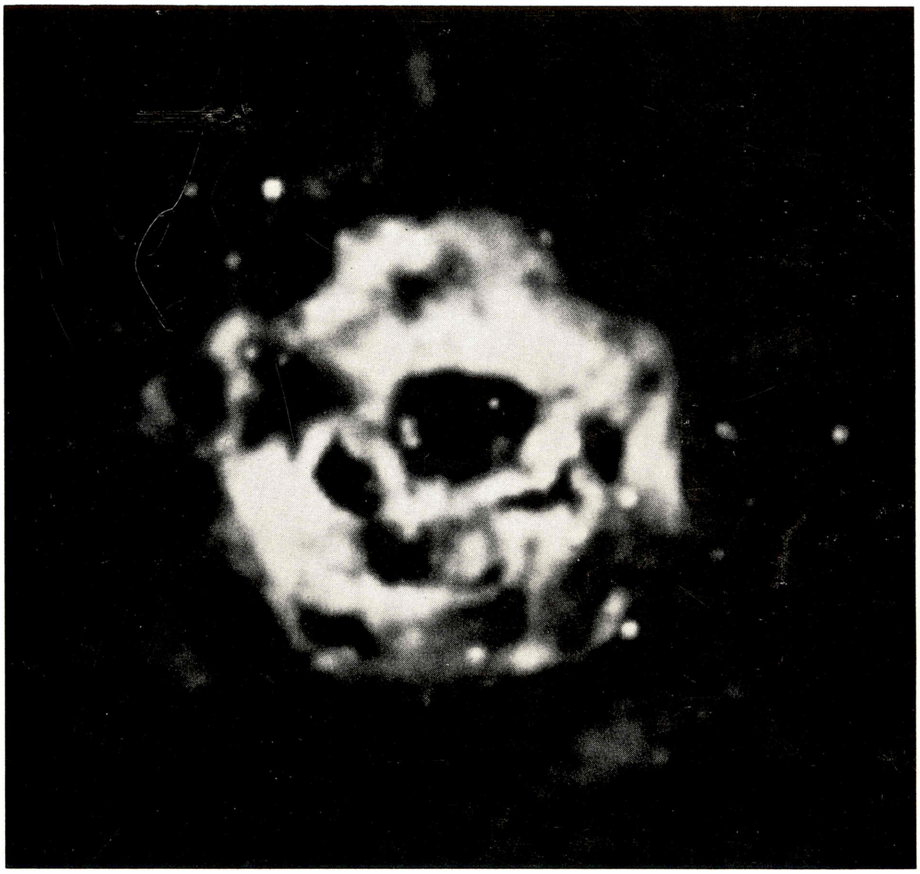
# NATIONAL RADIO ASTRONOMY OBSERVATORY





# PROGRAM PLAN 1988

# N A T I O N A L  R A D I O  A S T R O N O M Y  O B S E R V A T O R Y

## CALENDAR YEAR 1988 PROGRAM PLAN

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# I. INTRODUCTION

"There is no richer field of science opened to the exploration of man in search of knowledge than astronomical observation; or is there ... any duty more impressively incumbent upon all human government than that of furnishing means and facilities and rewards to those who devote their lives to ... success in these pursuits."
John Quincy Adams, 1842

The National Radio Astronomy Observatory is funded by the National Science Foundation under a management contract with Associated Universities, Inc. The Observatory operates major telescope systems for research in radio astronomy and carries out research and development in related fields of advanced technology and data processing.

The four major telescope systems operated by the NRAO for scheduled astronomical observations are: the 27-element Very Large Array telescope (VLA) located on the Plains of San Agustin, near Socorro, New Mexico; the 12-meter millimeter wavelength telescope on Kitt Peak, Arizona; and the 140-foot telescope and the 300-foot meridian transit telescope in Green Bank, West Virginia. Additionally, in 1987 test observations were begun with the first completed antenna of the Very Long Baseline Array.

Allocated observing time remains at a premium as all NRAO telescopes continue to be heavily oversubscribed. Increasingly sophisticated astrophysical problems require the assimilation of large multi-wavelength databases across the electromagnetic spectrum: radio astronomical observations are an integral part of contemporary research programs. A major goal of the NRAO has been the continual development of state-of-the-art instrumentation so as to widen the accessibility of broad regimes of the radio spectrum while at the same time to increase the instrumental resolution, sensitivity, and dynamic range. New technologies are rapidly transformed to practical working receivers and operating systems which expand the observing potential of existing telescopes.

Section II of this Program Plan summarizes the research that visiting investigators are planning to undertake with the NRAO telescopes during 1988. More than 70 percent of the available observing time will be used for this purpose.

Section III of the Plan describes the continuing research instrumentation developments which will take place at the Observatory during 1988. These include instruments which are used directly as integral elements of the telescope-receiver-computer data acquisition chain or which are part of the off-line signal and image processing and data-analysis scheme. The instrumentation expenditures fall equally heavily on the electronics and computer hardware areas. A dynamic electronics research and development effort is one of the driving forces behind the application of technological advances to astronomical instrumentation and therefore is a vital part of the NRAO. Likewise, imaginative approaches to the optimal use of available computer resources are crucial to the total astronomical data acquisition and analysis process. Highlights of the 1988 effort in these areas will include development of multi-beam receivers, spectrometers, and control hardware for millimeter-wave observations at the 12-meter telescope; the rapid installation of 327 MHz receivers and low-noise, K-band HEMT amplifiers on many of the VLA antennas; and completion of an extremely versatile and efficient spectral processor for spectroscopic and pulsar observations at the 300-foot telescope.

Subsequent sections give the detail of the expenditures required for operations and maintenance of the Observatory and their breakdown according to geographic cost centers. Included are specific sections to describe in detail the arrangements made by the National Science Foundation for the NRAO support of portions of the USNO and NASA programs in astronomy. Provision has been made for: (1) operation of the Green Bank four-element interferometer for the USNO (Section VI), (2) the production and installation of 8.4 GHz receivers for VLA support of the 1989 encounter of the NASA Voyager spacecraft with Neptune (Section VII), and (3) installation of a 75 MHz capability on the VLA with support from the U. S. Naval Research Laboratory.

Appendices to this Plan include a summary of the scientific programs of the NRAO permanent staff, a list of the staff and their principal research interests, an organizational chart for the NRAO, a list of various committees associated with the NRAO, and the 1988 VLBA Program Plan.

## II. SCIENTIFIC PROGRAM

The following summary, by telescope, illustrates the diverse range of scientific topics that have been proposed for observation during 1988 at the NRAO. Each of the programs has been designed to take advantage of the particular qualities of the NRAO instrument on which it is undertaken A part of the NRAO mission to the astronomical community lies in its obligation to provide forefront instrumentation to adequately meet the programmatic requirements of its scientific user community. The demand for telescope time is now higher than at any time in the history of the NRAO--a clear reflection of the impact that the sensitivity and versatility of the NRAO instrumentation continues to have on many areas of scientific interest.

### The Very Large Array

As a widely accessible, user-friendly, powerful, and productive astronomical research tool, the VLA stands out as overwhelmingly successful. Almost two hundred research papers annually attest to the acceptance of the instrument among a broad spectrum of researchers experienced in multiwavelength investigations on subjects ranging from solar physics to cosmology. Each year brings new improvements in software and hardware to broaden the research capacity of the instrument. A large fraction of the programs now make use of the VLA's multi-configuration design capability so that source morphologies on all resolution scales can be integrated into the physical analyses. Mosaiced images of important sources which subtend large areas of the sky can now also be produced.

Solar physicists using the VLA during 1988 have planned a major coordinated campaign to observe coronal magnetic structures while the Solar

Maximum Mission x-ray instrument is still operable. Ultraviolet supporting observations from SMM and ground-based H-alpha images and magnetograms are also planned. The rise of a new solar cycle presents an excellent opportunity to understand the physical relationship between the magnetic field which defines coronal loops and the hot plasma which it channels. Planetary studies with the VLA will primarily follow up previous studies. Observations of Jupiter at 327 MHz will help to refine our knowledge of the Jovian magnetic field and supplement information gleaned from spacecraft fly-bys. Further observations of the Saturnian atmosphere and ring system will complete the multiwavelength, multiconfiguration study of the planet with its ring system fully open. Observations of the Galilean satellites, Ganymede, and Callisto will be used to determine their surface thermal emissivities, when combined with existing radar results, can help us to visualize what the surfaces of these bodies must be like. Latitudinal variations in the abundances of ammonia and water in the atmosphere of Uranus will be studied.

The suitability of the VLA for numerous stellar research programs has been well proven during the past half-decade as radio wavelength results have appeared in the literature. The coming year will prove to be no exception. The VLA survey of active cool stars of spectral type F, G, K, and M will continue as a means of identifying those stars in which detectable microwave emission can serve as a valuable diagnostic of the star's chromospheric activity and coronal magnetic fields. Spectra of the newly discovered emitters will be sought in hopes of providing constraints on the radiation mechanisms of the quiescent, the slowly varying, and the burst emission. Systematic observations of two recent radio novae will be continued and supplemented with infrared and optical light curves as a means of determining the velocities and masses of the ejected shells. A study of flares on red-dwarf stars, in search of narrow-band emission, will assist in identifying possible emission mechanisms, such as plasma emission produced by a moving disturbance or electron-cyclotron maser emission. Exploratory observations of the newly discovered millisecond pulsar, PSR 1821-24, will be undertaken with potential benefits to fundamental timekeeping, astrometry, cosmology, and gravitational-wave detection.

VLA observations of supernova remnants and the circumstellar environment of stars, including planetary nebulae, provide a detailed look at regions influenced by the advanced stages of stellar evolution. Multi-configuration observations of the Crab Nebula supernova remnant are scheduled for completion in 1988. For the first time, radio images with a resolution comparable to optical images will be available, and questions regarding the detailed magnetic field structure of the Crab, the nature of the filaments, and the existence of radio proper motions can be addressed. Observations of the Cygnus Loop are designed to clarify the morphology and physics of the radio filaments and the interaction of the supernova remnant shock wave with the interstellar medium. In Kepler's supernova remnant radio observations are needed in order to understand the origin of the optical knots in the context of recent models. Remnants in the external galaxy, M33, will help test for the dependence of brightness on diameter in accordance with the predictions of theoretical models for remnants. For the planetary nebula NGC 6302, VLA hydrogen recombination line observations should facilitate the determination of the electron density and distance of the nebula. The mass loss environment of several evolved supergiant stars and Mira variables will be probed with observations of existing OH and $H_2O$ masers in their circumstellar envelopes.

The resolution and spectral line capabilities of the VLA are powerful tools for investigating star formation regions in the Galaxy. New observations will attempt to clarify the complex morphologies of the dense star forming gas in relation to known bipolar outflows. Knowledge of the energy balance and kinematics of the regions will be important in analyzing models of rotation, infall, or turbulence to explain the observational parameters of well-studied objects such as Cepheus A, AFGL 2591, or G10.6-0.4. For a number of highly luminous IRAS compact HII regions, the VLA will be employed to determine the multiplicity--single star or cluster--of the exciting sources and aid in determining the initial mass function of luminous stars in star formation regions. Another sample of IRAS sources will be surveyed in order to better define a new sample of Young Stellar Objects (YSO), ultimately to study statistically the inter-relationships between YSO activity, such as collimated mass outflow with the properties of the local environment, such as disks and mass accretion. In the region of Mon R2, ammonia line observations will be used to unravel the kinematics of a shell-like, high density structure, which is apparently produced by the pressure of supersonic outflow. A study of polarized extragalactic background sources in the region behind the high-velocity bipolar molecular flow in L1551 will help map out the magnetic field value associated with the star formation process. Hydrogen recombination line maps of several ultracompact HII regions will be obtained for a study of the small scale physical properties and dynamics of the ionized gas in order to test theories of how the arc-shaped ionization fronts are produced during important phases of massive star formation. Multiple frequency continuum observations of compact HII regions will help evaluate the amount of cold dust in those sources in comparison with the infrared and millimeter wavelength data on warm dust to get a full picture of the dust content of compact HII regions and its observational consequences.

Global parameters of the Galaxy and the interstellar medium, especially near the galactic center, will be the focus of many VLA programs. A possible detection of positronium in the direction of the galactic center will be thoroughly pursued in order both to confirm the 6 cm recombination absorption line and to search for similar recombination lines in other wavebands accessible to the VLA. The occurrence of positrons in the galactic center, if confirmed, could add much to understanding the centers of other galaxies. Ammonia line observations of condensations in the inner molecular ring of the Galaxy will address questions over the possible fueling of the galactic center and serve as input to the study of other galactic nuclei. OH observations in the same region will also help clarify the kinematic and geometric relationship between molecular gas and radio continuum sources in the central portion of the Galaxy. For distant extragalactic sources seen through the inner Galaxy, observations of scatter broadening will provide comparisons with the same phenomenon in the outer Galaxy and a better understanding of differences in the electron populations in the two different environments. Multiconfiguration images of the

Galactic Center with the highest dynamic range in the 90 cm waveband will be completed. The continuum and recombination line images of many of the detailed features (threads, loops, and arcs) seen at shorter wavelengths will clarify their spectral properties and emission mechanisms. At 327 MHz a survey of nearly 400 square degrees of the inner galactic plane has also been proposed as a means of identifying unknown supernova remnants and studying the populations of both thermal and nonthermal radio sources in the Galaxy.

Multiconfiguration studies of the radio properties of nearby galaxies, many times in conjunction with the analysis of optical, infrared, or x-ray data, continue to produce important results. The kinematic properties of the very brightest blue compact dwarf galaxies, which are undergoing violent bursts of star formation, will be determined with high resolution HI observations in order to search for indications of tidal interactions, assess the efficiency of star formation, and give valuable information on each galaxy's total mass. In an attempt to differentiate the thermal and nonthermal spectral components, 90 cm observations of a similar sample of dwarf galaxies will be obtained. Direct comparison with the spectra of normal spiral galaxies will help determine the physical source of both spectral components and ultimately the evolutionary stage of dwarf galaxies. A similar separation of spectral components will be undertaken at the highest VLA resolutions in order to study optimally the dynamics and spatial distributions of nuclear gas and the physics behind the tremendous star production efficiencies for megamaser galaxies and a statistically complete sample of luminous IRAS galaxies.

Improved spatial resolution HI synthesis maps of individual galaxies, such as M82 and NGC 404, when combined with existing CO maps, will allow a detailed study of the interstellar medium to be carried out. Twenty centimeter continuum images will play an important role in the multi frequency study of a large sample of non-interacting spiral galaxies, with the goal of elucidating the physical nature of the spiral portion of the Hubble sequence. VLA observations of background continuum sources behind the disks of a sample of spiral galaxies will be used to probe the interstellar clouds in the intervening galaxies for parameters such as the abundance of cool gas and its cloud size distribution. Hydrogen continuum and line maps of selected elliptical galaxies will also be obtained for the determination of well-measured mass distributions and for spectral and morphological studies of jets and potential tidal interactions.

Studies of radio galaxies will take full advantage of the power of the VLA as numerous programs will attempt to relate observable morphologies, spectral properties, and polarizations to source models. Systematic, dual frequency, matched-array, high resolution observations of sources with double hotpsots in their extended lobes are planned. Observable trends in their characteristics should provide useful constraints on models for their formation. The hotspots, lobes, and jet of Pictor A will be imaged more completely in order to better characterize the particle acceleration region where optical visibility indicates an extremely short lifetime. Optically identified hotspots in a number of other radio source lobes also require extensive multifrequency VLA observations. Improved observations of the polarization properties of the large rotation measure source Hydra A will be undertaken in order to thoroughly map its magnetic field environment to compare with the magnetic field structure found in Cyg A. A sample of high redshift radio galaxies will form the basis of a multi-wavelength VLA study of radio/optical relationships as a function of radio power, morphology, and redshift.

VLA 327 MHz observations of radio galaxies and cluster sources promise to play a crucial role in understanding the evolution of steep spectrum synchrotron sources. For the quasar 3C 273 a 327 MHz search for a diffuse feature related to the well-known jet is planned. The detection of an extended radio halo around the entire object is also expected. The rich cluster of galaxies, Abell 2256, will be the target of a 327 MHz mapping program in order to study the relation of the individual radio sources to each other and to the cluster radio halo. A snapshot survey of a complete sample of the most distant and compact Abell clusters will be undertaken to supplement the lower resolution Ooty survey at 327 MHz. The complete survey of very steep spectrum sources in these clusters should help establish their radio luminosity function and other group properties. In the Hydra I cluster of galaxies, the effects of the cluster environment on the morphologies and dynamics of individual galaxies will be surveyed for comparison with the abundant data on the closer Virgo cluster.

