A BRIEF PROFILE OF THE NATIONAL RADIO ASTRONOMY OBSERVATORY

Since its founding in 1957, the National Radio Astronomy Observatory (NRAO) has been a major force in the development of radio astronomy. This field, pioneered in the United States, has blossomed to become a central element of modern astronomy throughout the world.

At the present time, the NRAO manages the operation of three major observing sites from its headquarters in Charlottesville, Virginia. The 300-foot diameter meridian transit telescope and the 140-foot diameter fully steerable telescope are both located at the original Green Bank, West Virginia site; the Very Large Array (VLA) telescope, a mobile array of twenty-seven 25-meter antennas, is located on the Plains of San Agustin near Socorro, New Mexico; and the 12-meter diameter millimeter-wave telescope is located on Kitt Peak near Tucson, Arizona. (Operation of the three-element Interferometer, also located in Green Bank, West Virginia, was discontinued for astronomical observing in 1978 when the VLA became operational; it is now operated by the NRAO exclusively for the U.S. Naval Observatory for purposes of time-keeping.) NRAO is constructing a new telescope, the Very Long Baseline Array (VLBA). The VLBA, like the VLA, is a synthesis telescope simulating an extremely large single antenna by a distribution of smaller antennas operating in concert. In the case of the VLBA, the ten individual antennas will be spaced from

Hawaii to the Virgin Islands and controlled from an operations center in Socorro, New Mexico.

The NRAO is operated by Associated Universities, Inc. (AUI), an independent, not-for-profit research management corporation, under the terms of a contract between the National Science Foundation (NSF) and AUI. The following responsibilities for AUI are included in the Scope of Work of this contract:

- Staff, manage, operate, and maintain the facilities ... of [the] Observatory ...;
- Provide scientific, managerial, and logistic support in the conduct of research programs in radio astronomy and related fields. The research shall be carried out by the staff of the Observatory, and visiting scientific investigators. The scientific merit of research proposed by visiting scientific investigators and by the Observatory staff shall be given the same consideration. The major criteria for the utilization of Observatory facilities shall be the scientific merit of the proposal, the competence of the individual or individuals, and the suitability of the Observatory facilities.
- Maintain a broad base research program at the Observatory in order to promote advances in and the utilization of knowledge in astronomy.
- Provide facility and logistic support to university and NRAO research programs in radio astronomy and related fields.
- Engage in education programs in radio astronomy and related fields as may be appropriate to the operation of the Observatory and as is consistent with the Program Plan.

These contractual requirements have characterized the role of the NRAO since it was founded.

The concept of a national observatory was unique when it was proposed in 1954--NRAO was the first national astronomical observatory. There were some who doubted that an open, visitor-oriented, national facility could efficiently serve its user community and at the same time provide a research environment that would be conducive to competitive research. The fact that NRAO has established and maintained the world standard in radio instrumentation and user service, together with the remarkable flood of scientific results from its users, is ample justification for the wisdom of providing such facilities.

USERS

The principal responsibility of the Observatory is to provide the astronomy community access to forefront research capabilities through the development of major national facilities. How large is NRAO's user group? What is its composition? What institutions do they represent? What is the participation of students? Is the Observatory primarily serving its external users or its own research staff?

Figure 1 shows the annual growth in the user group over the history of the Observatory, from the modest beginnings, before the first major telescopes were built, to over 650 long and short-term visitors today. The largest increase in the number of visitor-users occurred as the VLA entered full operation in 1981. The use by Observatory staff, both permanent scientists and postdoctorals (Research Associates) can be seen to represent about 7% of all Observatory users.

