arcsec) and one which is truly superb (< 0.5 arcsec), for which optical astronomers will go to remote sites to achieve. With the addition of four new antennas, and by using the Los Alamos VLBA antenna as well, the imaging capability of the VLA will be improved by nearly an order of magnitude.

For many astronomical problems, the VLA does not have adequate resolution, and the VLBA will give good imaging properties only on angular scales greater than those which correspond to the minimum spacing of about

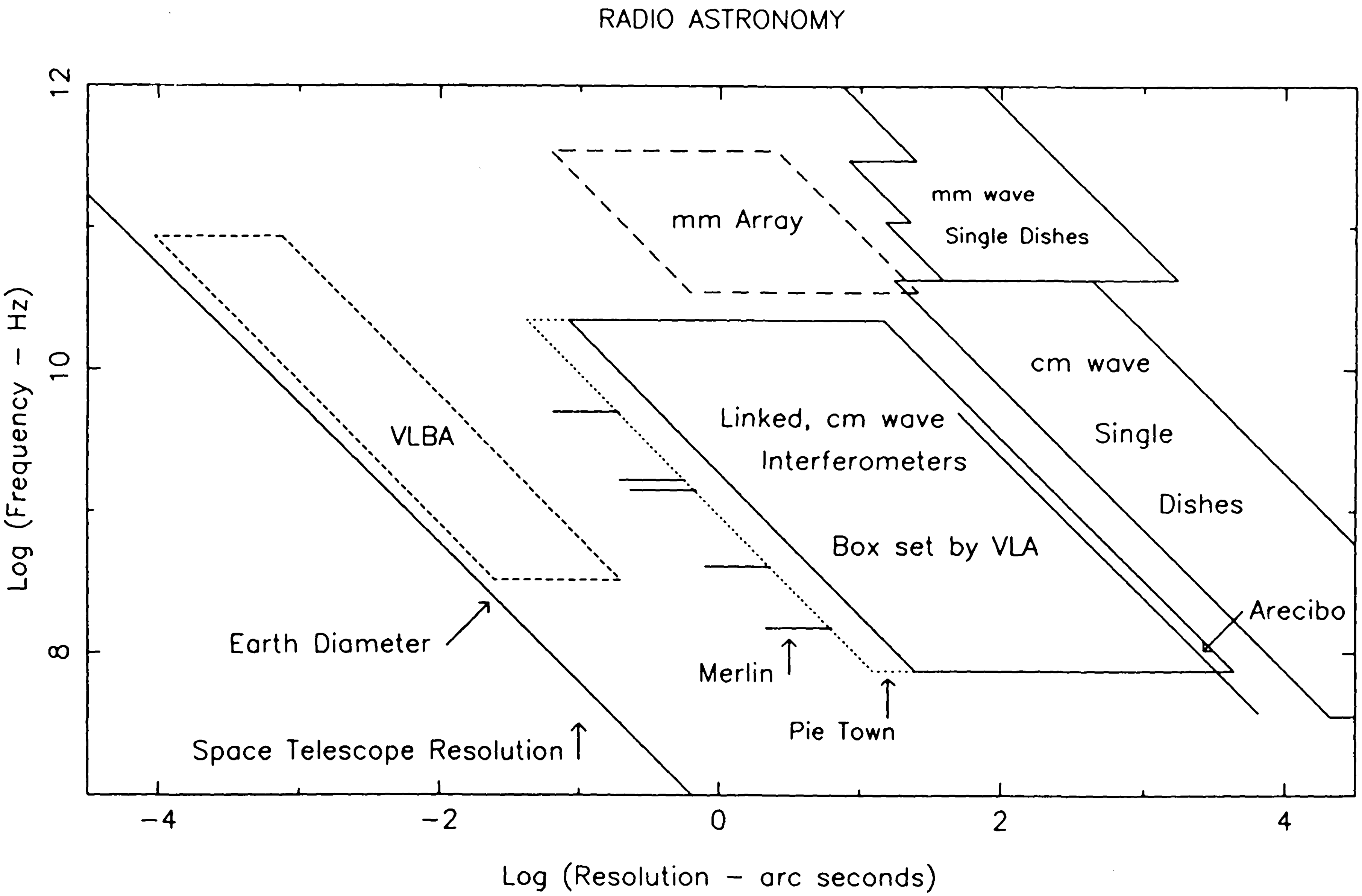

RADIO ASTRONOMY
Log (Frequency – Hz)
12
10
8
Log (Resolution – arc seconds)
−4
−2
0
2
4
mm Array
mm wave
Single Dishes
cm wave
Single
Dishes
VLBA
Linked, cm wave
Interferometers
Box set by VLA
Arecibo
Earth Diameter
Merlin
Pie Town
Space Telescope Resolution

Figure 2.

250 km. Between 35 and 250 km, roughly corresponding to angular resolutions of 0.01 to 0.1 arcseconds at centimeter wavelengths, there is a gap in antenna spacing corresponding to resolutions of interest to a wide range of astronomical problems and which is particularly important for studies of stellar and extragalactic sources. The required intermediate spacings may be implemented to a limited extent by providing the necessary communications between the existing VLA and VLBA antennas, but high quality imaging requires the construction of new antennas to provide the missing spacings intermediate between the VLA and VLBA.

The location of the Pie Town and Los Alamos VLBA antennas was chosen to partially sample this range of spacings, and so that the later construction of four additional antennas located at Dusty NM, Bernardo NM, Vaughn NM, and Holbrook AZ could provide complete imaging on these intermediate scales.

The following modes of operation will be possible with the combined 33 element array and may be implemented in stages.

- Using several VLA antennas independently with the entire VLBA to provide short-baseline data for VLBA imaging, by placing up to four VLBA backend systems at the VLA site. Each VLBA backend would allow a VLA antenna to participate independently in observations with the full VLBA using both polarizations at 100 MHz bandwidth. By dividing the available IF channels between several VLA antennas, more than four VLA antennas could be used simultaneously with the VLBA at narrower bandwidth for experiments in which inner uv coverage is more critical than sensitivity per baseline. Processing would be done at the VLBA correlator, which can handle up to 20 stations. This first step requires equipping four VLA antennas with VLBA recording systems, but does not involve the construction of any new antennas.

- The Dusty, Bernardo, and Pie Town antennas together form a 70 km extension of the VLA, while the Vaughn, Holbrook, and Los Alamos antennas extend the array to a total of 250 km. These six antennas could be operated together with the VLA as a real time, fully phase stable array to extend the resolution of the VLA by nearly an order of magnitude. This mode exploits the superb sensitivity of the VLA. Alternately, by using tape recorders at four VLA antennas, the VLBA will be able to image sources up to an order of magnitude larger than at present. In this mode the sensitivity is less than that of the real time expanded VLA because of the bandwidth restriction imposed by the tape recording system.

3. SUBMILLIMETER TELESCOPE

Recent initial results from the effort to develop a laser metrology system for the GBT have been very promising and, if they continue to be successful, they could form the basis for the construction of a large aperture, submillimeter telescope by employing an active surface. A national submillimeter facility that builds on the pioneering work of the Caltech Submillimeter Observatory and Univ. Arizona/MPI Submillimeter Telescope is a logical step in long-range national plans for this spectral region. NRAO will keep abreast of developments in submillimeter astronomy, become involved in the technology required where possible and appropriate, and foster opportunities for collaboration in submillimeter astronomy, with the long-term goal of establishing a national facility.

VIII. FACILITY MAINTENANCE, UPGRADING, AND EXPANSION

1. MAJOR MAINTENANCE PLAN

The past several years of very restricted budgets have severely limited the Observatory's ability to keep up with maintenance requirements. Some of the needs, such as the VLA track and electrical power systems, have attracted widespread attention. Others, although less visible, are also important. At present, NRAO allocates what funds it can to maintenance on the basis of urgency--safety and impact on operations being the criteria. The funding must be increased, by several million dollars spread out over the next five years, if we are to catch up.