Observations of quasars with the VLA continue to address questions related to their morphological dependence on environment and evolution. For a complete sample of quasars from the low frequency Molonglo Synthesis Telescope, high resolution VLA observations will be used to test predictions of the "unified schemes" for quasars based on relativistic beaming. Another quasar sample distributed evenly in the redshift/radio luminosity plane will be used to evaluate evolutionary effects that have been preliminarily found in earlier, less well controlled samples. VLA observations of the unusual object 1042+178 will help determine if the sources are a product of gravitational lensing or not. Data on the component spectral indices, variability of the fluxes, and small scale structure will serve as important diagnostics of the lensing phenomenon.

The 300-foot Telescope

Programs carried out with the 300-foot dish will emphasize the large scale survey work for which the telescope's large collecting area and transit design are so uniquely suited. Receiver upgrades, innovative source tracking hardware and the introduction of a more flexible operating system are all developments which have enhanced the usefulness of the telescope for specific programs. Ever larger numbers of galaxies of differing Hubble type to fainter limits fall within the range of detectability in the 21-cm line of neutral hydrogen. Investigation of the HI content of SO galaxies will underpin a multiwavelength analysis of their star formation history in the context of their local environment. An HI study of Sc spirals will aim to establish distance indicators in an effort to measure deviations from the Hubble expansion at intermediate redshifts. A search for HI in rarely detected Sa spirals will improve our understanding of the physical basis for the Hubble sequence. Other HI surveys will probe galaxies in the Bootes Void for characteristics that may relate to their low density environment and continue a search for galaxies in the Zone of Avoidance.

Long term variable source monitoring will continue to be a fundamental part of the 300-foot program. Multi-observatory, multi-frequency observations of known extragalactic decimeter wavelength variable sources are required in order to more fully establish the characteristics of variability and to test proposed alternative production mechanisms. The long term polarization and flux density study of a sample of compact sources begun in 1972 will continue in order to follow carefully long term spectral evolution trends.

In the Galaxy, the second phase of a patrol for transient and highly variable sources at 6 cm is in progress. It is hoped that real time detection of transient sources might lead to immediate multi-frequency studies to explain the unstable source characteristics. Millisecond pulsar searches are similarly time consuming but have potentially large payoffs. More candidates are required to better understand the physics of neutron stars and as resources for further timing and astrometry programs, ranging from the investigation of gravitational waves in the early universe to the dynamics of the solar system. A polarization survey of the galactic continuum radiation will ultimately yield the magneto-ionic properties of the interstellar medium.

<u>140-foot Telescope</u>

The versatility of the 140-foot telescope continues to influence the wide range of programs that it carries out.

The 140-foot telescope is an important element in VLBI experiments, partly in coordination with other VLBI Network antennas, partly with European VLB stations, and partly on independent VLB experiments. The milliarcsecond resolution capability of VLBI observations is used to investigate the structural, spectral, and temporal properties of nuclear features in galaxies and quasars in order to understand the physics of their central energy engines and for further study of superluminal motions. Galactic VLBI programs concentrate on regions of circumstellar or star formation maser activity for direct dynamical clues to the evolution of these objects.

Molecular line observations utilizing the K-band sensitivity to search for yet undetected species in the interstellar medium will enhance our understanding of the chemical environment and its evolution under varying physical conditions. Programs are planned which will survey the general properties of the recently identified molecules $C_2S$ and $C_3S$ in cold dust clouds, and to search for the HCCO radical which is also suspected to be present in these objects. On-going study of oxygen-containing organic molecules in dark clouds will follow up earlier detections. The program has shown a surprising richness in the chemistry of cold dust clouds where there is now an opportunity for meaningful comparisons of observation and chemical reaction network theories. A new, very sensitive search for the centimeter lines of methylamine ($CH_3NH_2$) in a variety of galactic sources will be undertaken since the molecule is ideally suited to trace high density molecular cloud condensations which are potential star formation sites.

A wide variety of galactic programs will take advantage of the frequency flexibility and exceptional sensitivity of the telescope. Observations of the 8.7 GHz hyperfine transition of $^3He^+$ in galactic HII regions and planetary nebulae will be used to test theories for the chemical enrichment of the interstellar medium and to set important limits on models of the Universe. Past $^3He^+$ emission measurements at Green Bank have clearly demonstrated the advantage of the 140-foot system for controlling ever-present deleterious systematic instrumental effects. Neutral hydrogen measurements toward bright stars in the galactic anticenter region will be used with uv and optical spectra to determine the distance, abundance, and ionization state of the HI anticenter shell of unknown origin. Ammonia inversion lines in the shocked molecular gas of the supernova remnant IC 443 will be observed to determine temperatures and to examine the chemistry of the gas. Few sources outside of the Orion-KL region have been adequately examined in order to understand the synthesis of molecular species under the influence of high temperature phenomena.

HI observations of southern, low surface brightness galaxies will be carried out as part of a large homogeneous and complete redshift survey of galaxies. Most of the candidates are too faint for optical redshift measures and yet are required for a detailed three-dimensional structural analysis of the nearby galaxy distribution. The HI line parameters of another homogeneous sample of Sc spirals will complement the sample observed at the 300-foot telescope as part of a determination of secondary distance indicators in an effort to measure deviations from the Hubble expansion at intermediate redshifts ($z < 0.024$).

A search for ammonia towards the radio galaxy Cen A will aim to determine the physical properties of the gas associated with the active regions of star formation in the galaxy. A first extragalactic survey for the 2-cm transition of formaldehyde will include galaxies that have already been detected in the 6 cm line so that detailed modelling of physical parameters of the molecular gas can be accomplished. A sample of the most luminous infrared galaxies exhibiting OH masers will be searched for methanol masers, which in combination with either $H_2O$ or $H_2CO$ maser detections can provide important clues to the physical conditions and radiative environments of those galaxies.

The 12-meter Telescope

During 1988 the NRAO millimeter-wave facility will be in heavy demand by observers seeking to take full advantage of its easy accessibility, user friendliness, spectral versatility, and superior sensitivity. Long a principal research tool for molecular line studies, the telescope has seen increasing demand for CO studies by both galactic and extragalactic observers alike, owing to the high sensitivity of the new SIS receiver. Demand for high frequency time also remains great, as observers investigate new lines and improve resolution for both continuum and line studies.

CO observations of objects in the Galaxy provide fundamental physical information about regions in diverse stages of stellar evolution. Conditions in the nearest cold molecular clouds possessing emission peaks in other wavebands will be mapped in detail, searching for new bipolar outflows and other structural features indicative of star formation. Several known bipolar flows will be mapped in both isotopic species of CO in order to place tighter observational constraints on outflow densities, temperatures, masses, and energies. A statistical study of the occurrence of broad winged CO emission associated with low luminosity stars will be undertaken in order to assess the influence of such low mechanical energy flows in restricting cloud collapse. CO observations of small galactic HII regions will play a key role in the investigation of the distibution of stellar masses that arise in numerous small gas clouds in contrast to giant HII regions which contain many dozens of OB stars. A deep survey of CO in a representative sample of planetary nebulae will follow the successful initial detections and mappings of the past observing seasons in order to determine how common the presence of molecular gas is in these evolved objects.

The observation of CO in external galaxies helps to characterize their global star formation properties in comparison to our own Galaxy. High resolution studies of the M31 spiral arms, for example, have already been initiated with the 12-meter telescope and continuing observations are needed to support preliminary differences between clouds seen in the arm and inter-arm regions. A sample of gas rich galaxies previously detected in [CII] will be investigated for CO emission in a program ultimately designed to test the reliability of CO as a trace of molecular mass in certain environments. CO will be mapped from a wider luminosity range of IRAS galaxies in order to elucidate the cause of the high apparent star formation efficiency in ultraluminous galaxies. A further sampling of infrared quasars at redshift, $z < 0.16$, aims to establish a firm evolutionary link between the ultraluminous infrared galaxies and optically selected quasars. Galaxies at the centers of known cooling flows will be searched for the presence of CO as a diagnostic of the star formation environment.

Other 12-meter telescope investigations use additional molecular lines to probe the wide range of physical conditions found in the interstellar medium. Transitions of CS will be used to map dense cores in nearby dark clouds having no embedded stars in an attempt to understand the energy balance in dark cloud cores. CS lines at 245 GHz will be used to help characterize the density structure and clumpiness in several bipolar outflow sources. A confirmation of the detection of vibrationally-excited $HCO^+$ will test its usefulness as a new probe of star-forming regions and as a sign-post of the existence of high temperature chemistry in the interstellar medium.

# III. RESEARCH INSTRUMENTS

As a purely observational science, progress in radio astronomy is tightly coupled to 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 1400 MHz VLA image of the Rosette Nebula shown on the cover of the NRAO program plan is an excellent illustration of this point. The angular diameter of the Rosette is 4 degrees, many times larger than the 0.6 degree beam width of the individual VLA antennas. In principal, it may seem that the VLA could not image such an object. However, this particular image is actually a mosaic of 29 separate but overlapping VLA images. Each of the mosaic fields has been separately observed and calibrated. The resultant whole is assembled from the parts with the aid of a maximum entropy tessellation algorithm. The "tools" needed to create this image include not only the appropriate software but also the speed and memory of one of the new NRAO mini-supercomputers. Together they provide a further dimension to the imaging capability of the VLA. Scientifically the rewards are evident. For the first time the bright annular ring of the Rosette can be seen to be surrounded by a more extensive, yet complete, fainter outer ring of luminous ionized gas. The origin, morphology, and excitation of the outer ring are as yet unknown. Nevertheless, the ability to directly observe, not idealize, such phenomena is invaluable. Fundamental knowledge such as this is unobtainable without a concerted and continuous program of instrumental construction, evolution, and improvement.

The National Radio Astronomy Observatory currently operates four major telescope systems for scheduled observations by the astronomical community in the United States:

(1) the 140-foot fully steerable radio telescope;

(2) the 300-foot transit radio telescope;

(3) the Very Large Array synthesis radio telescope; and

(4) the 12-meter millimeter wave telescope.

In addition, preliminary test observations with the first of the VLBA antennas has also begun.

Each of these telescopes 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 and computer hardware 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 four 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 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 instruments. 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 plan and budget.

One of the more 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 resolutions 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" which has been submitted to the NSF. However, the single-dish telescopes, as well as the VLA, have also benefited by access to rapid data handling and manipulation hardware and software. The ability to rapidly position-switch the 140-foot telescope and the 12-meter telescope--and to deal with the greatly increased data rate--has led to a remarkable improvement in instrumental stability which directly translates into an ability to observe and study fainter and 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 plan is designed to realize these opportunities. The following table shows the planned distribution of funds for the Research Equipment account as currently dictated by the anticipated funds and 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 Research Equipment plan follows the table. It is important to note that most of the RE projects extend over several years; those for which monies are allocated in 1988 are not necessarily planned for completion in 1988. However, the expeditious completion of all construction projects, and the subsequent application of the instrumentation or software produced to visitor research endeavors, is a primary goal of the NRAO development program.

RESEARCH EQUIPMENT
($ in thousands)

| | Expenditure 1987 (est) | Expenditure 1988 (plan) | Estimated Add'l Cost | Estimated Completion Date |
|---|---|---|---|---|
| 1. Laboratory and Test Equip. | $ 20 | $ 20 | $100/yr | continuing |
| 2. Miscellaneous Projects | 120 | 50 | 200/yr | continuing |
| 3. Very Large Array | | | | |
| 327 MHz Receivers | 40 | 20 | - | 1988 |
| 22-25 GHz Improvements | 130 | 70 | 170 | 1989 |
| 1.3-1.7 GHz Improvements | - | 10 | 600 | 1991 |
| Synchronous Computer Upgrade | 10 | 10 | 150 | 1990 |
| Imaging Computer Additions | 35 | 20 | 150 | 1990 |
| Phased Array Processor | - | 10 | 40 | 1989 |
| Image Storage Unit | 15 | 5 | 40 | 1990 |
| 4. 12-m Telescope | | | | |
| 8-feed 220-230 GHz Receiver | 10 | 20 | 50 | 1990 |
| 1-mm SIS Receiver | 15 | 15 | 125 | 1990 |
| 70-115 GHz SIS Upgrade | 10 | 10 | 30 | 1989 |
| Hybrid Spectrometer | 25 | 25 | 50 | 1989 |
| Telescope Control Upgrade | 20 | 20 | 70 | 1989 |
| 5. 300-ft Telescope | | | | |
| Spectral Processor | 85 | 35 | | 1989 |
| Adaptive Array Receiver | 15 | 10 | 40 | 1989 |
| Multibeam L-band Receiver | - | 10 | 250 | 1991 |
| LAN Interface | - | 20 | 30 | 1989 |
| 6. 140-ft Telescope | | | | |
| Spectrometer/Computer | 10 | 10 | 200 | 1992 |
| 32-GHz Receiver | - | 10 | 100 | 1991 |
| LAN Interface | - | 20 | 30 | 1989 |
| 7. Common Development | | | | |
| Millimeter Device Development | 110 | 65 | 150/yr | continuing |
| Advanced Spectrometer Development | - | 5 | 20/yr | continuing |
| Class VI Evaluation | 10 | 5 | 10/yr | continuing |
| Communications | 10 | 5 | 10/yr | continuing |
| TOTAL | $690 | $500 | | |

Laboratory and Test Equipment

The need to continually improve the telescope instrumentation brings with it a concomitant need to improve the laboratory diagnostic equipment. For example, the optimization of FET and HEMT amplifier design for new frequency ranges requires access to a suitable network analyzer. Extension of the NRAO frequency capability to 350 GHz implies a need for additional signal generators and noise sources. Diagnostic equipment for computer networks are needed. Such items, for all the NRAO laboratory sites, are included in this budget line. Included also are enhancements to existing test equipment.

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.

Very Large Array: Electronics

Over the course of the past two years a staged enhancement of VLA electronics has begun to provide both very much greater sensitivity at high frequency (22-25 GHz) and to permit astronomers to exploit unique scientific opportunities at low frequency (300 MHz). Improvements at both these ends of the frequency spectrum constitute the principal thrust of the 1988 plan for development of VLA electronics. In addition, initial design and prototyping will begin on an improvement to the "workhorse" L-band system on the VLA and on a dedicated phased-array processor for stellar and pulsar observations.

327 MHz Receivers: Observations of a large number of astronomical objects benefit from a lower observing frequency than 1.35 GHz, the lowest frequency currently supported on the VLA. Some objects radiate more strongly at lower frequency while others are so large that a larger field of view is needed: 327 MHz observations address both these needs. By the end of 1988, all 28 antennas will have been equipped with prime focus, 327 MHz receivers, and the VLA will be a very exciting low-frequency synthesis telescope with a unique capability.

22-25 GHz Improvements: Many important ammonia-line experiments, such as accretion disks, circumstellar material, distant star-forming complexes, and extragalactic line observations, demand an upgrade to the VLA K-band performance. An attainable improvement at 24 GHz by a factor of 5-6 means a tremendous boost in speed and sensitivity. The 1988 plan calls for continued installation of an improved front-end amplifier for the 1.3 cm band that will reduce the system temperature to 150 K using HEMT (high electron mobility transistor) amplifiers developed at the NRAO Central Development Laboratory. Antennas are equipped with the new amplifiers at a rate dictated by their cycle through the antenna maintenance facility (one antenna every 4-6 weeks).

1.3-1.7 GHz Improvements: HI imaging is the single class of spectral line observations most in demand 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 very precise angular or frequency resolution is needed. Currently the VLA provides 18-21 cm system temperatures of 50-60 K, with a significant fraction of this temperature coming from room-temperature polarization splitters and long wavelength paths. However, by adapting the VLBA L-band receiver to the VLA and locating the amplifier in its own cryostat (making use of the X-band refrigerator compressor), it should be possible to reduce the system temperature to less than 30 K. Design work will begin in 1988.

Very Large Array: Computing

The VLA computing environment includes two identifiably separate functions, viz telescope control/data acquisition and data reduction/imaging Enhancements are needed in both these functional areas The evolution of the VLA to higher frequency, to higher angular resolution, to more rapid temporal sampling, and to higher spectral resolution brings with it increasing demands on the data-taking and data-processing hardware and software. As the scientific benefit from such instrumental evolution is certainly commensurate with the technical effort expended in achieving this evolution--indeed the former is predicated on the latter--these demands need to be addressed expeditiously. Thus the 1988 Research Equipment plan continues to support the necessary augmentation of these facilities.