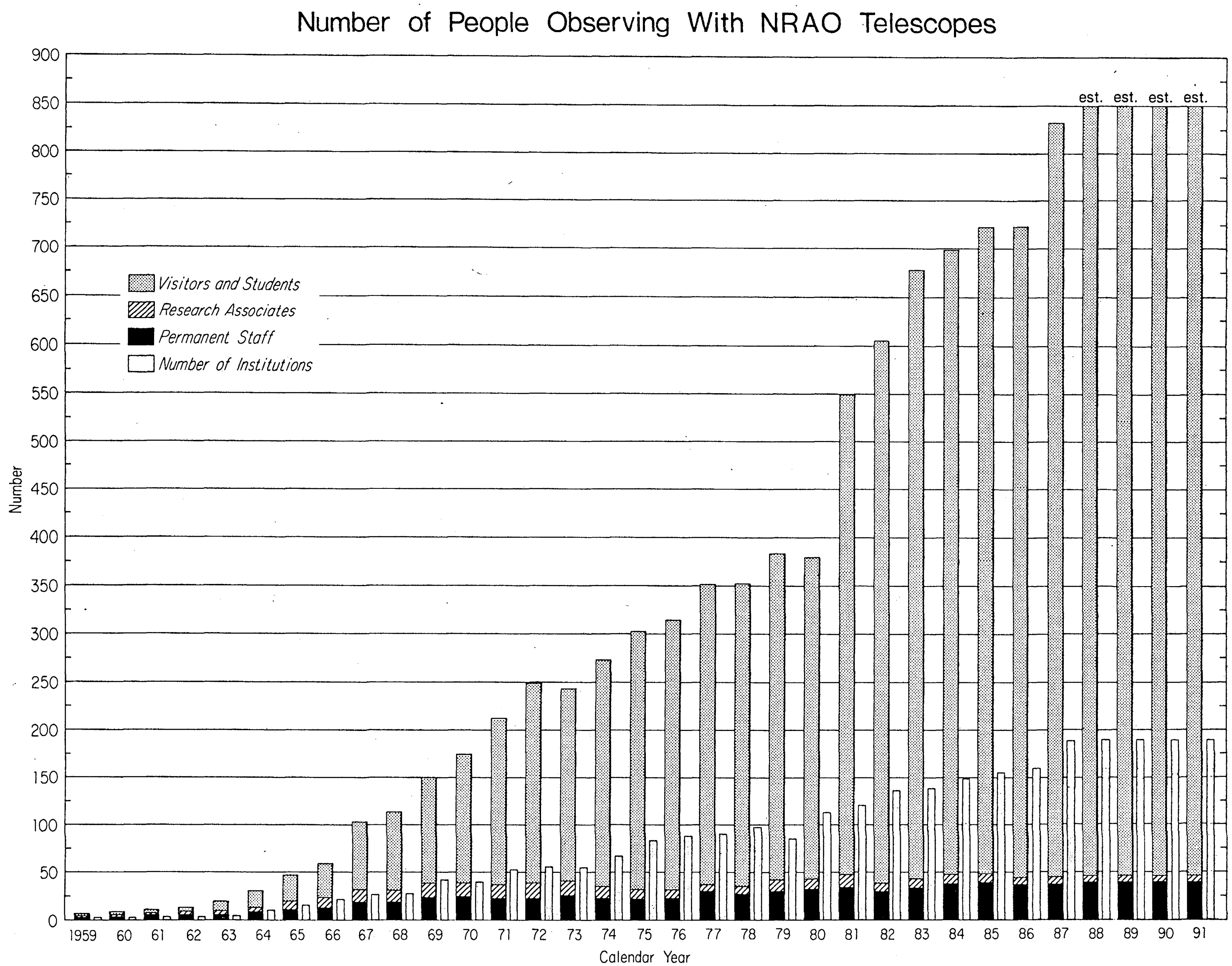


Figure 1. This bar chart shows for each calendar year the number of NRAO permanent research staff and the number of NRAO research associates (postdoctorals) who use the telescopes. In addition, it shows the total number of visitor-users of NRAO telescopes and the number of institutions from which the NRAO visitors come. The significant jump in these last categories for 1981 reflects the increased use of the VLA.