Very Large Array

The VLA Rail Track System. The VLA rail track system consists of two standard gauge railroad tracks which run along each 13-mile arm of the array. During operations the antennas rest on concrete foundations 100 feet from the main rail line. Each station is connected to the main line by a short spur rail line and a track intersection. There are about 80 miles of (single) track in the system. The combined weight of the transporter plus the antenna is about 300 tons. With 24 wheels on four trucks, this gives a loading of 50,000 pounds on each of the 12 axles, high but not unusual load in the railroad industry. The track system currently has about 800,000 feet of (single) rail on the main line and 46,000 feet in the antenna spurs. There are 190,000 ties and 72 intersections. The entire track system was constructed with used materials. The rail, for example, dates from 1902 to 1956.

Since the VLA began full operation in 1980, the rail system has received inspection and a modicum of upkeep. Now, at roughly ten years of age for much of the system, more major maintenance is required. The main, but not the only, problem is a deterioration of the rail ties. This has become serious because the rate of deterioration has accelerated beyond what would normally be expected. In particular those ties that came from wet regions of the U.S. are deteriorating rapidly in the dry conditions of New Mexico. A second major concern is the deterioration of the spur intersections. These intersections are the weakest elements in the system. Other maintenance items in the track system besides the ties are: replacement of clogged ballast; realigning, gauging, and upgrading antenna spur lines; replacing bad rail sections; repairing and smoothing joints; and cleaning and dressing ballast.

Rail maintenance is now done by a four-man VLA rail crew augmented by seasonal help. In the past year a tie extractor and a surplus ballast tamper have been added to the rail maintenance equipment. Tie replacement is continuing at about 3500 ties per year. The condition of the rail system is gradually improving. Over the next few years, while the tie maintenance program continues, increased effort will be made in aligning the spurs and redesigning and rebuilding the intersections. This last item is the major cost share of the rail maintenance program.

The Power Distribution System. Electrical power is supplied to the antennas of the VLA by buried cable running along the arms--three cables, one for each phase, per arm, operating at 12.45 kV. These cables were installed between 1974 and 1980. The type of cable selected was highly recommended and in wide use throughout the U.S. by electric utility companies. The extruded polyethylene insulation on these cables is now known to be subject to failures which increase rapidly in rate with cable age. Experience with the cable at the VLA is following the industry-wide pattern.

Polyethylene cable deteriorates with age owing to a process known as "treeing." A "tree" is a growing channel which propagates through the insulation, probably due to ion or electron bombardment. The number and size of trees in a cable is primarily a function of time in service, operating electric field strength, and the presence of manufacturing impurities. As treeing progresses, the dielectric strength of the insulation deteriorates until voltage surges due to switching transients or nearby lightning strikes break down the insulation and the resulting arcing produces a ground fault. The only solution is to replace the power cables. Steps to slow the cable degradation and minimize the disruption of operations will allow the cable to be replaced over many years. The total cost is estimated to be approximately $1.35M. About 25 percent of the cost has been borne by NASA as part of the Voyager/Neptune encounter project, and all cable has been replaced to the ends of the C-configuration at NASA expense. For 1991, the goal is to finish the recabling out to the end of the B configuration. This will represent the completion of 30 percent of the array, but leaves 420,000 feet of cable yet to be laid. At present installation rates it would take six to seven years to finish recabling. Funds to double the installation rate are included in the major maintenance line of the budget projections table at $150k per year.

Other maintenance needs at the VLA comprise a long list of smaller items: overhaul of antenna transporters and installation of new transporter control systems, overhaul of electrical generators and upgrading of electrical power system controls, rebuilding of waveguide manholes, bringing fuel storage tanks into compliance with new regulations, replacement of machinery and selected vehicles, and improvement of painting facilities. The VLA site road system is badly in need of maintenance. The large "cherry-picker" crane needs to be replaced.

Green Bank

Many of the maintenance requirements at Green Bank are related to environmental/health considerations. The sewage treatment plant must be modernized. The water tower must be painted inside and out, and a water filter system installed. Asbestos must be removed from the old 300-foot telescope control building. The recreation area requires a new well. Various buildings require new roofs. Finally, superficial cracks in the concrete of the 140-foot telescope pedestal must be grouted and sealed.

12-Meter Telescope

Within two or three years the fabric covering on the 12-meter telescope dome must be replaced. The estimated cost approaches $400k. Other 12-meter telescope needs include replacing the trailers that house visitors, adding a sun screen to the dome to prevent damage by the sun and wind, and repaving the road.

2. ARRAY TELESCOPE COMPUTING PLAN

Since the original design goals were specified in 1969, the power of the VLA for imaging radio sources has increased steadily. The following table gives the changes in selected image parameters.

Development of VLA Imaging Power

	Goal 1969	Achieved 1980	Achieved 1988
Speed (images per day)	3	200	200
Image size--Routine (pixels)	128x128	512x512	1024x1024
Image size--Maximum (pixels)	512x512	1024x1024	4096x4096
Spectral Line Channels (full array)		8	512
Dynamic Range--Routine	100:1	500:1	2000:1
Dynamic Range--Maximum	100:1	2000:1	100,000:1
Maximum Sensitivity (mJy)	0.1	0.05	0.005
Resolution (arcseconds)	1	0.1	0.07

Each increase shown in the above table has required computing resources beyond those originally anticipated. The growth in demand for computing resources has outstripped our ability to provide them within the annual operating budgets of NRAO. Only a small fraction of the scientific investigations that are exciting but exceptionally computer-intensive can now be supported. The operation of the VLBA is expected to increase the computing demand by 65 percent over the demands of the VLA alone. In order to rectify this situation, the NRAO submitted to the NSF in September 1987 a proposal, "Array Telescope Computing Plan," which creates a joint VLA/VLBA computing environment suitable for the needs of both arrays.

The essence of the plan is the recognition that the imaging burden of the synthesis arrays covers a broad spectrum: some observations require only modest computing resources while others may require the full power of a large supercomputer. Given this distribution, the design of the appropriate computing facility for VLA/VLBA imaging incorporates hardware resources which span the same spectrum from the modest to the very powerful. Doing this is cost effective and leads to a plan for a computing facility which is a combination of computers, of varying computational capacity, loosely coupled together.

From a careful estimate of the mix of scientific programs that we expect to be run on the VLA and VLBA, once the latter is fully operational, we conclude that 60 percent of the total projected computing demand will originate from VLA users, with the remaining 40 percent coming from VLBA users. But only 10 percent of the VLA projects and one percent of the VLBA projects account for over 70 percent of the computing demand. These computing intensive projects will be handled at supercomputer centers, either national (NSF) facilities or other supercomputer centers where NRAO users have access. NRAO does not plan to operate a supercomputer center itself. The outline of the computing plan is shown schematically in Figure 3.

Data from the remaining 90 percent of the array telescope projects will be processed at an NRAO computing facility, or at the user's home institution, or most likely, at some combination of both. We have assumed in this plan that the burden of processing the data from these projects will be shared equally between NRAO and user home institution facilities. The NRAO facility is to consist of a networked set of second-generation