Synchronous Computer Upgrade: Recognizing that the on-line ModComp computers could no longer keep up with the VLA data rate, and neither did they have the spare capacity to handle the digital control of the new receivers on the array, particularly the 327 MHz system, a phased upgrade to fast, 32-bit, machines was begun in 1984. The new computers can process all the data that the correlator provides, viz., 351 baselines of 512 spectral channels in each of two polarizations. This is an increase of a factor of 16 over which the original on-line computers could handle. Data verification, validation, and calibration thus becomes a much more important function to the new on-line computers. To facilitate these tasks in 1988, the intent is to provide additional memory, disk storage, and tape handling capabilities to the synchronous computing system. In addition, a real-time display of the data flow will keep the astronomer abreast of possible changes in instrumental performance in a readily interpretable visual format.

Imaging Computer Additions: Access to the full data rate of the VLA provided by the new on-line computers--the factor of 16 mentioned above--is, of course, 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 DEC-10 calibration computer. 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, in 1988, prior to the expected start of funding for this proposal in 1989, some modest enhancement of the disk storage capacity of the CONVEX imaging computer is planned.

Phased Array Processor: Study of impulsive phenomena with the VLA is made possible not by the imaging capability of this instrument but simply by the large collecting area and instantaneous sensitivity afforded by the superb receiving systems. Here the desire is to measure rapidly all the Stokes parameters of the emission from flare stars and pulsars as a function of time. The positions are known and the objects are true point sources; the astronomer seeks simply the intensity and polarization as a function of time. For such an observation the signal from all the antennas needs to be added, in phase, in a special microprocessor and sampled rapidly. The phased array processor is designed to provide precisely this capability. In 1988 we intend to begin the design and prototyping of this instrument.

Image Storage Unit: The image storage unit (ISU), designed and built in the Central Development Laboratory in Charlottesville, is a video disc emulator which is attached to the IIS display. The ISU is capable of storing 256, 512x512 images and playing them back at a rate of six per second. This is useful to astronomers who wish to visualize data reduction step-by-step, or who need to store and display spectral line cubes using movie and blinking techniques. The first ISU is attached to the VLA "pipeline"; additional units are needed for the CONVEX imaging computer.

The 12-meter Telescope

The successful resurfacing project of the former 36-foot telescope has provided users with a 12-meter, millimeter-wave telescope with a surface accurate enough to support useful observations at frequencies as high as 350 GHz. At the highest frequencies the Kitt Peak site at 6200 feet altitude is the limiting factor. Superior telescopes at superior sites are likely to provide astronomers with better opportunities than the 12-meter telescope at wavelengths shorter than 1 mm. However, in the 1 mm window, 200-300 GHz, the capability of the 12-meter is unsurpassed. Already there is heavy pressure on the 12-meter telescope for observations of the J = 2-1 lines of CO and its isotopes. The pressure arose in part from a shortage of days with good atmospheric transparency at 1.3 mm and in part because the mapping of extended regions--molecular clouds or galaxies--is intrinsically time-consuming. The mapping process can be significantly accelerated by introducing a multi-feed receiver capability. Tests with a 4-beam, 230 GHz receiver in 1987 have been very successful. In 1988 the intent is to provide an 8-beam capability to users. By 1992 this should increase to 32 beams.

8-feed, 220-230 GHz Receiver: Located at one of the four receiver bays on the 12-meter telescope, this receiver will provide eight spatially separate 220-230 GHz beams in the sky. The beam separation is 80" and the half-power beamwidth is approximately 30" at this frequency. The initial installation involves Schottky-diode mixers, but in the future this could easily be upgraded to SIS mixers. The 8-channel output of the receiver will be fed into the hybrid spectrometer which is designed to handle eight independent IFs. Tests of all eight channels will be conducted in early 1988.

1 mm SIS Receiver: A dual channel, 200-300 GHz SIS receiver based on junctions developed at the University of Virginia will be designed and built at the Central Development Laboratory. It should provide half the SSB system temperature of the present Schottky receiver with substantially less complexity. If this application is successful, the technology will be extended to the 220-230 GHz multi-beam initiative.

70-115 GHz SIS Upgrade: The NRAO 3 mm SIS receiver on the 12-meter telescope, with an L-band HEMT IF amplifier, provides a SSB system temperature which is unequaled elsewhere In 1988 the intention is to improve this receiver even further by replacing the active element with a niobium junction (either from Hypres Corporation or from IBM) that will permit operation at 4 K. At such a "high" temperature a closed-cycle cryostat can be used which will eliminate the overhead presently needed to fill the 2.5 K cryostat with helium every 48 hours or so

Hybrid Spectrometer: In order to provide the greater frequency coverage 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 is under construction. The 2.4 GHz total bandwidth and 1536 spectral channels to be 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 array receivers under development at the Central Development Laboratory. The complete spectrometer should be on the telescope by the end of 1988.

Telescope Control Upgrade: The expanded capabilities of the new instrumentation for the 12-meter telescope, for example, the hybrid spectrometer, the fast beam-switcher, and lower noise receivers, all have the effect of increasing the data rates at the telescope. The multi-feed receivers further exacerbate this trend. Since the existing control computer cannot be further expanded, it will be replaced by a DEC-11/44 and a network of dedicated microprocessors. The user-interface software will be a straightforward adaptation of the 300-foot interface; thus the new 12-

meter telescope control computer will foster adoption of an NRAO-wide "standard" telescope interface.

300-foot Telescope

Since the 300-foot is a transit telescope, it is manifestly a survey instrument and, given the mesh construction of its surface panels, it operates effectively at the longer wavelengths, $\lambda > 6$ cm. For 25 years the enormous collecting area of the 300-foot telescope, together with the very sensitive receivers available at Green Bank, has provided astronomers with an opportunity for exceptional sensitivity in the OH and HI lines as well as in the continuum. These characteristics have been, and continue to be, exploited to the benefit of those astronomers interested in discovering new pulsars, extending knowledge of the gas content in galaxies to higher redshift, or attempting to determine the nature and distribution of weak radio sources. However, as a survey instrument the 300-foot telescope is limited by the capabilities of its back-end instrumentation.

Enhancements to the 300-ft telescope thus call for those improvements that will optimize the performance of the telescope as a survey instrument. The first pivotal step in this direction--replacement of the control computer--was completed in 1986. More than just a hardware replacement, the new computer includes modern user-interface software that dramatically increases the versatility of the telescope control. The following items in the Research Equipment plan are needed now to exploit fully this versatility.

Spectral Processor: This is a pipelined, fast Fourier transform spectrometer, incorporating real-time interference excision and flexible time and frequency-merging capabilities. It improves on existing instrumentation in two major areas. Spectral-line observations will have greater resistance to interference since spectral estimates are produced once every 10 microseconds instead of once every 10 seconds as is the present case. It will also increase the available number of spectral channels, providing 2048 channels across 40 MHz as compared to 384 channels across 10 MHz in the present autocorrelator. Secondly, the spectral processor will greatly improve pulsar data-acquisition capabilities at the 300-ft telescope It will provide 256 channels times 4 polarizations across a 20 MHz bandwidth with full dedispersing capabilities. The spectral processor will thus allow highly automated and accurate pulsar timing programs to be performed. It should be completed, and available for visitor use, in 1988.

Adaptive Array Receiver: Low-frequency receivers, frequencies less than 1 GHz, are mounted on a traveling carriage that briefly tracks the source in hour angle. Presently the beam degrades badly at hour angles greater than 10 minutes at 400 MHz. However, implementation of an array receiver together with a suitable combining network will permit sources to be tracked for more than an hour with near-maximum efficiency. This will facilitate pulsar observations, scintillation surveys and searches for redshifted hydrogen lines in an astrophysically important band (400-500 MHz).

Multibeam L-band Receiver: Observations of extragalactic hydrogen as well as those Galactic HI observations that have as their goal the mapping of HI column density with minimum contamination by "stray" radiation benefit by a multibeam capability. One receiver can benefit both programs. In the case of extragalactic studies, the telescope time can best be utilized by a receiver with seven or more independent feeds (two polarizations each) mounted in the focal plane. If the amplifiers are very low noise HEMT L-band amplifiers giving 25 K or less system temperature, very large regions of the extragalactic sky may be surveyed with high sensitivity. With a somewhat different feed arrangement, the same receiver could be used to illuminate as many as four unblocked regions of the 300-foot telescope so as to provide a "clean" HI beam--essentially free of stray radiation--with a beam efficiency of greater than 98 percent. Such a receiver will provide the first reliable maps of the HI column density in the northern Milky Way.

LAN Interface: One of the most serious impediments facing astronomers at the 300-foot telescope is the inability to access the data that they have collected during an observing run. Disk space is limited, the analysis computers are several generations out-of-date, and connectivity is non-existent. To surmount these considerable difficulties, we will begin in 1988 to create a fiber-optic LAN in Green Bank such that data will be transmitted from each of the telescopes in real time to a central file server which the astronomer can access from any terminal/workstation on site. This will permit the astronomer not only to have access to sufficient dedicated computer power but also to configure NRAO computer resources for special needs and tasks.

## 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.

In 1987 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. Now 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. The high-frequency performance of the telescope was also improved by application of a tilting, lateral focus, mechanism for the subreflector. This resulted in an increase of a factor of two or more in K-band aperture efficiency at large hour angles and provides one motivation for extending the frequency range of the telescope above the present 25 GHz.

Although the frequency flexibility and sensitivity of the 140-foot telescope are exceptional, the operational flexibility is limiting. The present control computer is an out-dated 16-bit machine which has limited capacity for expansion. It thus cannot make effective use of the dual receivers and the new data-taking procedures and data-processing algorithms that have the potential to greatly reduce the operational overhead as well as further improve the sensitivity, particularly the spectral sensitivity, of the telescope. The Research Equipment plan in 1988 thus calls for a higher frequency capability and initiation of work on a new control system, spectrometer and digital hardware interface that, when complete, will permit a more versatile operation.

Spectrometer/Computer Development: There are three interrelated aspects to this project to improve the spectral sensitivity of the telescope by improving the backend performance. First, a concerted investigation of the cause of baseline ripple will be pursued which will involve extensive experimentation with reflection spoilers, absorbers and rapid switching techniques. Second, digital hardware interfaces between the telescope RF instrumentation and the control computer will be redesigned and built in anticipation of the next generation control computer. Finally, construction of a new spectrometer will be begun for the 140-foot telescope which will, as in the case of the 300-foot telescope, allow very rapid spectral estimates to be obtained, interference to be excised, and greater spectral resolution to be attained.

32 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 45 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 43 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 here than 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.

Holographic maps of the surface of the 140-foot telescope were made in August 1987 and were used to guide a resetting of the surface panels. The global rms error in the figure of the primary reflector improved from approximately 1.0 mm to 0.6 mm. The aperture efficiency at 256 GHz has improved from $\lesssim$ 20% to 27%. This suggests that observations at 32 GHz are feasible and that it is prudent to begin construction of an amplifier at this frequency. Work on the design will begin at the Central Development Laboratory for this purpose.

LAN Interface: As with the 300-foot telescope, the astronomer at a workstation at the 140-foot telescope will benefit by access to a LAN connected via fiber optics to a network file server in the Jansky lab. A coherent site-wide LAN is a necessity.

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 Schottky diodes specialized to our millimeter-wave, cryogenic, application. The University of Virginia also does subcontract work in an attempt to develop niobium SIS junctions for application at the higher frequencies.

Development of Cryogenic FET/HEMT 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 and hence the sensitivity of almost all observations performed at the NRAO is improved with the development of these amplifiers.

GaAs FET amplifiers have been designed at 0.3, 1.5, 5.0, 8.3, 10.7, 15, and 23 GHz. Over 200 units have been constructed. Work in 1988 focuses on incorporation of lower noise, wider bandwidth HEMT (high electron mobility transistor) devices. Design of very wide-band amplifiers for IF use is under investigation.

Advanced Spectrometer Development: The intention at the 300-foot, at the 140-foot, and especially at the 12-meter telescopes is to provide a multibeam capability at the same frequencies in most demand The backend requirements are of particular concern; we continue to investigate promising technologies. Here in 1988 we set aside monies for support of an investigation of such technologies as acousto-optical (AOS) and surface acoustic wave (SAW) dispersive elements as possible reactive elements for the next generation of spectrometers.

Class VI Evaluation: The need for the power of a Class VI supercomputer--60-100 achieved megaflops--to reduce those compute-intensive VLA observing programs has prompted the NRAO to take advantage of the NSF supercomputing initiative in order to evaluate the problems and prospects for running AIPS on a supercomputer. In 1988 the thrust will be to optimize AIPS for the supercomputer as well as to support visitor imaging programs on the CRAY at the NSF Carnegie/Pittsburgh Center for those projects with demonstrable need and proper preparation of the data to be imaged.

Communications: The communications project includes hardware necessary for digital communications among NRAO sites and with the NSF supercomputer center. This includes multiplexer equipment as well as some modems. The multiplexer equipment handles the inter-site DECNET capability, the Socorro-Green Bank fiscal communication and remote terminal access. When completed it will be possible to log on to most NRAO computers from any terminal connected to the digital switch.

## IV. OPERATING EQUIPMENT

The distribution of funds (in thousands of dollars) in the various equipment accounts is as follows:

| | | |
|---|---|---|
| 1. | Maintenance, Shop, and Repair Equipment........... | $25 |
| 2. | Office and Library Furnishings and Equipment...... | 30 |
| 3. | Living Quarters Furnishings....................... | 10 |
| 4. | Building Equipment................................ | 10 |
| 5. | Observatory Services.............................. | 25 |
| 6. | USNO Related Services............................. | 40 |

Item

1. Maintenance, Shop, and Repair Equipment

Funds planned in this account provide for the replacement and/or acquisition of items for the shops and maintenance divisions. Items included in this account are: tractors and mowers, replacement trucks and other vehicles, machine shop equipment, and auxiliary items and accessories to be used with existing equipment.

2. Office and Library Furnishings and Equipment

These funds provide for replacement, updating, and acquisition of communications equipment, typewriters, business data and text processing equipment, copying machines, and other major office furnishings. In 1988 we will begin to furnish the AOC building in Socorro. The need for the entire range of office furnishings for the building will have a marked effect on this budget item.

3. Living Quarters Furnishings

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

4. Building Equipment

These funds provide for items that are generally attached to and become a part of the buildings. Included are such items as small air conditioners, small heating units, water heaters, etc.

5. Observatory Services

These sums provide for small equipment additions in graphics arts and information services. Items such as cameras, film processing units, projectors, measuring equipment, etc., are included in this amount.

6. USNO Related Services

These funds are incorporated in USNO agreement with the NSF for support of the operation of the Green Bank interferometer.

## V. OPERATIONS AND MAINTENANCE

The NRAO is administratively divided along functional lines into eight operating divisions. These units include both the individual operations at the three observing sites and the integrated operations which encompass all four geographic locations. The geographic distribution of personnel in these eight units is given in Section XI.

### A. General and Administrative

Serving the needs of the entire Observatory, this unit is comprised of the Director's Office, Fiscal Office, and Business Office. Total Materials, Supplies, and Services (MS&S) funding will be $272k. Further major budget items, such as the rent and maintenance of the Charlottesville Edgemont Road building, communications, and utilities, will require $368k. The management fee paid to Associated Universities, Inc., will be $420k.

### B. Research Group

The NRAO scientific research group, composed of staff scientists and students (summer, co-operative, and Ph.D.), engages in independent research and competes for observing time on an equal basis with visiting scientists. They are expected to carry out research of the highest caliber while at the same time assisting visiting astronomers in effective utilization of NRAO instruments and facilities. Because they are at the forefront of research in their individual areas of expertise, they are a valuable asset to the NRAO in posing new problems and stimulating new approaches to observational problems. The staff advises the technical divisions about modifications to equipment or the design of new equipment and participates in the checkout and calibration of the instrumentation. They are distributed between the

Charlottesville and Socorro sites as 50 percent and 41 percent, respectively, with the remainder in Tucson or Green Bank.

In 1987 the NRAO summer student program was augmented by an award of $65,000 from the NSF Research Experiences for Undergraduates (REU) program to Associated Universities, Inc. Sixteen students were supported through this award. In 1988 a modest NRAO summer student program is planned, seven students. Once again, support for additional students will be sought through the REU program With these two sources of support in 1988, the expectation is that the program will be restored as a vital element in NRAO's commitment to the training of future radio astronomers.

Over 25 percent of the overall NRAO travel budget will be expended in the Research Group primarily for travel by staff and visitors from U.S.-based institutions to carry out observing programs at NRAO telescopes or by visitors to travel to Socorro or Charlottesville data-analysis facilities ($141k). During 1988, $30k is planned for foreign travel by the staff, and $20k is available for qualifying U.S. scientists who need travel support to observe at unique foreign telescopes.