The number of institutions using NRAO telescopes has also grown dramatically over the years, with a 50% increase attributable to the VLA. Universities represent 64% of the institutions, other observatories and government laboratories 33%, and private industries the remaining 3%. The overwhelming majority of these institutions lack the resources to design, build, maintain, and operate telescopes comparable to those at NRAO. Nevertheless, many of these institutions actually participate with NRAO in the design and fabrication of sub-elements of advanced systems. This includes not only individual university groups who bring their own observing equipment to NRAO telescopes but also working teams operating out of universities and government laboratories who assist in the design and, in some cases, actual construction of new instrumentation. Maintenance of such capabilities in these institutions is important to the future of NRAO as a national observatory.

It is also important to note that in keeping with a growing interdependence of all areas of astronomy, the NRAO user community is rapidly growing to accommodate new observers from the optical, infrared, X-ray, and related areas.

The NRAO Student Program is illustrated in Figure 2. The vast majority of the student users are graduate students from universities having Ph.D. programs in astronomy. A large increase in graduate student users occurred when the VLA began operations. As with the other categories of users, this increase is due not only to the research opportunities the VLA presents but also to the operational convenience of this instrument which has been facilitated by the efforts of the Observatory staff.

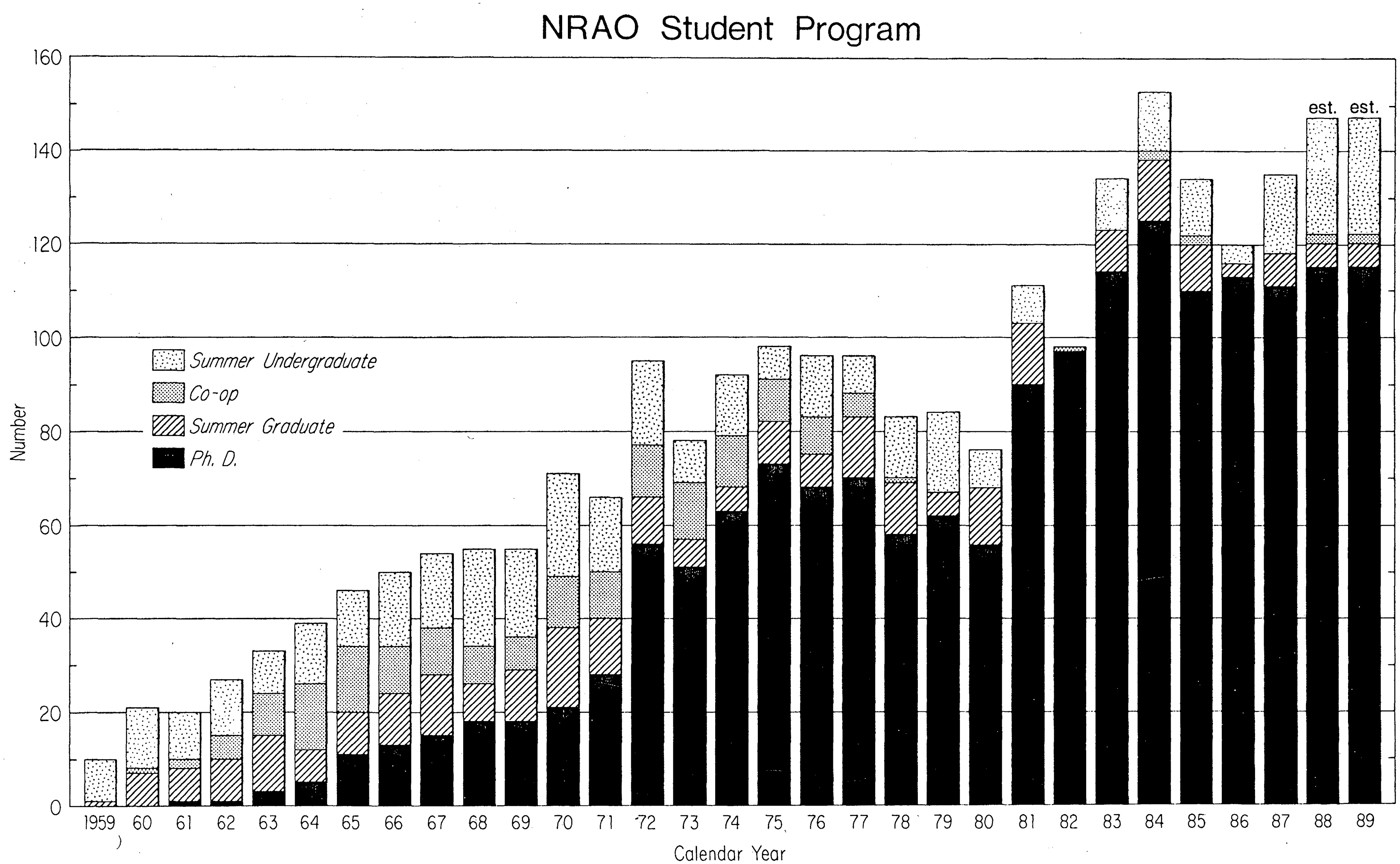