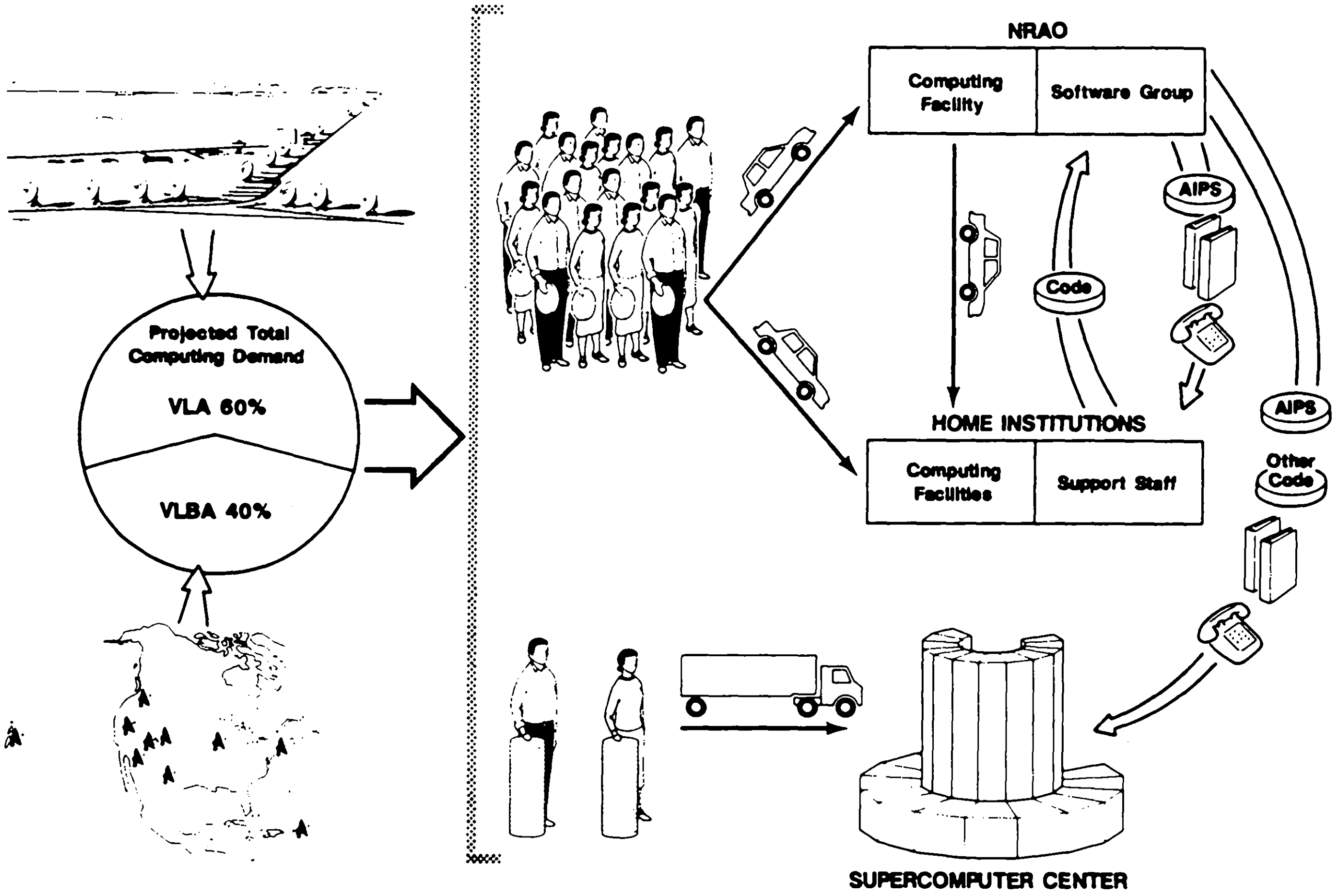


Figure 3. - An illustration of the main features of the Array Telescope Computing Plan. The off-line computing requirements of the VLA and the VLBA will be met by computers at the NRAO, at users' home institutions, and at supercomputer centers. The data processing needs of about 90% of the users will be met at the proposed NRAO facility and/or at their home institutions. A few users with extremely computer-intensive projects will take their work to supercomputer centers. The NRAO will directly support computing outside the Observatory by exporting and documenting AIPS and other code, and by communication with staff at our users' institutions and at supercomputer centers. Code developed at user institutions will also be imported for inclusion in the NRAO distributed packages.

mini-supercomputers, high performance imaging workstations, and a mass storage and archive system.

The software plan for the proposed computing system has three elements:

- Continued development and support of AIPS for use at NRAO and export to other facilities, including supercomputer centers and user home institutions;
- Research in image processing, including new algorithm developments that will be incorporated into AIPS;
- Code optimization for efficient use of the machines available.

In 1988 the Array Telescope Computing Plan was reviewed by the NSF Division of Astronomical Sciences and received highly favorable reviews by our (anonymous) colleagues in astronomy and computer science. Nonetheless, the plan was not funded owing to overall budget limitations within the Astronomy Division. In the meantime the total world-wide computing resources devoted to VLA image processing and AIPS *outside the NRAO* continues to increase. The NRAO now provides only one-fifth of the total computing power dedicated to data processing in AIPS whereas in 1986 it provided one-half. The results of the latest (December 1988) AIPS site survey revealed that computing resources equivalent to two Cray X-MP processors running full-time are dedicated to AIPS. In a very tangible way, this demonstrates the enormous computing needs of astronomers engaged in radio astronomical imaging. Unfortunately, it is also sobering to realize that two full-time Cray X-MP processors are but one-sixth of the dedicated resources we estimate in the computing plan that are required by astronomers using the VLA and VLBA to process data for projects that do not require the power of a large supercomputer. Radio astronomy is seriously under-computed. The need for the realization of the computing plan remains urgent.

The Observatory has updated the Array Telescope Computing Plan. An Addendum to the Array Computing Plan re-examines the scientific needs, reviews the hardware implementation, and reassesses the plan for software and algorithm development. The basic philosophy of the Plan remained the same following this review. The incremental equipment and costs associated with implementation of the computing plan are included in the budget schedules.

3. VLA CORRELATOR REPLACEMENT

The VLA provides a maximum bandwidth of 100 MHz, obtained by a pair of separately tuned, 50 MHz wide IF bandwidths. These bandwidths were set by technological limitations current some fifteen years ago and can now be greatly expanded. In conjunction with greatly improved IF transmission capability, a full 1 GHz bandwidth, in each polarization, can be implemented. A 2 GHz capability is even possible in the future The new correlator will make the VLA a much more powerful and flexible spectroscopic instrument. It will allow more spectral resolution and targeted spectral coverage of up to eight frequencies with the same observing band.

Virtually all current observing is sensitivity-limited, if not in total intensity then in polarization. The planned improvement in sensitivity of up to an order of magnitude will make possible a wide range of programs and studies not now possible. In particular, it will further expand the emphasis of the VLA on targets of astrophysical interest rather than those selected on the basis of the strength of their radio flux. One of the greatest impacts of the VLA has been its speed which has allowed the study of meaningful samples of objects in acceptably short observing periods For short "snapshot" observations, the bandwidth increase may be used to increase the speed by an order of magnitude or by using bandwidth synthesis to greatly improve the image quality.

The increased bandwidth will greatly benefit imaging of large objects, especially at high resolution. Bandwidth synthesis, in which the visibilities generated by a spectral line correlator are individually gridded for the image, will be used to obtain a spread in the effective baseline for any pair of antennas corresponding to the range of frequency used. The new correlator will also mean greatly increased sensitivity and field-of-view as the current correlator forces drastic reduction in sensitivity in order to obtain wide fields of view.

A 1 GHz correlator may be implemented using eight pairs of oppositely polarized IFs, each 125 MHz wide. These IFs need not be contiguous, so that at higher frequencies, where much more than 1 GHz of tuning is available, different frequencies of particular interest can be utilized. The 125 MHz wide IFs would be digitized at the antennas, and the digital signals sent to the correlator through optical fiber links. Recent technical advances in high speed digital circuitry may also permit sampling of up to 2 GHz bandwidth before sampling.

One gigahertz bandwidths will not, in general, require new antenna feeds since all bands except 20 cm and 90 cm already allow this bandwidth. There are, however, great rewards in redesigning the 20 cm feed to allow both greater efficiency and wider tuning range, especially below the current limit of 1250 MHz, to allow high redshift searches of HI. To better observe the molecular transitions of ammonia, a wider bandwidth feed at 1.3 cm is desirable. Increasing the bandwidth to 2 GHz would require new feeds at all bands.

The VLA correlator is based on a custom designed ECL circuit that has since found widespread use in other radio astronomy applications. By modern standards, however, the bandwidth and spectral resolution of the VLA is correlator limited. This has greatly restricted the kind of research done with the VLA due to the inability to do wide field imaging and high spectral resolution line searches, such as looking for redshifted hydrogen. The present correlator only supports a 100 MHz (in each polarization) IF bandwidth, which limits the sensitivity to continuum sources.

Modern correlator design, based on the FX approach, removes these limitations and is especially suited to arrays with large numbers of elements, such as the VLA. The VLBA correlator is being built on this architecture. The new VLA correlator might provide 1024 channels of spectral resolution in each of the eight pairs of IFs being returned from the antennas. Full polarization will be available with the same number of channels except with perhaps a reduction to 512 channels when using the full 1 GHz bandwidth.