## C. Charlottesville Operations

Observatory Services in support of research and development throughout the entire Observatory are provided by the central library, the technical illustrations and drafting service, and the Observatory visual information service. In 1988, the MS&S budget of $440k for these areas is earmarked primarily for publication support (page charges) of papers based on data obtained with the NRAO telescopes as well as for the book and periodical expenses of the four NRAO libraries.

The Computer Division operates the NRAO central computer in Charlottesville and the VLB MKII processor and assists in the development of programs for computers at the telescopes. An astronomical image-processing group develops and maintains image processing and analysis software that is currently operating in Charlottesville and at the VLA as well as at more than 200 institutions world wide. As has been the case in previous years, a major portion of the MS&S for this Division will be used for computer-related expenses and maintenance. A new CONVEX C1 mini-supercomputer, purchased with the University of Virginia on a cost-sharing basis, serves as a development computer for the NRAO image processing software system AIPS. It has been optimized to run this software for the benefit of visitors and staff. The third of four scheduled payments on the C1 will be made in 1988.

### D. Technical Development

Observatory-wide technical research and development support are concentrated at the Central Development Laboratory. Work on radiometer improvements and the exploration of state-of-the-art techniques for expanding wavelength capabilities insures that the Observatory will have forefront instrumentation in the foreseeable future. A subgroup at the Central Lab is heavily involved in the development of new millimeter-wave amplification devices. During 1988, $70k is budgeted for MS&S and $105k for rent of the Central Development Laboratory on Ivy Road.

### E. Green Bank Operations

The five divisions at Green Bank are responsible for maintaining and operating the 300-foot telescope, the 140-foot telescope, and the interferometer (for the USNO). New instrumentation specifically for the single dishes is developed on site. Some workshops, electronics, and graphics support is also provided for Observatory-wide activities. These five divisions and their 1988 budgets for MS&S are: Telescope Services ($124k), Electronics ($129k), Plant Maintenance ($113k), Administrative Services ($104k), and Scientific Services ($75k). An additional $312k will be spent on communications and utilities. It is also estimated that food services and housing will bring in revenues of about $155k. The operation of the Green Bank interferometer for the USNO affects the Green Bank Operations budget as a credit of $847k (see Section VI).

F. Tucson Operations

Two divisions in Tucson are responsible for the maintenance and operation of the newly resurfaced 12-meter, millimeter wavelength telescope at Kitt Peak. The Electronics Division will be devoting a major portion of their 1988 effort to the installation of a new control computer and its digital hardware, a new spectrometer, and a multi-beam receiver. The Operation and Maintenance group handles all visiting astronomer logistics and observing support, which for 1988 will include continued software development for improved telescope control and data acquisition. The two Tucson subgroups will require the following MS&S budgets for 1988: Operations and Maintenance ($117k) and Electronics ($120k). An additional $189k is programmed for building rent, communications, and utilities. Miscellaneous revenue will total about $16k.

G. Socorro Operations

Activities surrounding the VLA are coordinated through six divisions which differ in detail from those in Green Bank due to the special requirements of array operations and geographic isolation. The VLA Scientific Services group will require a MS&S budget of $82k. The Computer Division and Array Operations Division, which are most critical to the mechanical functioning and data collecting capabilities of the telescope, will require MS&S budgets of $754k and $10k, respectively. Other services related to the efficient functioning of the operation are: Engineering and Services Division ($403k) and Administrative Services ($446k). Communications, utilities, and building rent (in Socorro) will amount to $1070k, while miscellaneous revenue of $124k is expected. Included in the above sums is $641k for computer rent and maintenance and more than $872k for electric power costs. A significant part of the communications expenditures will be devoted to remote observing costs.

## H. VLBA Operations

As the first five VLBA antennas become operational in 1988, the pace of VLBA operations quickens appreciably. In the long-term we anticipate a combined VLBA-VLA operations program, thus we categorize, initially, the VLBA operations into divisions similar to the existing VLA operations groups. The total MS&S budget for VLBA operations of $666k is comprised of $10k for Scientific Services, $26k for Administrative Services, $210k for Engineering Services, $205k for Electronics, $27k for the Computer Division, $12k for the Array Operations Division, and $176k for other expenses, including an estimated $85k for electric power and $45k for communications and data links.

A summary of the CY 1988 budget for these operations units is provided in the following table:

| | Personnel | Salaries, Wages & Benefits | Material, Supply, Service | Travel | Total |
|---|---|---|---|---|---|
| | | ($ in thousands) | | | |
| <u>Operations</u> | | | | | |
| A. General & Admr. | 26 | 1,158 | 1,060 | 92 | $ 2,310 |
| B. Research Group | 28 | 1,706 | 10 | 191 | 1,907 |
| C. Cvlle. Oper. | 18 | 742 | 440 | 23 | 1,205 |
| D. Technical Develop. | 15 | 631 | 175 | 15 | 821 |
| E. Green Bank Oper. | 88 | 3,381 | 702 | 38 | 4,121 |
| F. Tucson Oper. | 28 | 1,140 | 410 | 40 | 1,590 |
| G. Socorro Oper. | 106 | 3,720 | 2,641 | 63 | 6,424 |
| H. VLBA Oper. | 18 | 502 | 666 | 32 | 1,200 |
| Common Cost Recovery | | | (271) | | (271) |
| Total Operations | 327 | $12,980 | $ 5,833 | $494 | $19,307 |
| <u>Design and Construction</u> | | | | | |
| VLBA | 68 | $ 2,764 | $ 8,873 | $263 | $11,900 |
| Voyager 2 | 12 | 385 | 567 | 25 | 977 |
| 75 MHz Capability | | | 400 | | 400 |
| Total Design & Const. | 80 | $ 3,149 | $ 9,840 | $288 | $13,277 |
| TOTAL | 407 | $ 16,129 | $15,673 | $782 | $32,584 |

1. Does not include commitments carried forward from 1987.
2. Gen. & Admr. includes $420k AUI management fee.
3. Green Bank Oper. includes $847k new funds for USNO interferometer support.

## VI. INTERFEROMETER OPERATIONS

In October 1978, the NSF entered into a Memorandum of Understanding (MOU) with the U. S. Naval Observatory whereby the NRAO would operate the NRAO's Green Bank interferometer on a cost reimbursement basis as part of the USNO's fundamental astrometry program and basic time service functions.

Over the past several years the NRAO has expanded and upgraded the interferometer in order to improve the data acquisition capabilities of the instrument by adding an east-west baseline link off the original north-south baseline in 1983/84, including the addition of a new 14.2-m telescope located some 30 miles west of the main Green Bank site, and during 1985 completed the acquisition and installation of a new MassComp computer system. In 1986 scientific support for the interferometer was improved by the appointment of an astronomer resident in Green Bank with responsibility for the USNO program. A workstation and fiber optic connection to the Green Bank site LAN are planned improvements in 1988.

Operating and maintenance costs and equipment replacements for the interferometer are planned at $886k in 1988, of which $40k is carried over from prior years' accumulations in construction programs and equipment upgrading projects.

Funding for the interferometer program is provided to the NRAO through an interagency transfer between the Naval Research Laboratory and the NSF for inclusion in AUI's contract with the Foundation. The 1988 interferometer allocation is shown in the following tables.

USNO Interferometer Schedule
($ in thousands)

| | 1986 Expended Actual | 1987 Expended Est. | 1988 New Funds |
|---|---|---|---|
| 1. Operations | | | |
| Personnel Compensation | $326.0 | $317.2 | $366.0 |
| Personnel Benefit | 84.0 | 88.3 | 94.0 |
| Material & Supply | 157.0 | 136.6 | 75.0 |
| Communications & Utilities | 38.0 | 42.0 | 41.0 |
| Travel | 2.0 | 2.0 | 4.0 |
| Common Costs | 202.0 | 176.0 | 227.0 |
| Total Operations | $809.0 | $762.1 | $807.0 |
| 2. Equipment | | | |
| Automotive | $ 12.1 | 0 | 0 |
| Test Equipment | 2.9 | $ 32.4 | $ 20.0 |
| G.P.S. Receiver | 23.6 | 0 | 0 |
| Computer Equipment | 0 | 0 | 20.0 |
| Total Equipment | $ 38.6 | $ 32.4 | $ 40.0 |
| 3. Design & Construction | | | |
| Interferometer Addition | 0 | $ 30.0 | $ 39.5* |
| Total Design & Construction | 0 | $ 30.0 | $ 39.5 |
| TOTAL | $847.6 | $824.5 | $886.5 |

* uncommitted carryover

## VII. VOYAGER 2 NEPTUNE PROJECT

In May 1985, the NSF and NASA entered into a Memorandum of Agreement (MOA) whereby the NRAO would develop, assemble, and install certain electronic equipment on the VLA antennas and then operate the VLA in conjunction with NASA's Voyager 2 Neptune mission. The utilization of the VLA for Voyager 2 data acquisition will commence on or about April 1, 1989, and end on or before October 1, 1989, with activity concentrated around the day of the closest approach of the spacecraft, August 24, 1989.

Under the terms of the MOA, the Observatory will outfit each of the VLA antennas with front-end receivers (28 plus 2 spares) and feeds (the latter to be supplied by the Jet Propulsion Laboratory) to receive the Voyager 2 spacecraft frequency (8.4 GHz), with the signal so received to be combined with the identical signal that will be received by the NASA/JPL Goldstone antenna and thus approximately double the data return expected from Voyager 2.

During 1988 fabrication of the front ends for the Voyager 2 program will be completed at the NRAO in Charlottesville, with all 30 front-ends functional and tested at the VLA by September and fully installed on the antennas by years end. The projected Voyager 2 cost for 1988 is expected to run about $1275k, of which about $298k is from 1987 funds carried over for commitment and expenditure in 1988.

Funding for the Voyager 2 program is provided to NRAO through an interagency transfer between NASA and NSF for inclusion in AUI's contract with the Foundation. The 1988 Voyager 2 program allocation is shown in the following table ($ thousands).

Voyager 2 Schedule
($ in thousands)

| | 1987 | 1988 | | | | |
|---|---|---|---|---|---|---|
| | Est. Exp. | New Funds | Carry-over | Available for Comm. | Comm. Fwd. | Available for Exp. |
| Personnel Compensation | $ 485.0 | $ 302.0 | | $302.0 | | $302.0 |
| Personnel Benefits | 136.0 | 83.0 | | 83.0 | | 83.0 |
| Material & Supply | 483.0 | 296.0 | $123.0 | 419.0 | $175.0 | 594.0 |
| Travel | 10.0 | 25.0 | | 25.0 | | 25.0 |
| Common Costs | 393.0 | 271.0 | | 271.0 | | 271.0 |
| TOTAL | $1507.0 | $977.0 | $123.0 | $1100.0 | $175.0 | $1275.0 |

Total funding for NRAO's participation in the Voyager 2 programs is scheduled to be $6304k, as shown in the following table.

| | 1985 | 1986 | 1987 | 1988 | 1989 | Total |
|---|---|---|---|---|---|---|
| Central Lab | $ 720.0 | $ 925.0 | $ 654.0 | $143.0 | $ 46.0 | $2488.0 |
| VLA Site | 531.0 | 1114.0 | 965.0 | 834.0 | 372.0 | 3816.0 |
| TOTAL | $1251.0 | $2039.0 | $1619.0 | $977.0 | $418.0 | $6304.0 |

At the completion of the program in 1989, the front-ends, feeds and other equipment acquired by the NRAO under the Voyager 2 program agreement will be retained by the Observatory, with title to all such property being transferred to the NSF.

## VIII. VLA 75 MHZ CAPABILITY

In July 1987 the NSF and the Naval Research Laboratory agreed to cooperate in providing a 75 MHz receiving capability on at least 14 antennas of the VLA. Under the terms of this agreement the NRAO will design, assemble, and install all the hardware instrumentation needed for 75 MHz observations, including RFI shielding where it is needed. The NRL will transfer to the NSF sufficient funds for this construction and installation in return for which the NRAO will provide the NRL with copies of the calibration data taken in the course of scheduled, routine test observations over the 2-year period June 1987 - June 1989.

The joint NSF/NRL cooperation on this project accelerates the construction of 75 MHz equipment, a project that had been slowed by lack of sufficient NRAO research equipment funds. Prior to the agreement only four VLA antennas had 75 MHz receivers. The NRL support calls for 14 antennas to be so equipped by September 1988. When this is accomplished the VLA will provide a major new observing capability by giving astronomers 20" angular resolution at a frequency where the current best resolution is many arcminutes. Useful and important observations at 75 MHz will be possible for thousands of previously unresolved extragalactic, galactic, and solar system objects.

Copies of the data taken for astronomical purposes will be made available to the NRL for their investigation in attempting to characterize the ionospheric transmission, reflection, and absorption at decametric wavelengths. If the NRL ionospheric modelling is shown to improve the calibration of the VLA at 75 MHz, the ionosphere data will be made available to the NRAO for the benefit of the astronomical observations.

The joint project is expected to cost $500,000, funded at $100,000 in FY 1987 and $400,000 in FY 1988, with funds provided to NRAO through an interagency transfer between NRL and NSF for inclusion in AUI's contract with the Foundation. Permanent equipment purchased by the NRAO with funds provided by NRL will remain the property of the NSF after the termination of the agreement in June 1989.

# IX. DESIGN AND CONSTRUCTION

The Astronomy Survey Committee of the National Academy of Sciences ranked the Very Long Baseline Array as the highest priority for major, new ground-based instrumentation during the decade of the 1980s. In May 1982, the NRAO submitted a proposal to the NSF requesting financial support for the construction of the VLBA.

A modest amount of design money was expended during the 1983-85 period, during which time the general array configuration was specified. Official funding for the construction phase of the project was released to the NRAO on May 15, 1985. During 1988, the first three antennas will be completed and put into operation. Construction will finish on two more, and specific hardware will be produced in the areas of electronics, data recording and playback, and monitor and control. Design specifications for the correlator will be further advanced. Construction will continue on the combined VLBA-VLA Array Operations Center which has been funded by the State of New Mexico. The planned activities for 1988 are outlined in more detail in Appendix E.

# X. PERSONNEL

## 1988 Full-Time Employment by Location

| | Estimated Distribution | | | | |
|---|---|---|---|---|---|
| | GB | CV | TUC | SOC | Ceiling |
| General & Administration | | | | | |
| Director's Office | | 6 | | | 6 |
| Fiscal Office | 7 | | | 5 | 12 |
| Business Management | | 8 | | | 8 |
| Subtotal | 7 | 14 | | 5 | 26 |
| Research Support | | | | | |
| Basic Research | | 14 | 1 | 13 | 28 |
| Charlottesville Operations | | | | | |
| Computer | | 12 | | | 12 |
| Observatory Services | | 6 | | | 6 |
| Subtotal | | 18 | | | 18 |
| Technical Development | | | | | |
| Central Lab | | 15 | | | 15 |
| Green Bank Operations | | | | | |
| Telescope Services | 31 | | | | 31 |
| Electronics | 22 | | | | 22 |
| Plant Maintenance | 14 | | | | 14 |
| Administrative Services | 11 | | | | 11 |
| Scientific Services | 10 | | | | 10 |
| Subtotal | 88 | | | | 88 |
| Tucson Operations | | | | | |
| Operations/Maintenance | | | 15 | | 15 |
| Electronics | | | 13 | | 13 |
| Subtotal | | | 28 | | 28 |
| Socorro Operations | | | | | |
| Scientific Services | | | | 8 | 8 |
| Engineering Services | | | | 30 | 30 |
| Computer | | | | 16 | 16 |
| Electronics | | | | 26 | 26 |
| Array Operations | | | | 11 | 11 |
| Administrative Services | | | | 15 | 15 |
| Subtotal | | | | 106 | 106 |
| VLBA Operations | | | | | |
| Scientific Services | | | | 1 | 1 |
| Engineering Services | | | | 1 | 1 |
| Computer | | | | 0 | 0 |
| Electronics | | | | 12 | 12 |
| Array Operations | | | | 3 | 3 |
| Administrative Services | | | | 1 | 1 |
| Subtotal | | | | 18 | 18 |
| TOTAL NRAO | 95 | 61 | 29 | 142 | 327 |

# XI. NATIONAL RADIO ASTRONOMY OBSERVATORY
## CY 1988 PROVISIONAL FINANCIAL PLAN
($ in thousands)

| | 1986 Actual Expend. | 1987 Est. Expend. | 1988 New Funds* | 1988 Uncomm. Funds Carried Over from 1987 | 1988 Total Avail. for Commit. | 1988 Commitments Carried Over from 1987 | 1988 Total Available for Expend. |
|---|---|---|---|---|---|---|---|
| I. OPERATIONS | | | | | | | |
| Personnel Comp. | $ 9,300.0 | $ 9,282.0 | $10,189.0 | | $10,189.0 | | $10,189.0 |
| Personnel Benefits | 2,393.0 | 2,599.0 | 2,791.0 | | 2,791.0 | | 2,791.0 |
| Travel | 424.0 | 508.0 | 494.0 | | 494.0 | | 494.0 |
| Material & Supply | 4,426.0 | 4,807.0 | 5,684.0 | | 5,684.0 | $300.0 | 5,984.0 |
| Management Fee | 380.0 | 400.0 | 420.0 | | 420.0 | | 420.0 |
| Common Cost Recovery | (344.0) | (393.0) | (271.0) | | (271.0) | | (271.0) |
| Total Operations | $16,579.0 | $17,203.0 | $19,307.0 | | $19,307.0 | $300.0 | $19,607.0 |
| II. EQUIPMENT | | | | | | | |
| Research Equipment | $ 961.0 | $ 690.0 | $ 400.0 | $ 100.0 | $ 500.0 | $ 100.0 | $ 600.0 |
| Operating Equipment | 105.0 | 115.0 | 140.0 | - | 140.0 | - | 140.0 |
| Total Equipment | $ 1,066.0 | $ 805.0 | $ 540.0 | $ 100.0 | $ 640.0 | $ 100.0 | $ 740.0 |
| Total: Oper. & Equip. | $17,645.0 | $18,008.0 | $19,847.0 | $ 100.0 | $19,947.0 | $ 400.0 | $20,347.0 |
| III. DESIGN & CONST. | | | | | | | |
| VLBA Project | $11,666.0 | $11,571.0 | $11,900.0 | $ 498.0 | $12,398.0 | $3,733.0 | $16,131.0 |
| Voyager 2 Project | 1,774.0 | 1,625.0 | 977.0 | 123.0 | 1,100.0 | 175.0 | 1,275.0 |
| 75 MHz Capability | - | 100.0 | 400.0 | - | 400.0 | - | 400.0 |
| Interferometer Addn. | - | | - | 39.0 | 39.0 | - | 39.0 |
| Total: Design & Const. | $13,440.0 | $13,296.0 | $13,277.0 | $ 660.0 | $13,937.0 | $3,908.0 | $17,845.0 |
| TOTAL PLAN | $31,085.0 | $31,304.0 | $33,124.0 | $ 760.0 | $33,884.0 | $4,308.0 | $38,192.0 |

* Includes USNO Funds $847k; NASA funds $977k; NRL funds $400k; NSF funds $30,900k.