Figure 2. This figure shows for each calendar year the number of Ph.D. students (including those few salaried at NRAO), NRAO co-op students, and NRAO summer students (undergraduate and graduate) who observed or worked at the NRAO during that year.

The Summer Student and Co-op Programs are a much smaller component of student usage of NRAO facilities, but these are important in the national programs. Both serve to introduce senior undergraduate and beginning graduate students to radio astronomy. The Summer Student Program focuses on astronomical research; the Co-op Program is conducted with university groups of engineers, applied physicists, and computer scientists. Both are important mechanisms for acquainting skilled scientists with issues of importance to the field of radio astronomy.

The extent to which NRAO is dedicated to its user community can be seen by examining Figures 3 and 4. Approximately 35,000 observing hours exist in principle in one year for all four of NRAO's telescopes taken together (4x24x365). The actual hours scheduled for observing with these telescopes are shown in Figure 3, where the recent totals are approximately 30,000, or 86%. The remaining 14% is scheduled for tests, calibration, preventative maintenance, installation of new equipment, and repairs.

The only periods when less than about 85% of the available time was scheduled for observing was in 1979-80 after the three-element Interferometer was closed and before the VLA began full operation, and in 1982-83 when the 36-foot millimeter-wave telescope was re-surfaced and re-christened as the 12-meter telescope. The telescopes, which operate 24 hours a day, are efficiently scheduled to produce as much observing as possible.

How is the observing time allocated to staff and visitor users? Different projects require differing amounts of time, but all grants of observing time are made on the basis of scientific merit. All proposals,