Although a 27-station correlator is needed to support the VLA, the design will permit the easy expansion to 33 stations necessary to support Pie Town and Los Alamos as well as the four proposed new antennas. In the interim it will be possible to replace one of the VLA antennas with the one at Pie Town in order to exploit the added resolution available for some types of observations that correlate the Pie Town antenna together with 26 VLA antennas.

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

In the second stage of the project, a fiber optics link will be run to the Los Alamos VLBA antenna as well as to the four new antennas at intermediate spacings between the VLA and the VLBA.

IX. 1991 Preliminary Financial Plan
Table 1
(NSF Funds, $ in thousands)

	Personnel	Salaries, Wages & Benefits	Material, Supply, Service	Travel	Total
Operations					
General & Administrative	24	$1,187	$804	$100	$2,091
Research Support	46	3,044	409	170	3,623
Technical Development	15	730	120	15	865
Green Bank Operations	65	2,876	265	27	3,168
Tucson Operations	28	1,348	435	35	1,818
Socorro Operations	117	4,934	2,395	65	7,394
VLBA Operations	49	1,723	508	90	2,321
Management Fee			520		520
Common Cost Recovery			(50)		(50)
Total Operations	344	$15,842	$5,406	$502	$21,750
Equipment					
Research			0		0
Operating			0		0
Total Equipment			$0		$0
Design and Construction					
VLBA	46	2,443	7,357	200	10,000
GBT Design & Construction	19	1,116	68,394	70	69,580
Millimeter Array Design	2	90	900	10	1,000
Total Design & Const.	67	$3,649	$76,651	$280	$80,580
TOTAL NSF	411	$19,491	$82,057	$782	$102,330

IX. Preliminary Financial Plan
Table 2
(NSF Funds, $ in thousands)

	New Funds	Uncommitted Carryover Funds from 1990	Total Available for Commitment	Commitments Carried Over From 1990	Total Available for Expenditures
Operations					
Personnel Compensation	$12,453		$12,453		$12,453
Personnel Benefits	3,487		3,487		3,487
Travel	502		502		502
Material & Supply	4,838		4,838	200	5,038
Management Fee	520		520		520
Common Cost Recovery	(50)		(50)		(50)
Total: Operations	$21,750		$21,750	$200	$21,950
Equipment					
Research Equipment	$0	$150	$150	$100	$250
Operating Equipment	0	0	0	0	0
Total Equipment	$0	$150	$150	$100	$250
Total: Operating & Equipment	$21,750	$150	$21,900	$300	$22,200
Design & Construction					
VLBA Construction	$10,000	$300	$10,300	$2,500	$12,800
GBT Design	69,580	3,363	72,943	150	73,093
Millimeter Array	1,000	0	1,000	0	1,000
Total: Design & Construction	$80,580	$3,663	$84,243	$2,650	$86,893
TOTAL NSF PLAN	$102,330	$3,813	$106,143	$2,950	$109,093

October 2, 1990

X. Budget and Personnel Projections

Table 1

(NSF Funds, $ in millions)

	1991	1992	1993	1994	1995	1996
Operations						
Base Operations	19.405	21.300	22.600			
VLBA Operations	2.345	5.000	7.600	34.900	36.800	38.700
Major Maintenance (1)	----	0.700	1.000			
Array Computing Plan (2)	----	0.600	1.600			
Total Operations	21.750	27.600	32.800	34.900	36.800	38.700
Equipment						
Research & Operating	----	1.000	1.000	1.300	1.500	1.700
Array Computing Plan (3)	----	2.100	2.000	3.000	----	----
VLA Receiver Upgrade ($9.5M)	----	1.800	2.300	2.200	1.200	----
Total Equipment	0.000	4.900	5.300	6.500	2.700	1.700
Total Operations & Equipment	21.750	32.500	38.100	41.400	39.500	40.400
Construction						
VLBA ($85M)	10.000	8.714	----	----	----	----
GB Telescope ($75M) (4)	69.580	----	----	----	----	----
Millimeter Array ($120M)	1.000	2.000	5.000	30.000	30.000	30.000
VLA Correlator Upgrade ($20M)	----	----	1.000	9.500	9.500	----
VLA - VLBA Link ($31M)	----	----	----	----	9.000	9.000

PERSONNEL PROJECTION (Full Time - Year End Ceiling)

	1991	1992	1993	1994	1995	1996
Base Operations	294	319	323			
VLBA Operations	49	90	97	447	456	458
Array Computing Plan	-	6	13			
VLBA Construction	47	7	-	-	-	-
GB Telescope Construction	19	21	21	20	-	-
Millimeter Array D & C	2	8	10	25	50	60
VLA - VLBA Link	0	0	0	0	12	15
Work for Others	16	18	19	20	21	18
Personnel Total	427	469	483	512	539	551

NOTES:
1) Incremental to on-going maintenance which includes routine minimum-level VLA track system and electrical cable replacement.
2) Incremental operations costs beyond those budgeted for computing in VLBA operations.
3) Incremental equipment costs beyond those budgeted for computing in VLBA construction.
4) Tables show NSF obligations; estimated NRAO expenditure schedule - $25.0M ('91), $21.0M ('92), $16.1M ('93), $10.6M ('94)

APPENDIX A

NRAO SCIENTIFIC ACTIVITIES FOR THE YEAR 1991

The NRAO permanent staff will investigate a number of topics in a variety of research areas during 1991, as described below. Visiting scientists will collaborate in some of this research.

1. The Sun

As the solar cycle approaches its maximum level of activity many observations are planned to study radio emission specifically associated with the active sun. Special attention will be focussed on the correlation of simultaneous X-ray and VLA imaging data during the course of a solar flare. Together these data will be used to trace the evolution of the electron distribution function. In addition, the VLA on-line control system will be modified to allow effective integration times of 200 milliseconds. Such fine resolution will permit studies to be made of time-of-flight effects during the impulsive phase of solar flares and to investigate the relation between radio solar microbursts and hard X-ray microflares. Observations of this kind will provide powerful new constraints to theories of impulsive flares.

2. Stars and Stellar Remnants

2.1. Stellar Radio Emission

The presence of nonthermal radio emission is a discriminating characteristic of the collapsed remnant of evolved stars--pulsars, and X-ray binaries, for example--while thermal radio emission, either in the continuum or in molecular spectral lines, is a signature of young stars or those shedding their outer envelope as they evolve along the giant branch. Both classes of objects will be studied intensively.

Recent VLA observations of very short time scale radio flux variations in V404 Cyg, Sco X-1, Cyg X-3, Cyg X-1, LSI+61303, and SS433 will be analyzed and modeled in terms of optically thick, relativistic plasma regions closely coupled to the accretion disk environment. If successful we will begin to understand the source of the subtle variations that occur in these energetic objects when they appear quiescent. A closely related project will deal with a very detailed analysis of the radio, optical, and X-ray data of the X-ray transients GS2000+35 and GS2023+336 (V404 Cyg). A preliminary interpretation invokes particle acceleration in quasi-perpendicular shocks to produce rapid bursts of particle acceleration in the X-ray binary environment. Finally, the proper motion studies of the radio lobes associated with the bright X-ray source Sco X-1 will be further constrained by a ninth year of monitoring observations on the VLA.

Pulsars will be observed both to study their period evolution and as probes of their formation kinematics. Accurate positions are needed for both studies. Using a grid of VLBI sources near strong pulsars, the VLBA will be used to establish pulsar proper motions and parallaxes to unprecedented accuracy. For the specific pulsar PSR 1758+24, it has been suggested that this object has "rejuvenated" the nearby supernova remnant G5.4-1.2 as it catches up with the decelerating shell. With the determination of a sufficiently precise position for the pulsar, this idea can be tested.

The thermal radio continuum emission from classical novae permits quite different questions to be addressed. In particular, the three frequency light curves of Hercules 1987 and Cygni 1986 will be used to estimate the lifetime of the optically thick ionized ejecta, the velocity of ejection, and the density gradients in the nova shell. Thermal molecular emission from the envelopes of evolved stars will provide similar information as well as insights into the circumstellar chemistry. Silicon monoxide masers will be used as probes of the inner envelope region where stellar mass loss begins, whereas VLBI observations of a large sample of OH masers will be used to infer the strength and distribution of magnetic fields throughout the envelopes surrounding late-type giant stars.