1988 PROVISIONAL FINANCIAL PLAN FOR OPERATIONS AND EQUIPMENT
($ in thousands)

| | 1986 | 1987 | 1988 Available for Commitment | | | |
|---|---|---|---|---|---|---|
| | Total Expenditure | Est. Expenditure | Wages & Benefits | M&S Services | Travel | Total Available |
| I. OPERATIONS | | | | | | |
| Gen. & Admr. | $ 1,753.0 | $ 1,875.0 | $ 1,158.0 | $ 640.0 | $ 92.0 | $ 1,890.0 |
| Research Sup. | 1,781.0 | 1,820.0 | 1,706.0 | 10.0 | 191.0 | 1,907.0 |
| CV Oper. | 1,351.0 | 1,206.0 | 742.0 | 440.0 | 23.0 | 1,205.0 |
| Technical Dev. | 730.0 | 685.0 | 631.0 | 175.0 | 15.0 | 821.0 |
| GB Oper. | 4040.0 | 3,925.0 | 3,381.0 | 702.0 | 38.0 | 4,121.0 |
| TUC Oper. | 1,508.0 | 1,540.0 | 1,140.0 | 410.0 | 40.0 | 1,590.0 |
| SOC Oper. | 5,380.0 | 5,945.0 | 3,720.0 | 2,641.0 | 63.0 | 6,424.0 |
| VLBA Oper. | - | 200.0 | 502.0 | 666.0 | 32.0 | 1,200.0 |
| Management Fee | 380.0 | 400.0 | | 420.0 | | 420.0 |
| CC Recovery | (344.0) | (393.0) | | (271.0) | | (271.0) |
| Total Operations | $16,579.0 | $17,203.0 | $12,980.0 | $5,833.0 | $494.0 | $19,307.0 |
| II. EQUIPMENT | | | | | | |
| Research Equip. | $ 961.0 | $ 690.0 | | $ 500.0 | | $ 500.0 |
| Operating Equip. | 105.0 | 115.0 | | 140.0 | | 140.0 |
| Total Equipment | $ 1,066.0 | $ 805.0 | | $ 640.0 | | $ 640.0 |
| TOTAL OPERATIONS & EQUIPMENT | $17,645.0 | $18,008.0 | $12,980.0 | $6,473.0 | $494.0 | $19,947.0 |

Note: See preceding page for design and construction allocations.

ESTIMATED CUMULATIVE QUARTERLY EXPENDITURE
FOR OPERATIONS AND EQUIPMENT
CY 1988
($ in thousands)

| Quarter Ending → | 03/31 | 06/30 | 09/30 | 12/31 | Total Available for Expenditure |
|---|---|---|---|---|---|
| Personnel Compensation & Benefits | $3,107.0 | $ 6,156.0 | $ 9,443.0 | $12,980.0 | $12,980.0 |
| Material & Supply* | 2,051.0 | 3,344.0 | 4,774.0 | 6,015.0 | 6,133.0 |
| Travel | 93.0 | 223.0 | 373.0 | 494.0 | 494.0 |
| Equipment | 276.0 | 368.0 | 516.0 | 665.0 | 740.0 |
| Total | $5,527.0 | $10,091.0 | $15,106.0 | $20,154.0 | $20,347.0 |
| Percent Distribution, 1988 | 27.2% | 49.6% | 74.2% | 99.1% | 100% |

Actual Expenditures, 1986-87

| | | | | | |
|---|---|---|---|---|---|
| 1987 (Est. @ 09/30 and 12/31) | 24.3% | 48.1% | 74.3% | 99.4% | |
| 1986 | 22.2% | 46.3% | 73.8% | 96.4% | |

* includes Management Fee and Common Cost Recovery

# APPENDIX A

During 1988 the permanent staff of the NRAO will be working in a number of research areas as described below. Some of the research will be carried out in collaboration with visiting scientists.

## A. STUDIES WITHIN THE GALAXY

### 1. Stars and the Stellar Environment

A program is underway to investigate the massive nebulae that surround certain massive early-type stars. Although the radio emission of the extended stellar winds of O-stars and Wolf-Rayet stars is now well understood, there remains considerable uncertainty as to the duration of the mass-losing phase. The ring nebulae which surround some early stars are believed to result from the interaction of the wind and the ambient interstellar medium. Recent observations have detected CO in the direction of these nebula. Future work will attempt to demonstrate the association of the CO with the nebulae and to infer from the CO data the mass of the nebulae and, as a corollary, the lifetime of the mass-loss stage.

There continues to be interest in the question of the variability of the thermal radio emission from Wolf-Rayet stars. Such variability would indicate a change in the structure of the wind. Recent observations of the optically variable WN star HD191765 will be analyzed to search for radio variability.

Specific studies of novae, recurrent novae, and related objects will be pursued both observationally and theoretically. The physics and evolution of ejected stellar envelopes are strongly influenced by their interaction with external gas or previously existing stellar winds. Studies of the radio emission of X-ray binaries also offer the potential of better understanding the source environment. Radio flaring events, quiescent and periodic emission will be related to shock expansion models produced in the X-ray source environment. Many of the models for X-ray binaries relate to the kinematic conical jet model derived for the enigmatic object SS 433. Observations are planned that will test the universality of the model to many X-ray binaries and aid in determining some of the kinematic parameters of the jets. Further to SS 433 itself, continuum millimeter-wave observations will be compared with lower frequency observations in order to determine the emission mechanisms extant in the region directly surrounding the object.

Recent optical and ultraviolet studies of the central stars of planetary nebulae have demonstrated that at least some of the stars are losing matter in stellar winds, although at a rate that is three orders of magnitude less than that of the early OB stars. Radio observations of some of the most compact planetaries were unable to detect the stellar winds directly, but the radio images show the more extended structure of the nebulae in some detail. These images will be used to explore the current theory that planetary nebulae result from the ejection of a stellar envelope into the region of a precursor stellar wind.

The flux density and positions of the two radio lobes and the radio core of Sco X-1 will continue to be monitored. This nearby galactic source has the same morphology as luminous extragalactic sources but it is so close that its motion can be determined. This is the only X-ray galactic binary system for which the proper motion within the source can be observed.

The accurate vertical motions of pulsars in the Galaxy are being investigated during multi-epoch VLA observations of a sample of pulsars. Analysis of the absolute position of each pulsar is compared with its position derived from pulse timing analysis. The background population of quasars found within about 10′ of each pulsar provides an accurate reference grid against which the astrometry is based.

2. Galactic Studies

The long-term program to monitor the proper motion of the galactic center radio source Sgr A* will be continued. Measurements during the four epochs between 1981 and 1985 have already resulted in the first two-axis measurements of the Sgr A* proper motion and are a considerable improvement over past single axis measurements. The motion is consistent with that expected for an object in the galactic center whose peculiar velocity is no larger than 40 km $sec^{-1}$. The differential astrometry experiment measures the position of Sgr A* with respect to three reference sources spaced in a triangle around Sgr A* at an average distance of 0°.5. The current estimated level of error of the technique is ± 0.50 milli-arcseconds per year. Ultimately it is hoped that improved analysis techniques and reduced errors will lead to much lower limits on the size of the peculiar motion in Sgr A* and to the possibility that it is a massive object.

Further mapping of CO around Sgr A will take advantage of the new SIS receiver at the 12-m telescope. The kinematics and distribution of gas near the center of the Galaxy will be utilized in a study of large scale phenomena such as (1) the apparent ejection of massive ($10^4$-$10^5$ $M_{sun}$) clouds at high velocity (200 km $s^{-1}$) from the vicinity of the nucleus, and (2) the interaction between Sgr A and the ambient GMCs, most notably the one at 50 km $s^{-1}$. The latter cloud is the site of the most recent star formation near the center, and its evolution may control the appearance of the region once the young, massive stars undergo mass ejection and pass through the supernovae stage.

The four HII regions, W43, G38.0, IC410, and the Rosette Nebula have been extensively surveyed in L-band continuum at the VLA. Wide field (2°) mosaiced images will be produced which have moderate resolution (20"). The images will be used in conjunction with HI, CO, and IR data to study their structure and evolution. The complex wide field imaging process should result in routinely usable software for wide field imaging and to a better understanding of the quality of the images when no single dish, zero spacing data is available.

The characteristics of H and He recombination lines at millimeter wavelengths will continue under study and may give us more understanding of the physics of ionized nebulae. The principal quantum numbers for millimeter wave transitions are small enough that maser amplification of the lines, important at centimeter and longer wavelengths, should not be a factor.

The thermal emission from dust clouds associated with star forming regions will be mapped at 1300 microns (12-m telescope) and at 450-800 microns (United Kingdom Infrared Telescope [UKIRT]). Combining these results with existing observations made in the far infrared will help determine the general thermal structure of the clouds, the distribution of their mass with respect to their energy sources, and the frequency dependence of the emission cross-sections.

The nature of the dense cores in the $\rho$ Ophiuchi molecular cloud remains a puzzle. During the past year regions have been identified where the impact of heating due to star formation has destroyed the $DCO^+$ molecule, and in other dense cores no such destruction has apparently occurred. The high resolution observations will be combined with a chemical and heating model to infer the time since heating began in that cloud, which should place interesting limits on the young star's age. Further observations are planned this year to elucidate the chemical impact of low mass star formation on their placental cores. In the IR16293-2422 region, a rotating disk surrounding a possible binary protostar was found, using the VLA and OVRO interferometers. There is convincing evidence that $NH_3$ is depleted onto grains in the central high density region, while $C^{18}O$ remains in the gas. Further work will measure the mass distribution in this disk. The large fractional ionization of carbon seen over extended regions in the Ophiuchius dark cloud by means of its radio recombination line emission is unique among Galactic molecular clouds. The ionization may arise either from embedded early-type stars within the cloud or from an external source unrelated to the molecular cloud. In the former case the CII should appear clumped, whereas in the latter a surface ionization is suggested. High resolution VLA observations of the n = 166 CII recombination line will be used to discriminate between these two possibilities.

A new receiver at the James Clark Maxwell telescope will enable further observations of the CI line at 492 GHz to be carried out. The observations will concentrate on the $\rho$ Oph BZ4 region where the CII radio recombination line arises in a region extended with respect to the JCMT beam. These observations should establish whether CI emission arises throughout the bulk of a cloud or is localized to an interface region near ionizing sources.

The density and ionization structure of the halo of the Galaxy will be probed as part of a study of the vertical structure of the interstellar medium in various ionization stages. Ultraviolet observations of various interstellar ions toward high latitude stars can now be compared with 21 cm neutral hydrogen observations for about 100 stars. The overall structure of the neutral interstellar medium, particularly its variations in total column density on various linear scales, will come under investigation. The large body of HI and interstellar reddening data will be analyzed in an attempt to assemble a self-consistent picture of the fluctuation spectrum of interstellar matter.

Observations of turbulence in the interstellar medium will proceed, using visibility measurements for a wide range of Fourier components in order to separate the portions due to macroscopic structure and those due to turbulent structure. The refractive interstellar scintillation and intrinsic variability of 1741-038, one of the most rapid interstellar scintillators known, will be analyzed using five frequency VLA data and two frequency Green Bank interferometer data.

3. <u>Interstellar Molecules</u>

Interferometric observations of the distribution of DCN in the Orion Molecular Cloud will be extended with the Hat Creek interferometer as part of a larger study of deuterium in the Galaxy. The abundance of deuterium in the Galaxy is an important clue to its chemical history, and it is most easily detected through its presence in abundant molecules, such as DCN. DCN is relatively insensitive to temperature, thus narrowing its possible chemical ancestors and marking it as a useful deuterium abundance sensor. Other molecules, such as $C_3H_2$, although well distributed in the Galaxy, seem to have more complex ancestral chemistry.

Several searches for molecular species in the interstellar medium continue. Following the discovery of PN, the first identified P-compound in the ISM, phosphorus chemistry will be pursued by searches for $PH_3$ and HCP. Analysis of the phosphorus chemistry used to explain PN predicts that HCP may be abundant while $PH_3$ will not be. A search for the HCCO radical will be made, based on frequencies accurately calculated from recent laboratory determined molecular constants. HCCO will test formation mechanisms for carbon-chain species of the form $C_nO$ and $C_nS$, which have recently joined the cyanopolyynes as identified C-chain species unique to interstellar chemistry. A search for protonated cyanocetylene ($HC_3NH+$) is planned, based on recently measured frequencies. This species should delimit ways in which $HC_3N$ itself, the progenitor of the cyanopolyyne chain series, is formed. An attempt to confirm the important interstellar ion $H_3O+$ will be made via its $(3,2) \rightarrow (2,2)$ transition at 365 GHz, following detection of a single line at 307 GHz last year which corresponds to its P(2,2) transition. This ion is central to the chemistry of the entire hydroxyl family, including water. Vibrationally excited HCO+ will be sought as a continuation of the successful program on vibrationally excited species which yielded CS $v = 1$

and SiS v = 1. Frequencies are recently measured. Vibrationally excited HCO+ will indicate whether molecular ions are themselves formed by mechanisms other than ion-molecule reactions (e.g., shock chemistry). The U. Massachusetts-NRAO K-band survey for the sources TMC-1, L134N, W51, and IRC+10216 will continue. It is planned to cover the region 18.0-21.0 GHz with a resolution of 0.12 km/s. More than half this region has been completed, and many new molecular lines, including many unidentified ones, have been found.

The $C_4H$ molecule has been identified as the only one of 71 known interstellar species which has a Zeeman splitting suitable for detecting magnetic fields as small as 7 $\mu$G in the dense star forming cores of interstellar molecular clouds. A search will be made for its Zeeman effect. A positive result is expected if the magnetic field is enhanced during contraction of the cloud core at anything like the theoretically expected amount. A negative result will prove that magnetic fields are expelled from molecular clouds during star forming processes and play no role in star formation.

A follow-up is planned of the remarkable discovery of the small-ring molecule $C_3H_2$ in 8 of 9 IRAS cirrus clouds searched. The ubiquity of so complex a molecule in such diffuse clouds points to a new type of interstellar chemistry. The apparent correlation of the $C_3H$ intensities with 12 $\mu$m IRAS emission, which arises from hot grains, suggests that the chemistry in question is formation on grain surfaces.