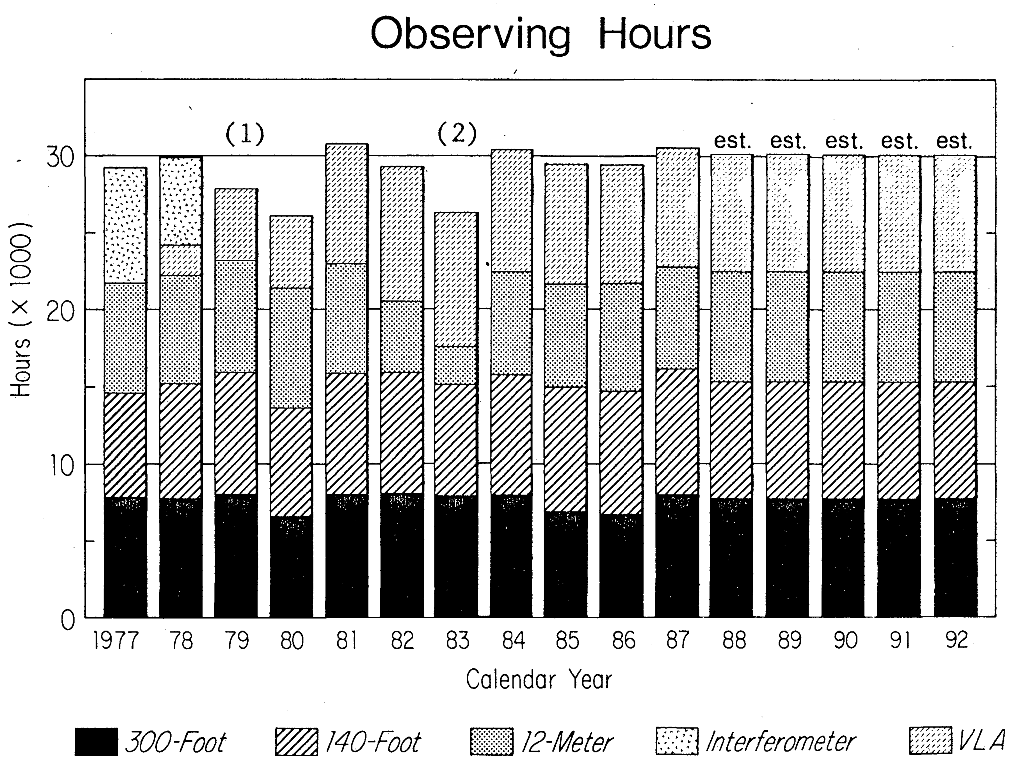


Figure 3. Hours scheduled for observing on each telescope during the last decade.
(1) Shutdown of observing on 3-element Interferometer and commissioning of the VLA.
(2) Resurfacing of the 12-meter millimeter wave telescope.