Finally, interaction of the outflowing circumstellar material with the external medium will be investigated in several ways. The central problem to be addressed is the seemingly paradoxical observation that the more complex molecules in circumstellar shells lie at successively larger distances from the central star where one would expect the large interstellar ultraviolet flux to make conditions especially harsh and unfavorable for the persistence of complex chemistry.

2.2. Emission Nebulae

Planetary nebulae, novae, and supernovae present exciting research opportunities in 1991. The density structure in planetary nebulae, usually modeled as an inverse square gradient with distance from the central star, has been found in several nebulae to more properly described by an equatorial toroid of nearly constant density. This surprising result and the kinematic signature that the toroids are seen bathed in winds approaching 100 km s^{-1} will be investigated further by imaging observations with the VLA and 12-meter telescopes.

The rate of expansion of planetary nebulae envelopes can also be observed directly by a time series of careful VLA images taken over several years. This technique will be extended in 1991 providing, for several planetary nebulae, a six-year time base of images. Combining these requirements of the angular expansion with optical radial velocity measurements will lead to a nebular distance determination much more reliable than that obtained through conventional statistical methods.

The surprising discovery of nonthermal radio emission from the presumably thermal shell of the old nova GK Persei will be examined in greater detail both in this object and in the nova V732 Sgr. Nonthermal radiation raises the spectra of particle acceleration processes operating within or at the interface of nova shells at energies one million times below those of supernova remnants. Particular insight into the process may be gained by observations of V732 Sgr because this is one of the two known novae for which light echoes have been seen. The presence of an echo indicates the existence of a dense shell of circumstellar material, and this may be the ingredient necessary for the production of a nonthermal remnant.

The far more energetic supernovae will be studied both by means of their radio emission at very early epochs and by studying the remnants of historical supernovae. The recent supernovae SN1979c, SN1980K, SN1986J, SN1988Z, and SN1990B will be observed to monitor their light curves and from this information to deduce the evolution of the energy content of these nebulae. The faint remnant G2.4+1.4 has recently been suggested to be not a supernova remnant at all, but rather a blister nebulosity formed by a fast stellar wind from an extraordinary Wolf-Rayet star Radio data to be obtained will constrain this hypothesis and determine whether the remnant is thermal or nonthermal and to examine the related question as to whether the peculiar star itself is the source of excitation for the nebula

2.3. Star Formation

Stars form in condensations called "cloud cores" within the larger environment of molecular clouds Although a census of the embedded stellar population within clouds is available for several clouds, a census of dense cores is complete for very few cloud complexes. The tally is most complete for the Rho Ophiuchus cloud, although little is known about the properties of most specific cores actively forming stars. To rectify this situation, VLA images in the spectral lines of ammonia and other tracers will be used to determine in each of the cores whether the core is collapsing, rotating, if it has become flattened, and whether its dynamical evolution is continuing or has reached equilibrium. An estimate of the mass of the prominent core IRAS 16293 in the Ophiuchus cloud will be made from measurements of the dust continuum emission from 0.3 to 1 mm. Previous observations show this object to be double (a proto-binary star?); the new observations together with high resolution CS(2-1) and formaldehyde mapping will be used to determine whether the second object is a star, whether both components originated in a common protostellar disk, or whether separate disks envelop the components.

Observations will be made of several other nearby molecular clouds to complete the census of cores. In the Orion cloud a series of ammonia observations are planned to measure the temperature of the known cores as well as to construct a preliminary census of the core population. In the DR21(OH) region a census just completed with the VLA will be extended to determine the core properties in this luminous cloud. In Taurus and several other clouds a search for cores will be made using large-scale observations of the thermal dust continuum emission at short millimeter wavelengths. Cores stand out as "hot spots" in the larger emission from the cloud owing to the localized increase in column density. From these observations we learn the physics of the dust emissivity, the dust opacity in the cloud, the mass of the cores, and the fragmentation of the cloud.

3. The Interstellar Medium

Questions involving the structure and composition of the galactic interstellar medium on both the largest and smallest scales will be addressed in the next year.

The large-scale structure of the interstellar medium is well described as a froth dominated by shells and bubbles of gas. An understanding of the energetics and energy transport in the interstellar medium depends on the determination of the prevalence, origin, and structure of the interstellar shells and superbubbles. Observations of atomic hydrogen will be used to establish the fraction of the ISM gas tied up in these structures or in old fragments of similar but pre-existing structures. In addition, estimates will become available from the same data of the fraction of shells that succeed in breaking into the galactic halo and hence transporting energy from the disk of the galaxy to the halo. HI and CO observations will be used to investigate specific interstellar shells seen in Orion to trace the interactions and interrelations between the molecular gas and the atomic gas.

At the other extreme, small-scale structure in the interstellar medium is observed in 21 cm absorption toward extragalactic objects and toward pulsars. Estimates of the smallest size scales, the HI turbulent scale, will be made using both these techniques. In the former case, HI absorption will be mapped across the milliarcsecond structure of VLBI sources while in the latter multiepoch observations of pulsars with high proper motions can be used to trace the structure of the ISM along lines of sight that differ by extremely small angles. The small-scale structure of the ionized component of the interstellar medium can be "observed" by the scintillation and angular broadening of OH masers from distant OH/IR stars. These observations also will provide a measure of the filling-factor and turbulence scale height in the inner galaxy.

4. Molecules and Astrochemistry

The emphasis in 1991 will be given to understanding the role of refractory compounds in the astrophysical environment. According to a recent analysis, both Mg compounds and P compounds, especially PO, will be detectable in cold molecular clouds. The biggest uncertainty presently is the lack of adequate laboratory data. Here the astronomical searches and laboratory spectroscopic work will usefully complement one another. In a related context, an investigation of the refractory compound silane (SiH_4) in circumstellar envelopes will reveal whether or not Si is depleted by adsorption onto grains. This will require mapping silane in large envelopes such as that in IRC 10216.

The understanding of shock chemistry will be pursued further by searches for shock-produced species such as SiO, C_3H_2, and H_2CO in molecular clouds exposed to external shocks. The role of chemistry on grains will also be assessed by studies of the ortho/para ratios in H_2CS and NH_2CN. If the relative excitation reflects equilibrium on grain surfaces, one would have a key indication that their formation process also included grain surface interactions.

5. Studies of the Galaxy

Galactic research has experienced a renaissance in recent years as new techniques and instrumentation provide exciting new opportunities We expect this trend to continue in 1991.

A clever way to determine the total mass of the galaxy will be evaluated. From VLA surveys of local group dwarf spheroidal galaxies, radio sources, both within those galaxies and in the distant background, will be cataloged. A comparison of the proper motion of the grid of local group galaxies relative to the grid of background sources, together with the radial velocity for each galaxy measured spectroscopically, will establish the orbit of each dwarf galaxy. The ensemble of galactic orbits will be used to determine the mass of the Milky Way galaxy, including all mass contained well beyond the optical disk.

The abundance, composition, distribution, and kinematics of gas in the halo of the galaxy will be revealed through a comparison of interstellar absorption lines and 21 cm HI emission lines. Resonance absorption lines, determined by IUE toward high latitude stars or by HST toward QSOs, will be compared with galactic 21 cm emission lines toward the same objects. In each case the 21-cm lines establish the total velocity extent of the ISM and, given this, the resonance absorption lines can yield abundance data for each specific velocity feature, each "cloud," along the line of sight.

In the heavily obscured interior of the galaxy which cannot be observed at optical/uv wavelengths, the extent of star formation will be probed by a fully sampled survey of H_2O masers. As water masers are among the earliest signposts of star formation, these lines are ideal probes of the distribution of current star-forming activity throughout the inner galaxy.

At the very heart of the galaxy lies the enigmatic compact object Sgr A^*. The variability of this object and its strong dependence of angular size on frequency imply, first, that the source is extremely small, less than 10 a.u. and, second, that the variability is due to an extrinsic cause, likely refractive interstellar scintillation. In addition to monitoring the variability, Sgr A^* will be observed by the VLBA to demonstrate the structural changes that refractive scintillation theories suggest accompany the time variation.