A search for $^7Li$ via its hyperfine spin-flip transition at 803 MHz is planned. According to some nucleosynthesis models of the galactic center which feature a massive central object or enhanced spallation reaction rates, $^7Li$ may be one thousand times over-abundant there, in which case it would be detectable. Thus, such theories will be assessed.

Observations of the shell of IRC+10216 with the Owens Valley Radio Observatory (OVRO) interferometer have shown that $HC_3N$ lies distributed in a shell, created by photochemistry in the outer envelope. Further observations will be made of photo-products. SiS, on the other hand, lies deep within the shell. Single antenna observations of vibrationally excited SiS hint that it is a good probe of the very innermost regions where dust forms and acceleration of the shell occurs. Interferometric observations at 1 mm at OVRO are planned to pursue this hint.

Formaldehyde is an abundant but fragile component of the interstellar medium. VLA maps of the core of OMC1 demonstrate that the violent environment of IRc2 has proven dangerous to formaldehyde and destroyed it in the gas phase. There is apparently a replenishment as new formaldehyde is liberated from grain surfaces. Maps will be obtained with the Hat Creek interferometer to detail this picture.

The 3 mm survey covering the region 69.5-115.5 GHz in Sgr B2 and Ori (KL) will be interpreted in light of comparisons with similar surveys carried out at Bell Telephone Labs and Onsala Space Observatory. Many lines not seen in the other surveys will be discussed, particularly those as yet unidentified. The chemistry of these two archetypical star-forming molecular regions will be reassessed.

## B. EXTRAGALACTIC STUDIES

### 1. Normal Galaxies

The local luminosity function at $\nu = 1.4$ GHz will be obtained from two statistically complete samples of galaxies. VLA maps of all 308 spiral galaxies with $B_T \leq +12$ mag and $\delta \geq -45°$ are being used to obtain flux densities of the weakest sources and fit the low end of the luminosity function. Radio "identifications" of all galaxies in the diameter-limited ($\theta \geq 1$ arcmin) Uppsala General Catalogue stronger than S = 150 mJy have been made from the Green Bank 1400 MHz sky maps, with follow-up VLA observations to confirm or reject doubtful cases. The resulting sample of galaxies is complete over a large volume ($\approx 10^7$ Mpc$^3$) and will determine the luminosity function up to $L \approx 10^{25}$ W Hz$^{-1}$ The combined luminosity function will be used to determine the amounts of evolution required to explain the counts and identifications of faint (S < 1 mJy) radio sources.

VLA maps of the entire IRAS Bright Galaxy Sample (BGS) will be made. This sample of 324 galaxies with $S_\nu$ (60 $\mu$m) $\geq 5.4$ Jy is the infrared analog of the radio 3CR and optical Shapley-Ames samples, and it thus represents the best sample for investigating the processes responsible for infrared emission in galaxies. There is a tight correlation between the far-infrared and radio continuum fluxes of infrared-selected galaxies. The VLA maps can be used to test its physical significance and limitations. The VLA maps may also be our best means for establishing the brightness distributions of the vast majority of the BGS sources; i.e., those that are unresolved in the IRAS survey at $\lambda = 60$ $\mu$m.

A large scale survey of CO in M31 will be carried out with the 12-m telescope with the aim of obtaining global parameters of atomic and molecular gas in that galaxy. The planned program will use a new technique to map large objects within a reasonable observing time, making full use of the available 12-m resolution in a multi-parameter galactocentric coordinate system. After investigation of some instrumental problems, it is hoped to complete this survey and to extend the technique to a complete sample of large, nearby galaxies. Small parts of the large, nearby galaxies have been studied by other workers in great detail, and many complete surveys of smaller, more distant galaxies already exist. However, until now it has not been possible to put the nearby galaxies of very large angular extent in context with the well studied, more distant galaxies. Software developed for this work will form the basis for analysis of future observations with the multiple beam systems being developed for the 12-m telescope.

New HI observations of a sample of optically studied elliptical galaxies are planned in an attempt to add significantly to our understanding of the kinematics of these systems. Twenty-one centimeter line profiles measure the total range of line-of-sight velocities, ordered and random. Existing data on one or two ellipticals give tantalizing evidence for infall in the outer regions since the total velocity range exceeds the sum of ordered and random velocities measured only in the central regions. Infall could arise from the cooling flows observed from X-ray data, but the small sample needs to be extended through the detection of more ellipticals in the HI line. It is hoped that a 50 percent detection rate can be achieved with integration times sufficiently long to reduce noise levels to a few tenths of a millijansky.

For spiral systems the study of the relationship between size and internal motions has proven to be particularly informative since these two parameters (internal motion is primarily rotational in disk systems) give important physical insight into global properties, e.g., mass, density, angular momentum, etc. The problem is more complex for elliptical galaxies since (i) random motion is significantly larger than rotational (in most instances), and (ii) their radial dependence is poorly known. It is hoped that a relation equivalent in physical content to that found for spirals is derivable with the ultimate goal of combining the two so that the full range of global properties of all galaxies may be delineated.

VLA observations of a large, complete sample of E/SO galaxies, obtained in 1986/87, will be analyzed to derive a radio luminosity function and study other radio characteristics of this class of galaxy. The primary emphasis of the study is to extend our understanding of these objects to weaker radio luminosities.

Observations of two clumpy galaxies made in 1987 with the VLA will be used to investigate the structure and possible variability of these objects. These galaxies are believed to be undergoing extremely rapid star formation, and a major goal of the study is to look for possible structural changes resulting from the expected extreme SN activity. Observations of a more extensive list of about 10 clumpy galaxies, begun in 1987, will continue with the goal of obtaining maps at several frequencies in order to study the radio structures and spectra of this unusual class of object.

Several Seyfert galaxies, mapped in HI with the VLA and in CO at the 12-m telescope, will be analyzed in an attempt to see how the nuclear phenomena affect disk morphologies. The kinematics of HI (which exists only at some distance from the nucleus) or of CO (which exists only near the nucleus and fills in the central "holes" found in the HI distribution) is not discernibly influenced by the nuclear activity. Although the disks do not appear to have been influenced, a more detailed analysis is warranted since subtle effects are not easily detected, especially in view of the wide variation in disk properties presented by entirely "normal galaxies." There are a few emission line galaxies which appear to have populations of O stars and Wolf-Rayet stars that are comparable in number. This unusually high ratio of WR stars implies that a sudden burst of star formation occurred very recently. VLA maps of two of the objects will be used to estimate the thermal component of the radio emission, so as to estimate the population of young stars, and CO observations will be made to get an indication of the amount of neutral gas remaining in these objects. A comprehensive study of the global properties of ring galaxies based on HI measurements is planned. There are a variety of such systems: many Seyferts, e.g., NGC 1068, possess an outer ring which appears as a low surface brightness extension of normal arm structure while others, e.g., Hoag's object, look almost like planetary nebula. Both examples are poorly understood. Both show 21 cm radiation, but have been only randomly studied by this technique. It is hoped that a systematic study will improve the situation.

Megamaser galaxies provide a unique opportunity to test models of infrared pumping and observationally sample the detailed kinematics of the remote interstellar medium. The failure to detect CH in the four brightest OH megamaser galaxies to limits of 6 mJy will be analyzed in light of current notions about the weak but "universal" pumping of galactic CH and the strong but unexplained OH megamaser excitation. In particular, it will be shown how far-IR radiation probably pumps the OH megamasers but cannot similarly pump CH.

A broad program of studying radio supernovae in external galaxies will continue along several fronts. Monitoring programs will focus on the archetypical radio supernovae SN 1979c and SN 1980k as they continue their decline in flux density, and the M82 discrete sources will be regularly checked for variations. New optically detected supernovae will be checked for radio emission, and the nuclei of spirals, where optical detection is difficult, will be observed for indications of supernova activity. An attempt will also be made to detect radio radiation from the early supernova, SN 1970g.

2. Radio Galaxies and Quasars

A radio and optical study of B3 classical double radio sources will be initiated as a means of reaching lower flux density levels than those previously attained in extensive studies of the 3CR sample. Long integration, 6 cm, VLA images will be made to confirm the structural types of the sample and to detect central components. Optical identifications of the central components will be investigated using deep CCD images. The long range goal of the project is to test whether the correlation of radio structure with absolute radio and optical luminosity remains valid at high redshift and whether the redshift cutoff around 2-3 holds for these fainter sources.

A comprehensive study of variability of extragalactic objects, begun in 1979, will be continued. The recently discovered variability on a time scale of 1-2 days, which has tentatively been attributed to refraction by SN generated turbulence in the ISM, will be further observed with the Bonn 100-m telescope. Still shorter time scales, down to several minutes, will be investigated using simultaneous observations obtained in 1986/87 with the VLA and the 92-m telescope. The analysis of longer time scale variability--up to six years--is presently in progress and should be completed during 1988.

VLBI observations will be used in a continuing study of the structure and dynamics of compact radio galaxies and quasars, with emphasis on sources which show unusual or complex behavior. Of particular interest will be the quasar 3C 454.3 which has shown periods of rapid expansion as well as quiescent periods. At the other extreme is the radio galaxy NGC 1275 which has shown only relatively slow changes over the past ten years. New observations with particularly good dynamic range will help to understand better the relation among the wide variety of dynamic phenomena which are currently observed, and will better constrain the widely used relativistic beaming models.

The diffusive shock acceleration process that has been suggested as the mechanism giving rise to the electron distributions, and ultimately the fluctuating continuum brightness in blazars will be theoretically studied. In the process, fast electrons diffuse around a shock many times before being convected downstream, gaining an amount of energy on every cycle that is proportional to the velocity difference between the upstream and downstream fluids. Blazars provide two important points for comparison with the theory: spectral shape and time variability. The predicted continuum shape from shock acceleration with synchrotron losses is consistent with the data, but a more powerful test is the comparison with the time variability. Theoretical calculations will assess the time dependent emission properties from fresh plasma that is introduced to a shock. The synchrotron signature of outbursts will be calculated for a variety of diffusion coefficients and for a variety of shock strengths. These theoretical predictions will provide a clean comparison with the data and will be an important test of the relevance of the shock acceleration process in the environment of blazars.

Specific radio galaxies, which are involved in ongoing studies, include M87, Fornax A, and NGC 326. Further analysis of 2 cm polarization VLA data for M87 is planned in order to understand the complex magnetoionic medium, which recent observations have revealed in the inner 2 kpc of the galaxy. For the maps of the large extragalactic radio source Fornax A, the Pittsburgh Cray X-MP supercomputer will be used to combine single dish and VLA data. Already it is possible to see a myriad of details in the radio lobes in both intensity and linear polarization. Analysis of the four frequency, multi-configuration data for the precessing galaxy NGC 326 will be completed. The total intensity and linear polarized intensity distributions show symmetries indicative of precession of the nuclear source, buoyancy, and ram pressure.

The search for gravitational lensing from a complete sample of the Most Luminous Quasars will continue with high resolution VLA observations of five sources previously observed with low resolution. This will give for the first time a statistical estimate of the occurrence of gravitational lensing.

The extensive long range investigation of the sidedness of radio jets in high luminosity sources will continue. The deep imaging that has been completed to date has detected counterjets in three of six cases, and clearly indicates that jets in double-lobed quasars are not only one-sided objects. In the multi-configuration imaging program, a complete sample of large, lobe-dominated 3CR quasars are being scrutinized with 0".35 resolution. Once counterjet emission is detected or improved limits are found for each of the objects, the observed jet/counterjet asymmetries will be related to other properties of the source, such as the brightness and placement of hot spots, the available source inclination indicators, and the apparent core power, apparent jet power and core prominence. The statistical studies ultimately aim at providing further constraints for source models.

3. Clusters of Galaxies and Cosmology

In the cluster environment nearly all giant elliptical galaxies for which sensitive X-ray images have been obtained show the presence of hot gas ($5\text{-}10 \times 10^6$ K). Since the gas infall time onto the central galaxy is greater than the gas cooling time, gas is expected to cool and condense out of the flow and possibly form stars. Searches for such gas in its neutral form are being carried out. The HI gas in the cooling flow elliptical galaxy, NGC 4406, will be mapped in detail to determine whether its spatial distribution matches the prediction of cooling flow theory. The HI profiles that have already been detected are unlike those found in elliptical galaxies rich in gas, and the HI properties are like those predicted for cooling flows.

The pressure of the hot X-ray emitting gas in cooling flows is high enough to make the density of co-existing neutral gas under pressure equilibrium of order $10^3$-$10^4$ $cm^{-3}$. Under such conditions molecular gas could form. A search for CO emission as a probe of the molecular gas will be undertaken with the 12-m telescope toward the cooling flow ellipticals NGC 4406 and NGC 4472. Successful observations will lead to important insights about star formation in cooling flow ellipticals, while failure to detect such gas will call the basic scenario into question.

The Green Bank 1400 MHz sky maps are being searched for evidence of clustering on scales larger than 100 Mpc in the redshift range $0.3 < z < 2$. Since the maps are confusion limited, every independent beam area ($\approx 10^{-5}$ sr) in a 1-sr region containing the north galactic pole contributes information and reduces the statistical noise. Preliminary analysis shows that differences between the flux density distributions in 2°x2° or larger squares are no greater than expected from random source distributions. A more detailed analysis will be made to set strict upper limits on the large-scale clustering of radio sources.

The density of sources and possible fluctuations of the cosmic microwave background are being measured at 30" resolution with the VLA at 4.8 GHz. The study is an extension of earlier work which obtained statistical constraints on source counts down to about one microjansky. Statistical modelling indicates that all of the previously reported fluctuations in the background are due to the effect of weak, unresolved sources and the limitations of the CLEAN process in removing their contribution to the sidelobes. The field now under investigation is coincident with a field which will be the target of a very deep optical study with the Hubble Space Telescope.

VLBI observations will be made of a sample of very distant ($z > 2$) quasars. The observed transverse velocities will be compared with those of a sample of nearby quasars in order to test the expected dependence on red shift and in this way to obtain an independent estimate of the cosmological deceleration parameter, $q_o$.

C. MISCELLANEOUS

The VLA will be used to study the solar wind in a novel high-time-resolution mode in which images of a background source near the sun are obtained, averaged over times as short as 5 milliseconds. Irregularities in the solar wind cause the source to scintillate on time-scales varying from milliseconds for diffractive effects to seconds for refractive effects. Previous observations ignored the information present in the mutual coherence of the electric field, which is the prime observable of an interferometric array such as the VLA. It is possible that more details of the fine-scale structure of the solar wind can thus be extracted. Theoretical investigations into the method for imaging very extended objects at radio wavelengths will continue. Previous work has shown that by pointing the array at a grid of positions spanning an object, and by then suitably processing the resulting data in a Maximum Entropy algorithm, high quality images of very large fields can be produced. This technique, known as "mosaicing," is now in standard use at the VLA and has allowed imaging of objects up to 3 degrees in size at a wavelength of 20 cm. The mosaicing technique is vital to millimeter wavelength interferometry, where the primary beam size is usually much smaller than the objects to be studied. Test observations of several large, bright objects will be carried out using the Berkeley array.

Tests of a new receiving system for galactic HI are scheduled for the upcoming year. The receiver design, as developed so far, selectively illuminates the 300-ft telescope to produce an extremely high main beam efficiency and very low sidelobes. Contamination of HI profiles by stray radiation entering the telescope's far sidelobes seriously limit the accuracy of 21 cm galactic spectra.

A remapping of the northern sky at 6 cm with the 7-feed receiver will take place on the 300-ft telescope. The new observations will fill gaps from the first survey and reduce the noise level by $\sqrt{2}$. Most of the routines needed to analyze single scans have been developed, and two-dimensional mapping will be possible as soon as FITS output tapes can be written by the single-dish program CONDAR.

Effects of the turbulent troposphere on radio astronomical imaging will be evaluated. The study will concentrate on understanding the causes of poor seeing and predicting the onset of bad observing conditions. A statistical summary of seeing at the VLA will be prepared.