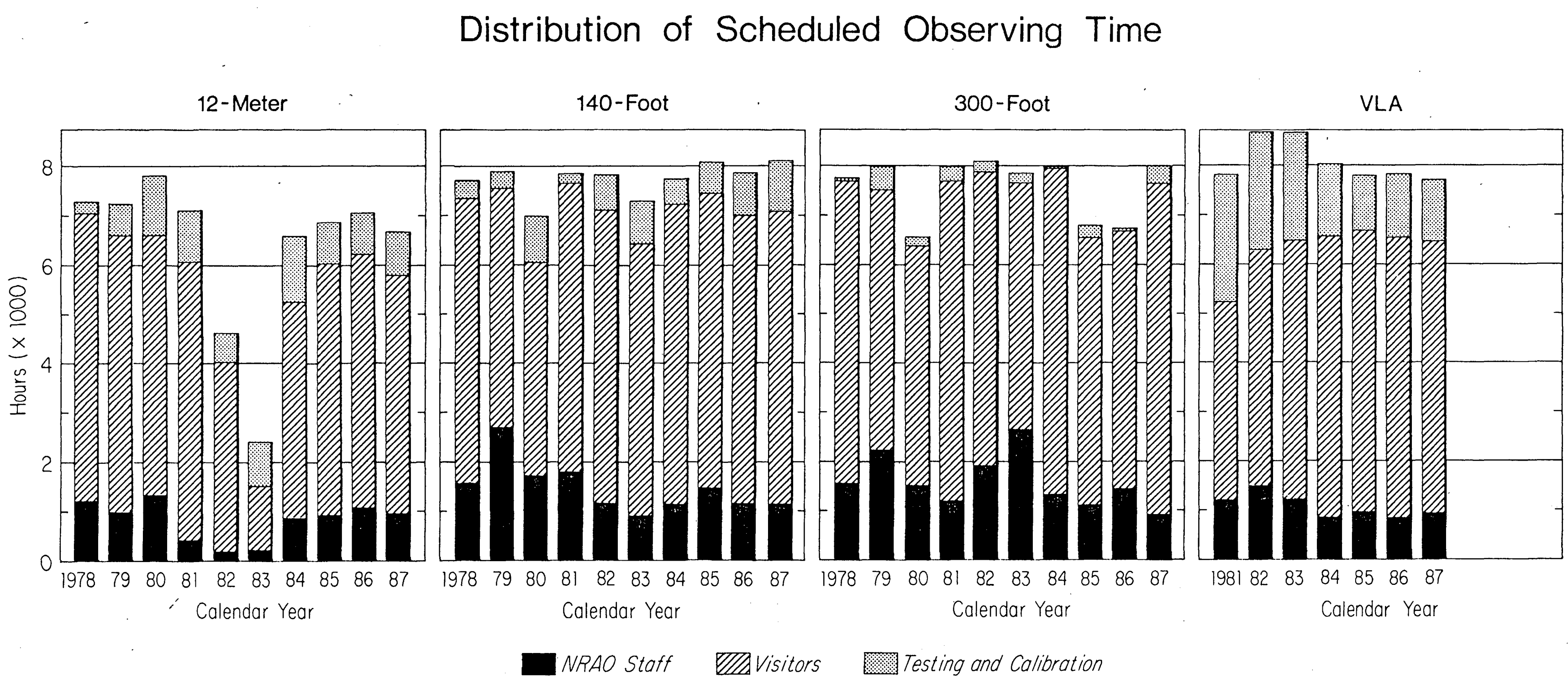


Figure 4. These graphs show the number of hours scheduled for calibration and for observing by the NRAO staff and by visitors on each telescope system during the last decade.

from staff and visitors alike, are refereed and graded for merit by anonymous referees selected from the community. The detailed scheduling is done by the site directors, with the assistance of a special committee in the case of the VLA. The rule that Observatory staff compete for time on the same footing as visitors is fundamental and has contributed a great deal to the excellent relationship between the Observatory and its user community.

Figure 4 shows the actual observing time distribution among NRAO scientific staff, visitors, and calibration and test time. Over time, the NRAO staff has qualified to utilize about 15% of the observing time, with some variation from telescope to telescope. This level of use is judged to be adequate to enable the Observatory staff to maintain a competitive research program of its own, which is necessary if the Observatory is to continue to provide effective leadership within the U.S. radio astronomy community.

STAFF AND OPERATIONS

The growth of NRAO's permanent full-time staff over the history of the Observatory is shown in Figure 5. The steady, smooth growth up to 1970 accompanied the construction of the 300-foot, 140-foot, millimeter-wave, and three-element Interferometer. The size of the operations staff was constant throughout most of the VLA construction period and increased in response to major new user requirements as operation of that instrument began in 1979. The recent decline in staff reflects the unbroken 4-year decline in budget levels. Personnel levels throughout the VLBA construction period are expected to follow the VLA pattern. Additional