6. Normal Galaxies

For many important questions concerning the distribution of matter in galaxies, star formation and the circulation of matter within galaxies, studies of external galaxies are less ambiguous than the same studies in our own galaxy because we can observe the whole galactic disk with equal clarity. Thus the emphasis given to research in normal galaxies is not unlike the emphasis of galactic work.

The star-formation process will be investigated in very different galactic environments. First, an extensive compilation of the observations of the various forms of interstellar matter in elliptical and SO galaxies has been completed. The analysis of these data will bring into focus two questions: Are SO galaxies which contain substantial quantities of cold interstellar matter quantitatively different from the SO galaxies without such material, and does the sample of galaxies emitting X-rays offer clues about the putative cooling flows which can be used to help us understand the evolution of the interstellar medium in elliptical galaxies? In fact, the state and amount of interstellar gas in elliptical galaxies has been a mystery for several decades. With the advent of sensitive millimeter-wave instrumentation, it has become possible to search for molecular gas in ellipticals, and such studies will be pursued actively in the next year. From the existing observations, we tentatively conclude that (1) the "missing " gas is not hidden in the form of molecules; and (2) the ratio of H_2 to HI is similar to that observed in the nuclei of normal spiral galaxies.

The relation of star formation to energetic activity in very luminous galaxies will be the focus of several studies.

- The southern galaxy Tololo 1924-416 is a starburst galaxy in a particularly active stage. The IR/optical spectrum is consistent with emission from massive stars persisting for at least a million years. Radio observations will be undertaken to search for evidence of supernova activity, similar to that seen in M82, and to increase our understanding of the number and characteristics of star-forming regions.

- A study of the normal spiral galaxies NGC 3504, NGC 5005, NGC 5033, and NGC 5055 will investigate the relation between regions of nonthermal radio emission and star formation.
- Comparison of the radio properties of a large sample of extremely luminous far infrared galaxies with a sample of starburst and Seyfert galaxies will attempt to uncover the relation between these two classes of objects.
- A sample of blue compact dwarf galaxies in the Virgo cluster will be observed to determine their total hydrogen content. These dwarfs are thought to be blue because the star formation in the galaxies is enhanced by tidal interactions between neighboring galaxies. The HI observations will tell us of their kinematics and provide clues to their formation and evolution.

The larger question of the interaction between one galaxy and its immediate neighbors or the interaction of a galaxy with its environment has a wide variety of ramifications that will be explored in 1991.

The interacting galaxies Arp 143 and NGC 2793 will be studied in the context of recent theoretical models. The particular suggestion that these systems are early phases of a merged system such as Arp 220 will be tested by VLA observations. The dynamics of several interacting groups of dwarf galaxies will be established by means of 21 cm observations, and from this information an estimate will be made of their mass fraction contained in dark matter.

Work will begin on a search for companion HI clouds near HII galaxies. The working hypothesis is that these galaxies have undergone an interaction with a companion cloud or galaxy which has triggered the violent burst of star formation we witness now. In conjunction with the HI observations of these HII galaxies, observations will be made of the properties of their continuum radiation.

These observations should allow a separation of thermal and nonthermal emission to be made and, from this, an estimate of the strength and orientation of the galactic magnetic field as well as the efficiency with which the radiating relativistic electrons are confined within the galaxies.

The confinement of HI in disk galaxies, like the confinement of relativistic particles, presents problems requiring attention. High velocity clouds at large distances from the mid-plane of spiral galaxies are seen in the prominent galaxies M101 and M33. Such clouds could be the result of tidal interactions between neighboring galaxies, dynamical warps, or the breakout of HI superbubbles from the galactic disk. The observations planned will assess these various possibilities. In any case, the presence of the high latitude clouds are a valuable diagnostic of the mixing and evolution of the interstellar medium within a galaxy.

7. Radio Galaxies and QSOs

VLA observations will be made to elucidate the origin of fine structure in the radio jets and lobes in the powerful radio galaxies 3C 219 and 3C 353 Competing models of the "partial" or disappearing" jets in 3C 219 have been given, based in one case on episodic outbursts in the nucleus and in another on adjustments to lack of force balance within a steady jet. These models may in principle be tested and distinguished by new higher resolution VLA observations of putative shock structures within and around these jets. Models of the bright and (possibly) dark filamentation in 3C 353 based on plasma instabilities or on the anisotropic cooling of the emitting particles may also be tested at higher angular resolutions than are now available from VLA imagery of the source.

Radio observations of the "tailed" sources in rich clusters of galaxies have the potential to provide information both on the transport of energy in the radio galaxies and on the intracluster medium. Early indications, to be pursued by new VLA observations, are that in comparison with classical doubles, the radio powers of this class of radio sources are relatively low. The collimated radio jets often abruptly disrupt at a few tens of kiloparsecs from the nuclei and the diffuse tails extend up to a few hundred kiloparsecs. In addition, bright filaments are often seen in these radio sources. Theoretical analysis and numerical simulations suggest that the jets likely disrupt by their growing intrinsic body and surface waves. Behind the jet/tail transition, the flows become low Mach number turbulent plumes. It is important to study the particle acceleration processes in a turbulent flow at large scale. Both the magnetic and hydrodynamic Reynolds numbers may be large in turbulent tails. This then provides a source of cascades which can lead to subsequent particle reacceleration.

Indications of particle acceleration will also be studied in the fine-scale filamentary structure of the lobes of Fornax A, Cygnus A, Pictor A, Hydra A, and 3C 295. In the latter two objects the properties of the foreground Faraday depolarization will be used to infer the magnetic fields within and around the luminous cluster radio sources.

8. Parsec-Scale Radio Jets

The parsec-scale radio jets commonly seen in the nuclei of radio galaxies and QSOs by VLBI techniques contain the information which we can use to determine the origin, energetics and persistence of galactic nuclear activity. Several VLBI observations are addressed to these questions in 1991; among them are the following:

- The acceleration of nuclear radio jets will be studied by multi-epoch observations of 3C 84. The goal is to determine the jet velocity as a function of distance from the nucleus of NGC 1275.
- Between 1979 and 1988, the parsec scale structure of 3C 120 was monitored with VLBI. Preliminary results show that new components appear about once per year and travel away from the core at about 2.5 milliarcseconds per year, an apparent speed of about four times that of light. This data will provide a unique opportunity to study the evolutionary history of many superluminal components in a single source. It should help determine which characteristics are constant and which can vary from one component to another.
- Preliminary detections have been made of superluminal motions in 3C 120 on scales of 50 to 100 parsecs. These detections were based on two epoch observations with 18 cm VLBI. In late 1989, the third epoch

VLBI observations were made in an attempt to confirm the motions on the 50 to 100 parsec scale. These data have now been correlated and will be analyzed over the next year.

The differences in appearance of nuclear jets, and to some extent the differences in luminosity, are accountable within the "unified model" of relativistic sources as resulting from differences in our viewing perspective. The unified model makes specific predictions that are amenable to tests. In 1991, VLA measurements will be made of the internal proper motion of a radio knot in the asymmetric base of the twin-jet source M84 which is thought to be viewed close to edge-on. If the knot is seen to move with superluminal velocity, the simple beaming model would be inadequate to account for the observation.

The simple twin relativistic jet model also predicts few subluminal and asymmetric parsec-scale radio sources. Two are already known, 3C 84 and 3C 274, and further examples would undermine the model. NGC 3894 is another potential example for which multi-epoch data will be analyzed, and a velocity determined, in 1991.

Finally, the emerging field of polarization observations will be employed to measure the strength and orientation of the magnetic field in The nucleus of 3C 138 and in the radio knot at the bend in the jet of 0106+013 where the jet appears to collide with a gas cloud near the nucleus of this galaxy.

9. Radio Surveys

Survey observations provide the raw material from which many diverse investigations germinate. As such they are an important part of the research done at the NRAO. Again in 1991 considerable effort will be devoted to survey observations and their interpretation.