# APPENDIX B

## SCIENTIFIC STAFF

(Does not include Research Associates or Visiting Appointments)

| | | |
|---|---|---|
| J. M. Benson | CV | Extragalactic radio sources; VLBI image processing. |
| R. C. Bignell | SO | Polarization and mapping of extragalactic radio sources; planetary nebulae; supernovae remnants. |
| J. N. Bregman | CV | Theoretical astrophysics; interstellar medium; cooling flows; quasars. |
| A. H. Bridle | CV | Extragalactic radio sources. |
| R. L. Brown | CV | Theoretical astrophysics; interstellar medium. |
| B. G. Clark | SO | VLBA control; software development. |
| J. J. Condon | CV | QSOs; normal galaxies; extragalactic radio sources. |
| T. J. Cornwell | SO | Interferometry, image construction methods, the maximum entropy principle, spectral analysis, extragalactic radio sources. |
| W. D. Cotton | CV | Extragalactic radio sources; interferometry, computational techniques for data analysis. |
| P. C. Crane | SO | Normal galaxies; interferometry; radio frequency interference. |
| P. J. Diamond | CV | Spectral line interferometry; VLBI; software development. |
| R. D. Ekers | SO | Synthesis techniques; galactic center; radio continuum properties of normal galaxies; cosmology. |
| D. T. Emerson | TU | Nearby galaxies; star formation regions; millimeter wave instrumentation. |
| E. B. Fomalont | CV | Interferometry; extragalactic radio sources; relativity tests. |
| M. A. Gordon | TU | CO; galactic structure; interstellar medium. |
| E. W. Greisen | CV | Structure of the interstellar medium; computer analysis of astronomical data. |
| W. M. Goss | SO | Galactic line studies; pulsars; nearby galaxies. |

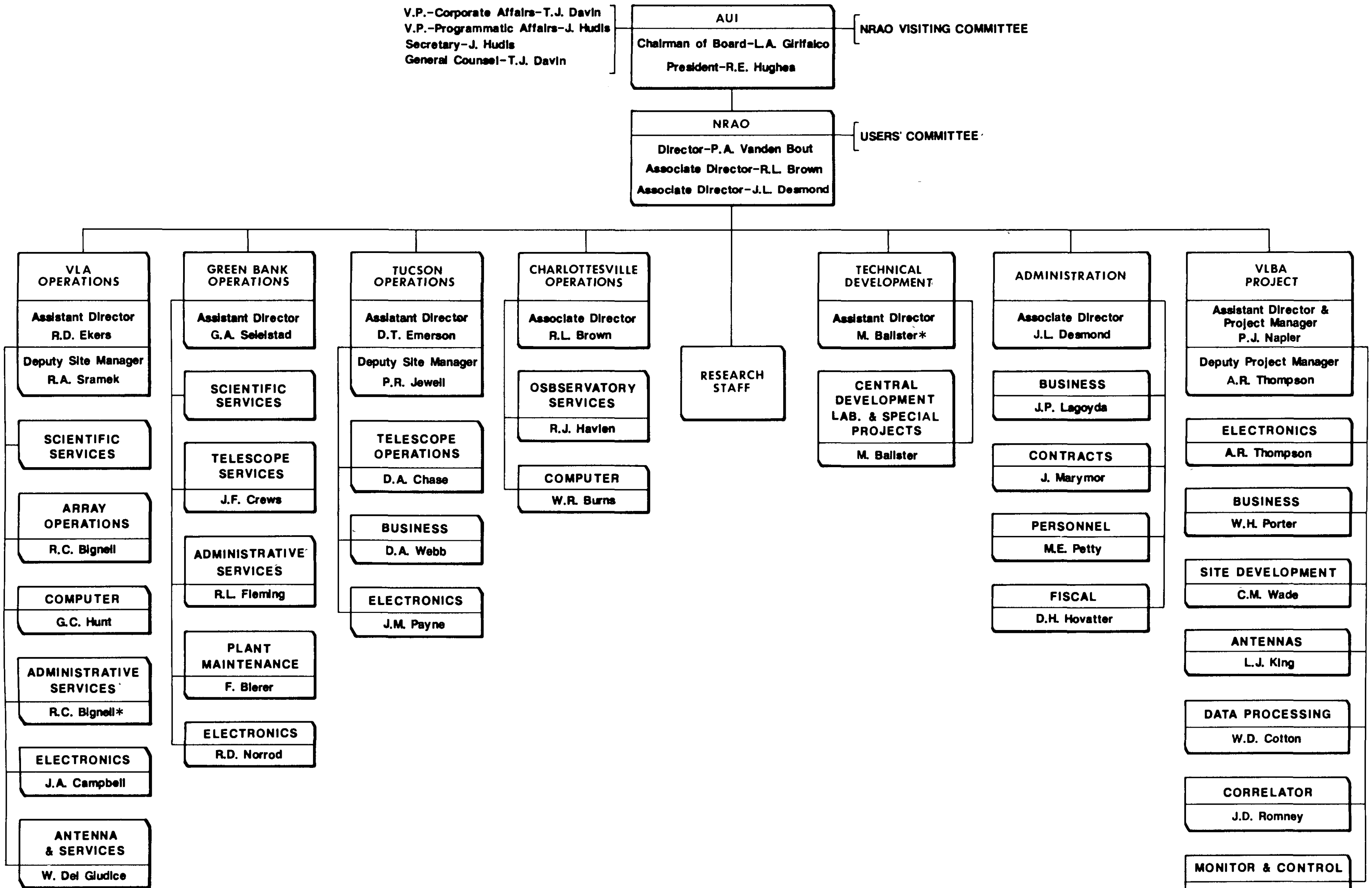
| | | |
|---|---|---|
| R. J. Havlen | CV | Galactic structure; clusters of galaxies. |
| D. S. Heeschen | CV | Variable radio sources; normal galaxies; QSOs |
| R. M. Hjellming | SO | Radio stars; theoretical astrophysics; VLA development. |
| D. E. Hogg | TU | Radio stars and stellar winds; extragalactic radio sources. |
| P. R. Jewell | TU | Circumstellar shells; interstellar molecules; cometary line emission. |
| K. I. Kellermann | CV | Extragalactic radio sources; VLBI instrumentation. |
| A. R. Kerr | CV | Millimeter wave development. |
| H. S. Liszt | CV | Molecular lines; galactic structure. |
| F. J. Lockman | CV | Galactic structure; interstellar medium; HII regions. |
| R. J. Maddalena | GB | Molecular clouds. |
| F. N. Owen | SO | Clusters of galaxies; QSOs; radio stars. |
| P. J. Napier | SO | VLBA development. |
| H. E. Payne | GB | Interstellar medium; extragalactic radio sources. |
| R. A. Perley | SO | Radio galaxies; QSOs; interferometer techniques. |
| M. S. Roberts | CV | Properties and kinematics of galaxies. |
| J. D. Romney | CV | Active extragalactic radio sources: VLBI; interferometer imaging. |
| A. H. Rots | SO | Nearby galaxies; spectral line interferometry; data display techniques. |
| G. A. Seielstad | GB | Quasars; active galaxies; VLBI. |
| R. A. Sramek | SO | Normal galaxies; quasars; astrometry. |
| B. E. Turner | CV | Galactic and extragalactic interstellar molecules; interstellar chemistry; galactic structure. |
| J. M. Uson | SO | Clusters of galaxies; cosmology. |

| | | |
|---|---|---|
| P. A. Vanden Bout | CV | Interstellar medium; molecular clouds; star formation. |
| J. H. van Gorkom | SO | Galactic center; nearby galaxies; clusters of galaxies; spectral line interferometry. |
| C. M. Wade | SO | Astrometry; stellar radio emission; minor planets; extragalactic radio sources; VLBA development. |
| R. C. Walker | SO | Extragalactic radio sources; VLBI; VLBA development. |
| S. Weinreb | CV | Millimeter wave development. |
| D. C. Wells | CV | Digital Imaging Processing; extragalactic research. |
| A. H. Wootten | CV | Structure; spectroscopy and chemistry of the interstellar medium in galaxies; star formation; circumstellar material. |

# APPENDIX C

## NATIONAL RADIO ASTRONOMY OBSERVATORY ORGANIZATION CHART

1 SEPTEMBER 1987




*Acting

# 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 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:

| | |
|---|---|
| G. K. Knapp (chairman) | Princeton University |
| R. J. Allen | University of Illinois |
| J. A. Baldwin | Cavendish Laboratory |
| A. Dalgarno | Harvard University |
| G. A. Dulk | University of Colorado |
| J. V. Evans | Comsat Laboratory |
| K. J. Johnston | Naval Research Laboratory |
| T. G. Phillips | California Institute of Technology |

## 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 twice a year.

The present membership is:

| | |
|---|---|
| W. A. Baan | Arecibo Observatory |
| D. C. Backer | University of California |
| J. Bally | AT&T Bell Laboratories |
| T. M. Bania | Boston University |
| J. A. Bookbinder | JILA/University of Colorado |
| J. O. Burns | University of New Mexico |
| F. O. Clark | University of Kentucky |
| J. M. Cordes | Cornell University |
| I. de Pater | University of California |
| J. M. Dickey | University of Minnesota |
| J. W. Dreher | Massachusetts Inst. of Technology |
| W. C. Erickson | University of Maryland |
| S. T. Gottesman | University of Florida |
| P. C. Gregory | University of British Columbia |
| M. P. Haynes | Cornell University |
| L. A. Higgs | Dominion Radio Astrophysical Observatory |
| J. M. Hollis | Goddard Space Flight Center |
| G. J. Hurford | California Institute of Technology |
| K. J. Johnston | Naval Research Laboratory |
| R. N. Martin | University of Arizona |
| G. K. Miley | Space Telescope Science Institute |
| J. M. Moran | Center for Astrophysics |
| R. L. Mutel | University of Iowa |
| P. Palmer | University of Chicago |

| | |
|---|---|
| D. B. Sanders | California Institute of Technology |
| D. R. Stinebring | Princeton University |
| H. A. Thronson | University of Wyoming |

VLBA Advisory Committee

The VLBA Advisory Committee will periodically review 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 will advise on broad aspects of 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 VLB projects. The Committee generally meets annually, but the exact meeting frequency will depend on the nature of current project activities and the rate of progress.

The current membership of the Committee is:

| | |
|---|---|
| R. Booth | Onsala Space Observatory |
| B. F. Burke | Massachusetts Institute of Technology |
| T. A. Clark | Goddard Space Flight Center |

| | |
|---|---|
| M. H. Cohen | California Institute of Technology |
| R. Frater | CSIRO, Division of Radiophysics |
| D. Jauncey | (alternate to Frater) |
| G. Greuff | Universita de Bologna |
| J. H. Lancaster | (unaffiliated) |
| M. J. Reid | Smithsonian Center for Astrophysics |
| M. Schmidt | California Institute of Technology |
| I. I. Shapiro | Center for Astrophysics |
| J. L. Yen | University of Toronto |

# APPENDIX E

## VERY LONG BASELINE ARRAY

### Revised Construction Plan and Budget for the VLBA

Included in this appendix is a further revision of the NRAO budget plan (BD65N1) and overview schedule for the construction of the Very Long Baseline Array (VLBA), reflecting the 1987 funding of $11.4M and the cut in anticipated 1988 funding from about $16M to $11.9M. Funding requested for succeeding years assumes constant funding with inflation added. Also included is a table (FIN07) outlining the planned utilization of Project funds during 1988.

Because of the importance of beginning construction of the correlator in 1988, the 1988 budget has been arranged to provide $679k for correlator hardware. This has required delaying as much as possible all other areas of the project, except that antenna and foundation construction has been maintained at two per year. The revised overview schedule reflects the slowed antenna procurement scenario described below and the presently planned order of station construction. Under this plan, the earlier stations will initially have only part of their complement of receivers and recording equipment, with the remainder to be provided later as funding permits.

### Antennas and Station

The antenna contract with Radiation Systems, Inc. (RSI) was forced into renegotiation yet again in 1987 due to insufficient project funding to maintain the contract at a three antenna per year level. The contract was recast to authorize the manufacture of two antennas in 1987, two in 1988, and two in 1989. The final antenna erection will not be complete until 1990. This change resulted in an overall price increase of $1,070,890, which is reflected in the Program Plan.

The status of the antennas authorized for fabrication and erection includes:

• Pie Town, NM: Although final acceptance of the antenna has not been made, the antenna is virtually complete except for the subreflector and its focussing mount. Outfitting is proceeding and first signals were observed through the antenna in early September using a prime focus feed at 610 MHz.

• Kitt Peak, AZ: The site work is complete and the antenna erection is approaching completion. Outfitting by NRAO personnel will begin in October.

• Los Alamos, NM: Site and foundation are complete. RSI's erection crews are on-site and antenna fabrication is proceeding.

• Fort Davis, TX: Due to the antenna erection schedule which requires a winter erection of this number 4 antenna, RSI requested (and was granted) a switch in the North Liberty/Fort Davis erection order. Fort Davis becomes the fourth site and North Liberty the fifth. The site, foundation, and building at Fort Davis are under construction. Work is proceeding and the site will be ready for RSI this fall.

• North Liberty, IA: The site, foundation, and building are under struction and are well ahead of the scheduled "need date."

• Brewster, WA: The same comment applies to the Brewster site as applies to North Liberty.

The remaining four sites: St. Croix, USVI; Owens Valley, CA; Hawaii; and Northeast are under either site selection or acquisition phase. All site selections are expected by early 1988. Additionally, work is continuing on the development and manufacture of the focus rotation mounts, subreflectors, and feed cones for the array antennas.

Array Operations Center (AOC)

Construction was initiated in August 1987 for the AOC building by the firm of Bradbury Stamm. Occupancy is scheduled for August 1988, and detailed planning for the move is underway.

Electronics

Front ends at 1.5, 4.8, and 23 GHz, for the first outfitting of the first five VLBA stations, will be complete by the end of 1987. In addition, for Pie Town only, front ends are ready for the 0.330 GHz, 0.610 GHz, 2.3 GHz, 8.4 GHz, 10.7 GHz, and 15 GHz bands.

A successful program of laboratory testing of the first two sets of electronics performed at the VLA site included verification of control and monitor functions, and phase stability of signals as a function of temperature. Further general tests were made as equipment was installed at Pie Town.

Plans for 1988 call for completion of two more outfittings for stations through number 6. Progress towards development of the 43 GHz front end will continue, with testing of the performance of SIS junctions and HEMT amplifiers for this band. Construction of the 43 GHz front ends is to begin in 1990.

The first two of the hydrogen maser frequency standards were delivered by Sigma Tau Standards Corporation in September, and a third unit was completed but retained by Sigma Tau for testing of the fourth maser. Masers 3 and 4 will be delivered in 1987 and masers 5-7 in 1988.

Data Recording

Substantial delays have been encountered in the development of the prototype data recording equipment by NEROC Haystack Observatory. The first recorder rack (REC) and the formatter for the previously shipped data acquisition rack (DAR) are now scheduled to reach the VLA for testing by NRAO engineers in late September. The second set of equipment from the prototype phase (Phase II) of the NEROC subcontract should be ready in December.

Procurement of long-lead items for the construction of two additional sets under the pre-production phase (Phase III) is in progress. This phase, to be largely completed during 1988, will provide the required final drawings, parts lists, and final cost estimates required for production in quantity. Phase III will also cover Haystack's construction and test of the first tape playback unit (PYB). However, development of the track data recovery electronics required to interface the PYB's to the correlator has now been undertaken by NRAO's correlator group.

After Phase III, NRAO will take responsibility for the production DAR's which contain the baseband conversion, sampling, and formatting electronics. Detailed plans are still under development, but it is presently proposed that NRAO produce the racks and about one-third of the modules and subcontract the other modules to NEROC. Construction of two such racks will be started at Charlottesville in late 1988.

It is planned that production of the REC's and PYB's will remain with Haystack until future phases of the NEROC subcontract.

Monitoring and Control

The Pie Town station computer has been used for control of the antenna, the receiver switching, and the data acquisition rack modules, in both technician/diagnostic mode and in actual observing mode. Work is progressing on making the system more nearly error free and more capable. The MicroVax computer, which will eventually serve as the array control computer, is now being used for software development of some of the programs which will be used to exchange information between the MicroVax and the Motorola station computers.

We expect to be able to support limited observations at Pie Town late in 1987 and to support unattended operations by mid-1988.

Correlator

After a year-long, intensive study, the correlator group has decided that the spectral-domain or "FX" correlator architecture can indeed realize superior performance at significantly reduced cost, with a reasonably low level of technical risk using current micro-electronics technology. This decision was accepted by VLBA project management early in 1987.

Final design is already well advanced, and the budget plan proposed herein permits the start of detailed development at the beginning of 1988. A PERT schedule has been developed for implementation of a seven-station, two-channel "subset" correlator by early 1990, given the continued funding proposed, and assuming data playback system elements become available as planned.

Central to both major sections of the correlator as now designed is a multi-purpose gate array, the "FX chip," which will serve both as a radix-4 FFT stage and as a cross-multiplier-accumulator. Specification of the FX chip has been aided greatly by the simulation software developed for studying the FX architecture. The chip design has been carried as far as possible without committing significant funding, and expressions of interest have been solicited from potential vendors. Final design and production of this gate array is expected to begin early next year.

Post Processing

Programming work continued to add to the AIPS package the programs needed to process VLBA data.