An extensive program to study the B3 survey of classical double radio sources in the radio and optical will continue. This study will attempt to extend the knowledge gained from the extensive studies of the 3CR sample to lower flux density levels. In the radio the plan is to finish the mapping of the sample with the VLA at 8 GHz in order to confirm the structural types of the sample and to detect the central components. Using the central component positions, optical identifications of the sample will be completed using deep CCD images from Lowell Observatory. Spectroscopy of the sample at KPNO and IR imaging with the IRTF are also planned for 1991. The long-range goal of the project is to test whether the correlation of radio structure with absolute radio and optical luminosity holds at high redshift and whether the redshift cutoff around 2-3 holds for these fainter sources.

VLA and optical studies of the statistical properties of radio galaxies in Abell clusters will continue The VLA finding survey for two samples of sources should be completed early in 1991. These two samples will allow the galaxies with radio luminosities over a range of almost four orders of magnitude to be studied. At the completion of the survey, the properties of the sample will be derived including the cluster luminosity function, the space density of radio galaxies in clusters, and the correlations with other cluster properties. More detailed VLA imaging and optical surface photometry are also planned for the sample in 1991.

A complete sample of 347 UGC galaxies in the declination band $+5° < \delta < +75°$ was identified with radio sources stronger than 25 mJy from the Green Bank 4.85 GHz sky maps made with the 300-foot telescope. The radio sources have been divided into two classes: those powered by stars and stellar remnants (starbursts), and those powered by black holes (monsters). Radio spectral indices have been measured for nearly all of these galaxies. For the first time, local spectral luminosity functions will be generated for the starburst and monster sources separately. A computer program will input these spectral luminosity functions, radio source counts obtained from 151 MHz to 5 GHz (with particular emphasis on the Green Bank 4.85 GHz counts recently obtained for 25 mJy < S < 10 Jy and VLA counts from 10 μJy to 25 mJy), and radio spectral index distributions to model the cosmological evolution of steep and flat-spectrum sources, starbursts, and monsters, independently.

Extragalactic infrared sources stronger than 200 mJy at $\lambda = 60$ μm from the new IRAS Faint Point Source Catalog were identified with sources stronger than 25 mJy at 4.85 GHz from the Green Bank sky maps, and these candidate identifications were recently confirmed or rejected with the aid of 4.86 GHz VLA D-array maps. Most of the identifications are with starburst galaxies that are quite strong ($S \sim 10$ Jy at $\lambda = 60$ μm typically) infrared sources, but a number of strong radio sources have been identified with a variety of weak infrared sources. Such radio identifications pick out the rare infrared quasars, BL Lac objects, elliptical radio galaxies, and systems of peculiar morphology that may be highly obscured Seyfert galaxies. This population of radio-loud infrared sources will be investigated during the next year.

Observations at 20 cm are planned of all 62 sources found above 16 μJy at 5 GHz in a survey area of 180 square arcminutes. The derived spectral index will be compared with the colors and optical properties derived from deep CCD optical images.

A systematic search for new radio supernovae in 103 nearby $(D \leq 20\ \mathrm{Mpc})$ bright $(B_T \leq +12)$ spiral galaxies will be continued with the VLA B-array at 4.86 GHz. Three epochs of data have been obtained at one year intervals, and the first two epochs have been mapped. Extinction by dust and confusion by stars do not affect the detection of radio supernovae. The existing maps demonstrate that Type II supernovae should be detectable essentially anywhere in the galaxies being monitored, so that their average Type II supernova rate can be measured.

10. Cosmological Studies

In 1991 fluctuations in the cosmic microwave background will be analyzed using a novel technique based on application of the VLA visibility data not on the sky images. The advantage of this technique is that it circumvents the problems in the interpretation associated with sidelobe contamination.

Further measurements will be made of the Sunyaev-Zeldovich effect, a distortion of the spectrum of the microwave background due to Inverse Compton scattering with 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 1 mK 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-Zeldovich distortion. Such small signals have to be confirmed by observations at other frequencies, especially so due to the past history of the observations of this effect as observers have failed to reproduce other observers results. The BIMA millimeter interferometer will be used to observe the Sunyaev-Zeldovich effect in the cluster 0016+16 at a frequency of 86 GHz. The observations will be made using a tessellating technique to measure the necessary short spacings.

Further attempts will be made to detect proto-clusters of galaxies through the observations of their (redshifted) 21-cm emission at a frequency of 333 MHz, thus probing a redshift of about 3.3. The VLA P-band system has been pushed to a sensitivity of better than 3 mJy/synthesized beam for spectral line channels of width 200 kHz. A number of tests located sources of interference; some of them were removed, others were dealt with by modifying the data-acquisition method and subsequent analysis. The analysis of the first 50 hours of observation has been completed and has uncovered some unexpected problems like the non-circularity of the VLA 300 MHz primary beam as well as a strong frequency dependence. No pancakes have yet been detected, but the data rule out structures of about 10^{14} $M_\odot$ in the surveyed volume.

11. Astrophysical Theory and Applied Studies

Objective ways will be developed to categorize the range and distribution of structural scales that are manifested in the radio lobes of strong extragalactic sources observed with the VLA. New tools are urgently needed to quantify the properties of multiple "hot spots" and complex filamentation that have been revealed by recent well-sampled high-dynamic range VLA images of radio galaxies and quasars. Methods based on reverse Fourier transformation of the images of individual lobes, on two-dimensional structure function analyses, and on brightness gradient (Sobel) filtering of VLA images will be developed and compared.

These methods will then be used to search for objective distinctions between properties of jetted and unjetted radio lobes in powerful extragalactic sources. They will also be used to characterize complex radio structures for comparison with the predictions of numerical MHD models of energy transport and synchrotron emission in radio lobes.

An analysis will also be made of the transfer of angular momentum within a disk galaxy, including the effect of viscous friction. The goal is to search for stable rotation states which may provide an explanation for the predominance of flat rotation curves in late-type galaxies.

A wide variety of theoretical and experimental studies will be pursued by the NRAO scientific staff that are oriented specifically to solve problems with the observing instruments or to enhance their capabilities. Among them are the following:

- An atmospheric monitoring program will be established with the VLBA to study effects on interferometer phase as a function of observing frequency, baseline length, and observing conditions.
- Phase calibration of the VLBA requires observations to be made of calibration sources very near each program source. The present list

of VLA calibrators is inadequate. To rectify this situation, observations will be made of nearly 1000 flat-spectrum sources north of declination 35 degrees chosen from the Green Bank 20-cm and 6-cm surveys. This work will produce a significant increase in the number of phase calibration sources and, as a by-product, a few new gravitational lens candidates should be uncovered.

- Problems experienced or anticipated resulting from propagation of radio frequency interference will be investigated and modelled. Preparations will be made to defend the allocations for radio astronomy at the 1992 World Administrative Radio Conference
- More detailed investigations will be undertaken of the causes of poor radio seeing resulting from turbulent conditions in the troposphere. The hope is that predictions can be made as to the onset of poor observing conditions.
- Studies will begin to define the instrumental techniques needed for orbiting VLBI. Issues to be studied include precise time transfer, very wideband data transmissions, precise orbit determination, space-qualified low-noise receivers, and space-qualified cryogenics.