Project Management

During 1987 the project office transferred from Charlottesville to Socorro. The electronics, correlator, and data processing activities will continue primarily in Charlottesville.

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VLBA BUDGET AND COST ESTIMATE (Constant $)

| | 1983,4 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992. | TOTALS |
|---|---|---|---|---|---|---|---|---|---|---|
| ANT STARTS/INSTLS | | 1/1 | 3/1 | 2/3 | 2/2 | 2/2 | 0/1 | | | |
| SITES | 32 | 194 | 2,205 | 1,604 | 1,441 | 1,596 | 749 | 12 | | 7,833 |
| ARRAY OPNS CTR | | | | | 158 | 210 | 3,000 | | | 3,368 |
| ANTENNAS | 1,088 | 2,460 | 6,532 | 5,589 | 5,321 | 5,394 | 713 | | | 27,097 |
| ELECTRONICS | 533 | 1,573 | 1,654 | 1,818 | 1,486 | 1,777 | 2,096 | 1,693 | | 12,630 |
| DATA RECORDING | 290 | 424 | 4 | 798 | 829 | 833 | 1,201 | 1,201 | 1,820 | 7,400 |
| MONITOR, CONTROL | 63 | 94 | 316 | 575 | 497 | 457 | 188 | 10 | | 2,200 |
| CORRELATOR | 322 | 133 | 208 | 412 | 1,154 | 779 | 500 | 194 | | 3,702 |
| POST PROCESSING | 0 | 0 | 0 | 75 | 105 | 151 | 1,452 | 2,006 | | 3,789 |
| SYST ENGINEERING | 54 | 86 | 76 | 25 | | | | | | 241 |
| MISC & SPARES | 0 | 0 | 0 | 0 | | | 400 | 2,200 | | 2,600 |
| PROJ MGT& SUPPORT | 272 | 374 | 641 | 649 | 627 | 535 | 540 | 504 | | 4,142 |
| OPNS TRAINING | 0 | 12 | 49 | 26 | | | | | | 87 |
| EXPENDITURES | 2,655 | 5,350 | 11,684 | 11,571 | 11,618 | 11,732 | 10,839 | 7,820 | 1,820 | 75,089 |
| CONTINGENCY | N/A | N/A | N/A | 498 | 323 | 55 | 629 | 3,634 | (998) | 3,320 |
| PERCENT CONT. | 0.0 | 0.0 | 0.0 | 4.3 | 2.8 | 0.5 | 5.8 | 46.5 | -54.8 | 4.4 |
| NEW FUNDS (1987 $) | 2,806 | 9,000 | 8,552 | 11,400 | 11,442 | 11,464 | 11,468 | 11,454 | 822 | 78,409 |
| CARRYOVER from prior years | | | | 669 | | | | | | |
| PROJECTED carryover from prior years | | | | | 498 | 323 | | | | |
| OPERATIONS (1987 $) | | | | 150 | 860 | 1,800 | 3,000 | 4,200 | 5,300 | 6,014 ('93) |

BD65N01 870917

17-Sep-87

VLBA BUDGET AND COST ESTIMATE (Current $)

| | 1983,4 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | TOTALS |
|---|---|---|---|---|---|---|---|---|---|---|
| INFLATION (%) | 0 | 0 | 0 | 0 | 4 | 4 | 4 | 4 | 4 | 4 |
| ANT STARTS/INSTLS | | 1/1 | 3/1 | 2/3 | 2/2 | 2/2 | 0/1 | | | |
| SITES | 32 | 194 | 2,205 | 1,604 | 1,499 | 1,726 | 843 | 14 | 0 | 8,116 |
| ARRAY OPNS CTR | 0 | 0 | 0 | 0 | 164 | 227 | 3,375 | 0 | 0 | 3,766 |
| ANTENNAS | 1,088 | 2,460 | 6,532 | 5,589 | 5,534 | 5,834 | 802 | 0 | 0 | 27,839 |
| ELECTRONICS | 533 | 1,573 | 1,654 | 1,818 | 1,545 | 1,922 | 2,358 | 1,981 | 0 | 13,384 |
| DATA RECORDING | 290 | 424 | 4 | 798 | 862 | 901 | 1,351 | 1,405 | 2,214 | 8,249 |
| MONITOR, CONTROL | 63 | 94 | 316 | 575 | 517 | 494 | 211 | 12 | 0 | 2,282 |
| CORRELATOR | 322 | 133 | 208 | 412 | 1,200 | 843 | 562 | 227 | 0 | 3,907 |
| POST PROCESSING | 0 | 0 | 0 | 75 | 109 | 163 | 1,633 | 2,347 | 0 | 4,328 |
| SYST ENGINEERING | 54 | 86 | 76 | 25 | 0 | 0 | 0 | 0 | 0 | 241 |
| MISC & SPARES | 0 | 0 | 0 | 0 | 0 | 0 | 450 | 2,574 | 0 | 3,024 |
| PROJ MGT& SUPPORT | 272 | 374 | 641 | 649 | 652 | 579 | 607 | 590 | 0 | 4,363 |
| OPNS TRAINING | 0 | 12 | 49 | 26 | 0 | 0 | 0 | 0 | 0 | 87 |
| EXPENDITURES | 2,655 | 5,350 | 11,684 | 11,571 | 12,083 | 12,689 | 12,192 | 9,148 | 2,214 | 79,587 |
| CONTINGENCY | N/A | N/A | N/A | 498 | 315 | 26 | 708 | 4,252 | (1,214) | 3,771 |
| PERCENT CONT. | 0.0 | 0.0 | 0.0 | 4.3 | 2.6 | 0.2 | 5.8 | 46.5 | -54.8 | 4.7 |
| NEW FUNDS, Current $ | 2,806 | 9,000 | 8,552 | 11,400 | 11,900 | 12,400 | 12,900 | 13,400 | 1,000 | 83,358 |
| CARRYOVER from prior years | | | | 669 | | | | | | |
| PROJECTED carryover from prior years | | | | | 498 | 315 | | | | |

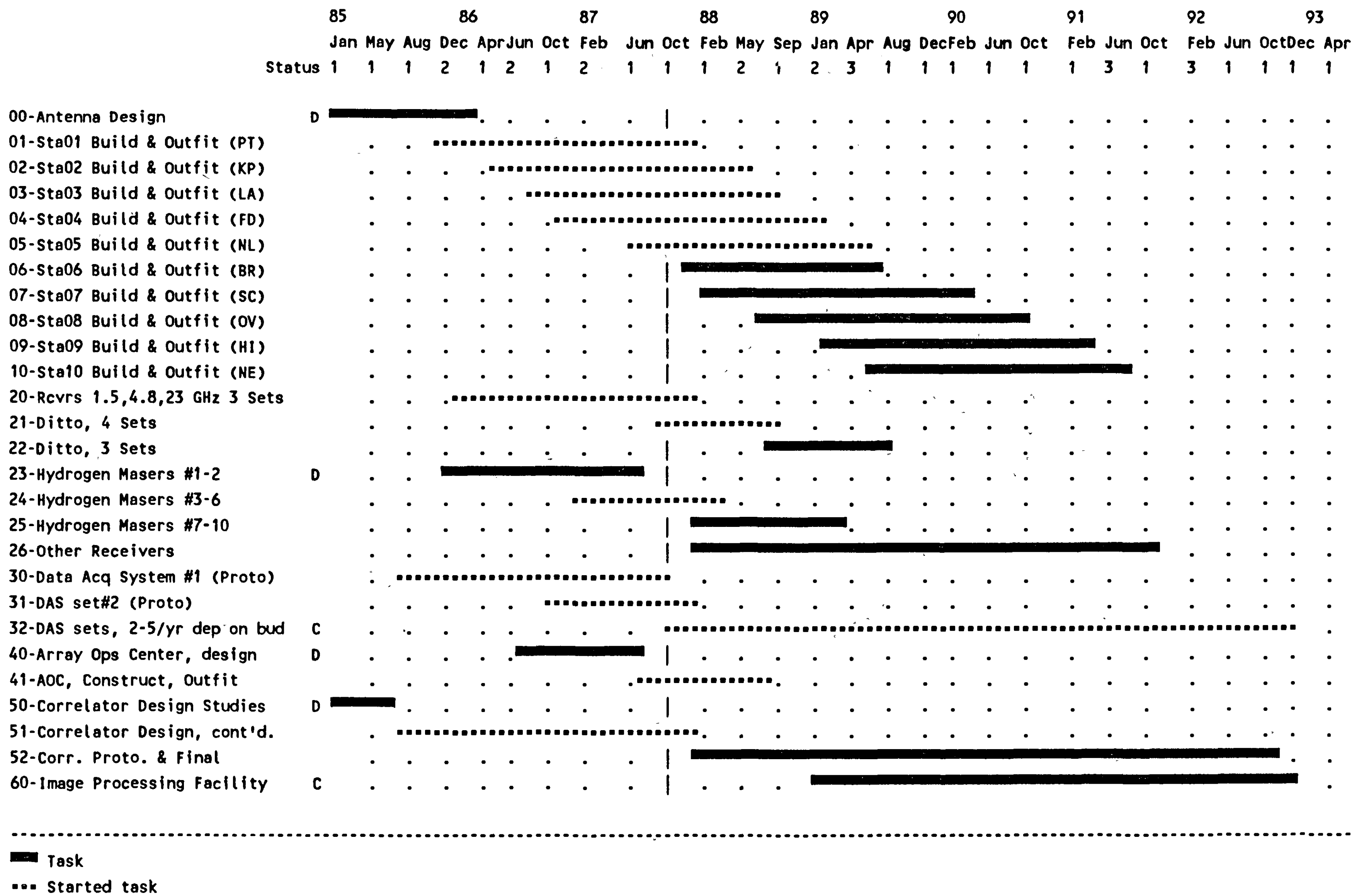
FIN07 870917/1
22-Sep-87

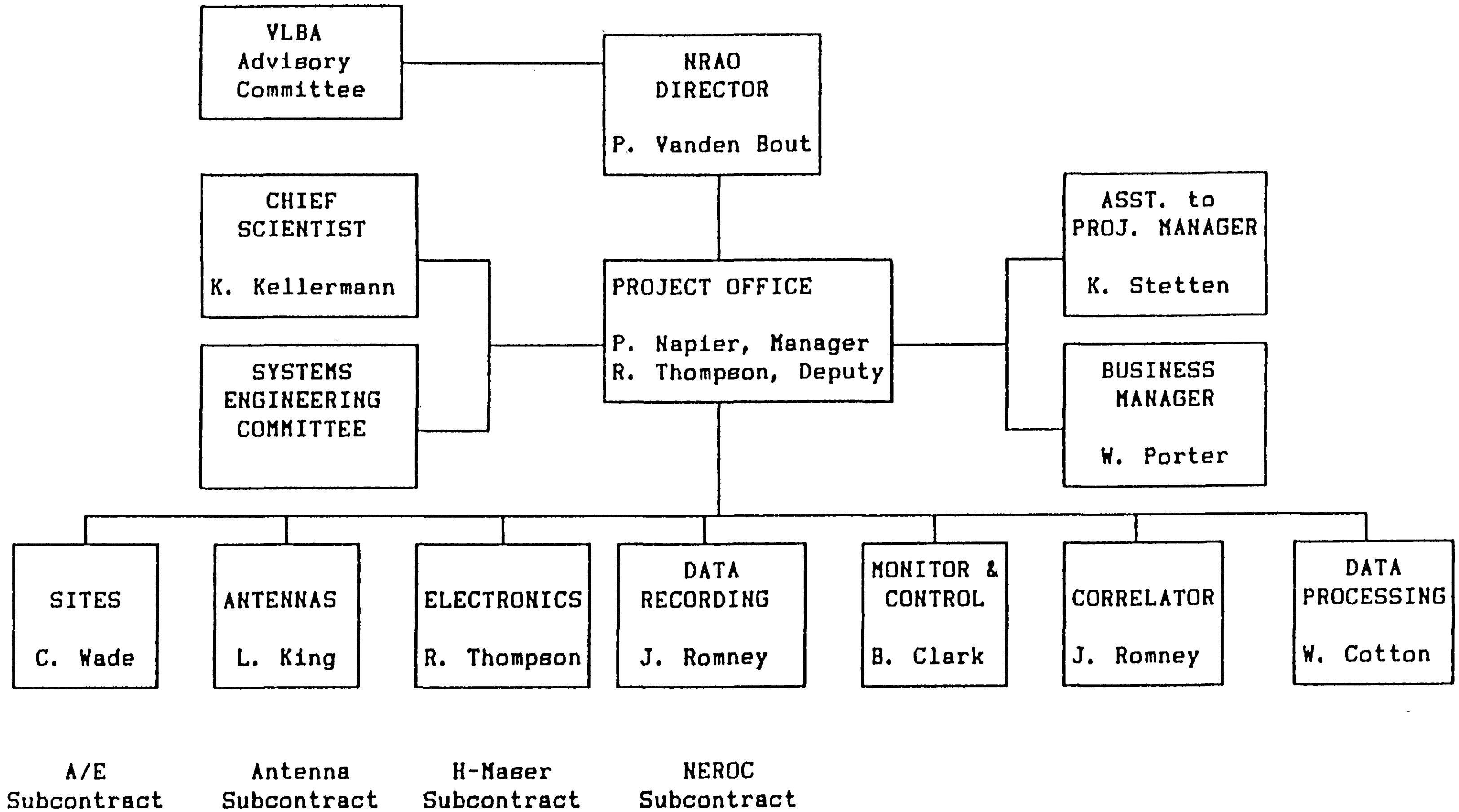
| 1988 Financial Plan VLBA Current '88 $ | Effort | Salaries & Wages | Benefits (@ 27.5%) | Materials Services | Travel | Contract Charges | Totals |
|---|---|---|---|---|---|---|---|
| Sub-project | Man-months | $k | $k | $k | $k | $K | $K |
| Sites | 36 | 170 | 47 | 378 | 62 | 842 | 1499 |
| Antennas | 93 | 324 | 89 | 199 | 62 | 4860 | 5534 |
| Electronics | 224 | 636 | 175 | 682 | 52 | 0 | 1545 |
| Data Recording | - | 71 | 20 | 230 | 26 | 515 | 862 |
| Monitor & Control | 66 | 174 | 48 | 110 | 10 | 175 | 517 |
| Correlator | 44 | 401 | 110 | 679 | 10 | 0 | 1200 |
| Data Processing | - | 66 | 18 | 16 | 10 | 0 | 110 |
| System Engineering | 24 | 0 | 0 | 0 | 0 | 0 | 0 |
| Array Oper. Center | - | 0 | 0 | 0 | 0 | 164 | 164 |
| Project Management | 132 | 326 | 89 | 206 | 31 | 0 | 652 |
| Operations Training | 17 | 0 | 0 | 0 | 0 | 0 | 0 |
| Planned Expenditures | 636 | 2168 | 596 | 2500 | 263 | 6556 | 12083 |
| New Funds, 1988 | | | | | | | 11900 |
| Carryover from prior years | | | | | | | 498 |
| Net Contingency | | | | | | | 315 |

VLBA Construction Staffing Plan
(Number of Personnel During Year)

| | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 |
|---|---|---|---|---|---|---|---|---|---|
| Sites | - | 2 | 2 | 3 | 3 | 3 | 3 | - | - |
| Antennas | - | 3 | 9 | 12 | 11 | 8 | 7 | - | - |
| Electronics | 7 | 18 | 19 | 19 | 23 | 23 | 22 | 18 | - |
| Data Recording | - | - | - | - | 2 | 2 | 2 | 2 | 2 |
| Monitor and Control | 1 | 5 | 5 | 6 | 5 | 5 | 4 | 0 | - |
| Correlator | 1 | 3 | 5 | 8 | 11 | 10 | 9 | 4 | - |
| Data Processing | - | - | - | 2 | 2 | 6 | 2 | 2 | - |
| System Engineering | 1 | 2 | 2 | - | - | - | - | - | - |
| Project Management | 7 | 10 | 13 | 11 | 11 | 10 | 10 | 10 | - |
| Operations Training | 0 | 1 | 1 | - | - | - | - | - | - |
| Totals | 17 | 44 | 56 | 61 | 68 | 67 | 59 | 36 | 2 |
| Estimated Man Years | 14.2 | 26.6 | 43.3 | 60.3 | 64.5 | 64.5 | 58.5 | 40.0 | |

Schedule Name: VLBA SCHEDULE OVERVIEW
Project Manager: Peter Napier
As of date: 23-Sep-87 11:55am Schedule File: C:\TLDATA\VLBAOV8A
An approximate bar chart keyed to Budget BD65






VLBA PROJECT ORGANIZATION
NRAO 1987 September