APPENDIX B

SCIENTIFIC STAFF

(Does not include Visiting Appointments)

P. J. Andre - Star formation; molecular clouds; pre-main sequence stars; circumstellar disks; magnetic field

T. S. Bastian - Solar/stellar radiophysics; radiative processes; plasma astrophysics; particle acceleration; interferometry; image deconvolution and reconstruction

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

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

J. A. Biretta - Active galaxies; quasars; VLBI techniques

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

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

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

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

P. C. Crane - Normal galaxies; radio interferometry and aperture synthesis; radio-frequency interference

L. R. D'Addario - Theory of synthesis telescopes; superconducting electronics; millimeter wavelength receivers; radio astronomy from space

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

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

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

C. Flatters - VLBI polarization studies of extragalactic radio sources

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

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

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

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

B. Glendenning - Starburst galaxies; scientific visualization

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

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

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

R. J. Havlen - Galactic structure; clusters of galaxies

D. S. Heeschen - Variable radio sources; normal galaxies; QSOs

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

W. Junor - Extragalactic radio sources; VLBI

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

A. R. Kerr - Millimeter-wave development

J. W. Lamb - Millimeter-wave instrumentation

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

H. S. Liszt - Molecular lines; galactic structure

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

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

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

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

S. K. Pan - Development of millimeter-wave devices

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

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

D. Puche - Kinematics of spiral galaxies; dark matter; groups and clusters dynamics

M. S. Roberts - Properties and kinematics of galaxies

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

G. A. Seielstad - Quasars; active galaxies; VLBI

R. A. Sramek - Normal galaxies; quasars; astrometry

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

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

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

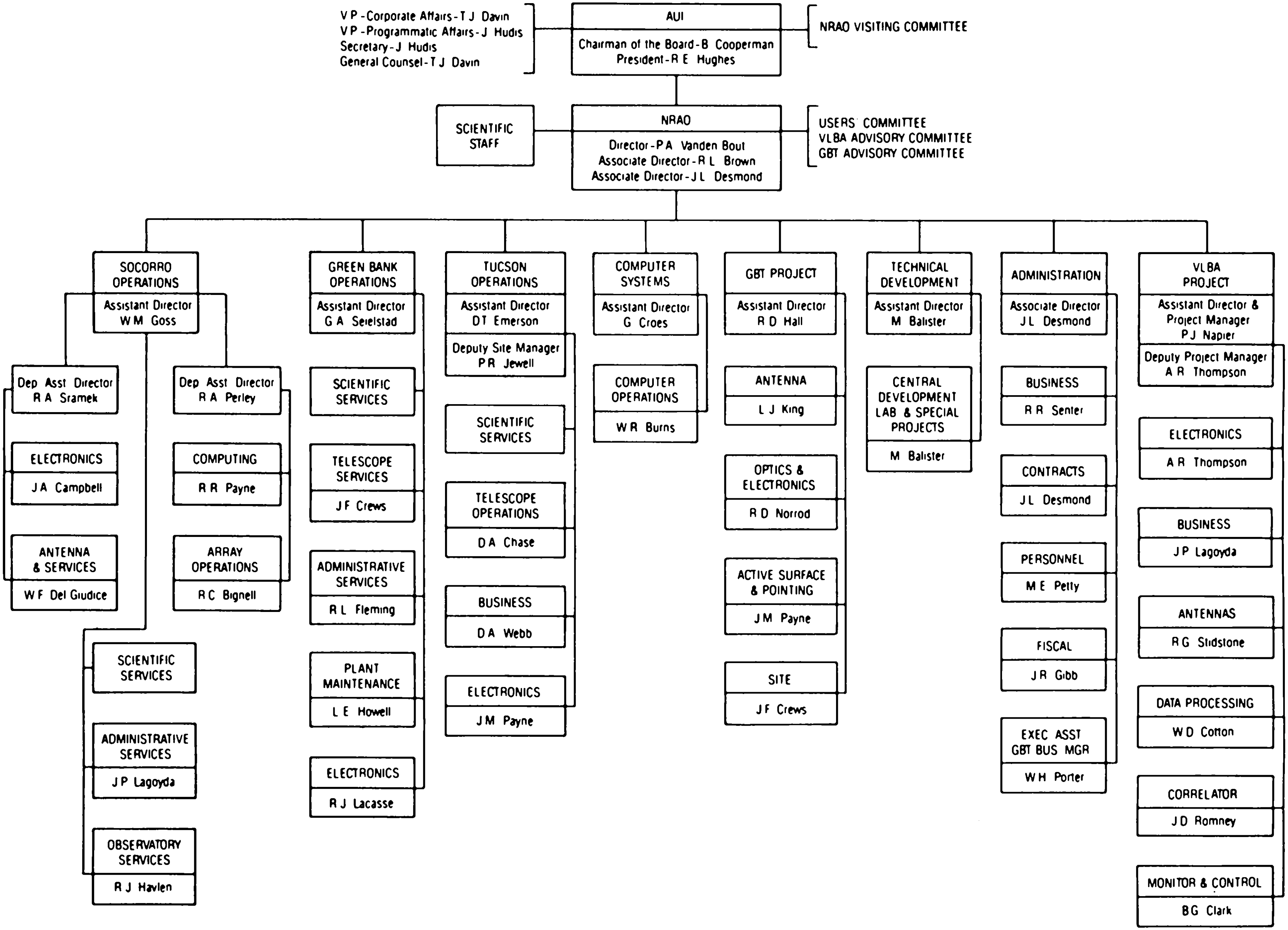
Q.-F. Yin - Normal galaxies; imaging techniques

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

J.-H. Zhao - Radio jets; galactic center; interstellar medium; clusters of galaxies; recombination lines

APPENDIX C

NATIONAL RADIO ASTRONOMY OBSERVATORY
ORGANIZATION CHART
1 OCTOBER 1990



APPENDIX D

NRAO COMMITTEES

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.

The current membership of the Committee is:

D. C. Backer, Chairman	California, Berkeley
F. N. Bash	University of Texas
M. H. Haynes	Cornell University
F. J. Low	Steward Observatory
A.C.S. Readhead	California Inst. of Technology
J. A. Tyson	Bell Laboratories

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.

The present membership is:

J. Bally	Bell Laboratories
C. L. Bennett	Goddard Space Flight Center
J. H. Bieging	California, Berkeley
J. Bookbinder	JILA/University of Colorado

F. H. Briggs	University of Pittsburgh
B. K. Dennison	Virginia Polytechnic Inst. & State U.
P. E. Dewdney	Dominion Radio Astrophysical Obs.
R. J. Dewey	Jet Propulsion Laboratory
J. Dreher	Ames Research Center
G. A. Dulk	University of Colorado
N. Duric	University of New Mexico
S. T. Gottesman	University of Florida
P. C. Gregory	University of British Columbia
M. P. Haynes	Cornell University
J. N. Hewitt	Princeton University
P. T. P. Ho	Harvard College Observatory
J. M. Hollis	Goddard Space Flight Center
S. Kulkarni	California Inst. of Technology
M. L. Kutner	Rensselaer Polytechnic Institute
A. P. Marscher	Boston University
C. R. Masson	Center for Astrophysics
D. O. Muhleman	California Inst. of Technology
R. L. Mutel	University of Iowa
L. J Rickard	Naval Research Laboratory
D. B. Sanders	California Inst. of Technology
F. P. Schloerb	Institute for Astronomy
D. B. Shaffer	Goddard Space Flight Center
S. M. Simkin	Michigan State University
R. S. Simon	Naval Research Laboratory
J. S. Ulvestad	Jet Propulsion Laboratory
A. E. Wehrle	California Inst. of Technology
J. M. Weisberg	Carleton College
L. M. Ziurys	Arizona State University

VLBA Advisory Committee

The VLBA Advisory Committee periodically reviews the status and progress of the VLBA. Its particular concern is with the broad elements of the project and especially those that directly influence the scientific capabilities and performance characteristics of the instrument. It advises on broad aspects of the design, scientific emphasis, and priorities as well as on general progress, to assist the Director and the project staff in assuring that the scientific and technical specifications are met and that the VLBA will be as responsive to the needs of radio astronomy as is possible.

The committee is appointed by the Director. It is composed of scientists and specialists whose interests encompass all areas of radio astronomy and technology of concern to the VLBA. An attempt is also made to maintain in the membership reasonable geographic distribution and representation of the major radio astronomy centers and foreign VLBA projects. The committee meets annually.

The current membership of the committee is:

D. C. Backer	University of California, Berkeley
R. S. Booth	Onsala Space Observatory
Y. Chikada	Nobeyama Radio Observatory
R. D. Ekers	Australia Telescope
D. Fort	California Institute of Technology
K. J. Johnston	Naval Research Laboratory
R. Porcas	Max-Planck-Institut fur Radioastronomie
M. J. Reid	Center for Astrophysics

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:

C. Heiles	University of California, Berkeley
R. A. Jennings	University of Virginia
J. D. Nelson	University of California, Berkeley
V. Radhakrishnan	Raman Research Institute
J. H. Taylor	Princeton University
P. Thaddeus	Center for Astrophysics
S. von Hoerner	Independent Telescope Consultant
S. Weinreb	Martin Marietta Laboratories
R. W. Wilson	Bell Labs