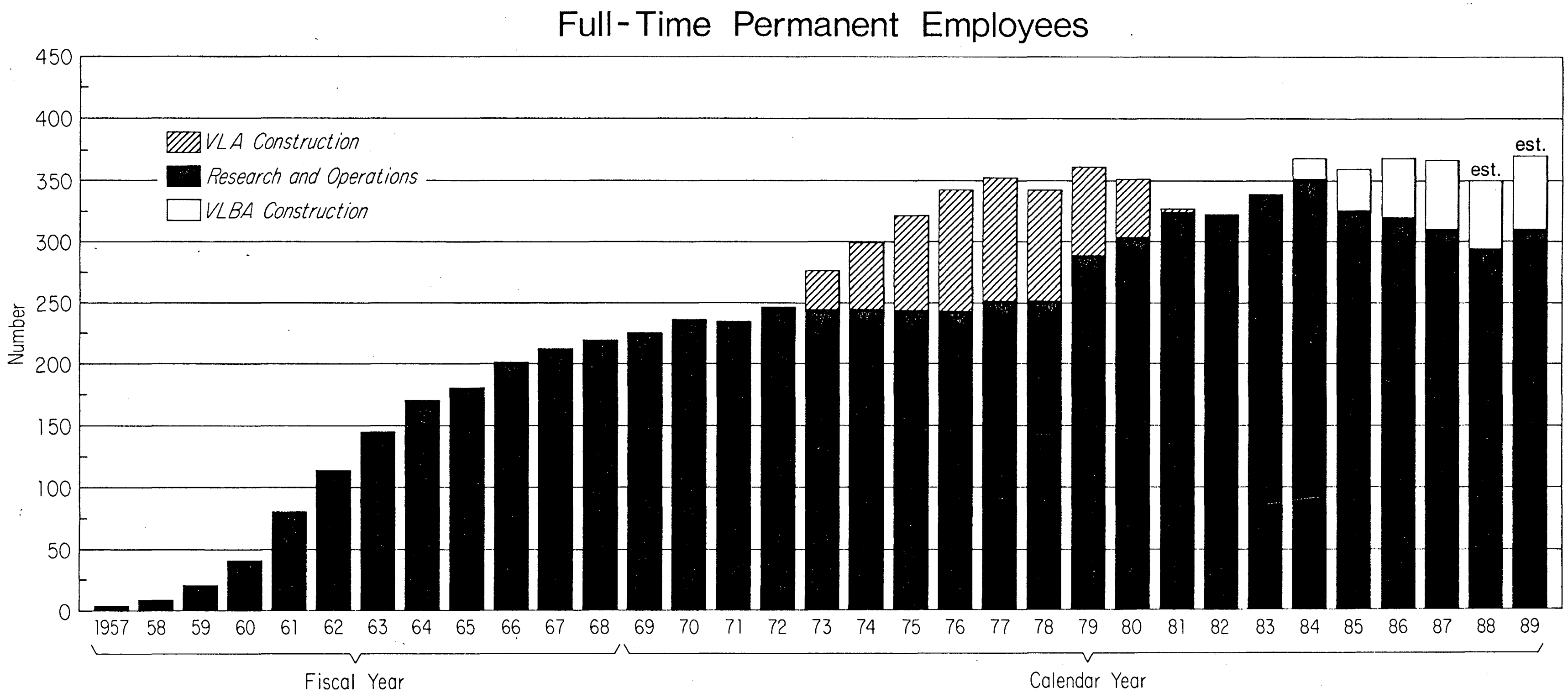


Figure 5. This figure shows the total number of NRAO full-time, permanent employees at the end of each year, projected into the future.

operations staff will certainly be required if this major new facility is to be operated efficiently at its completion. Many of these new operations staff are expected to be drawn from the construction staff.

It should be noted that following full operation of the VLA the number of NRAO users doubled (100%) and is still increasing as is the number of student users, but the staff to serve these users is now only equal to that of 1979, the year that marked the half-way point in assembling the VLA staff.

The composition of the scientific staff at NRAO is given in Table 1, where the scientific staff is defined as all professional employees holding a Ph.D degree. The total Ph.D. staff is 65 employees, 18% of all full-time permanent employees. Of these 65, 28 form the basic research staff, or 8% of all full-time permanent employees. Twenty-two of the 65 members of the Ph.D. staff hold tenured positions, or 6% of the staff. These numbers are consistent with the original intention that the Observatory have a small, dedicated research and development staff.

BUDGETS

The history of the NRAO budget for operations and equipment (excluding budgets for construction, e.g., VLA and VLBA construction) is shown in Figure 6. The annual budgets are shown in actual NSF funds received (current year dollars) in millions. An inflation index given by NSF is also plotted for these years, with an estimated extrapolation to 1988 and 1989 of 4% each year. Correcting for inflation, the 1988 Observatory budget is approximately equal to that received for NRAO

Table 1

Ph.D. Staff Classification/Distribution

Basic Research Staff	Total
Postdoctorals	6
Associate Scientists	3
Scientists	15
Senior Scientists	4
Total	28
Other Ph.D. Staff	
Operations/Management	14
Electronics	8
Computing	4
VLBA Construction	11
Total (6 tenured)	37
Total Ph.D. Staff (22 tenured)	65
NRAO Staff	
Operations	295
Construction: VLBA	64
Voyager	8
Total Staff	367

Fraction of staff with Ph.D. degree	-	18%
Fraction of Ph.D. staff with tenure	-	34%
Fraction of total staff with tenure	-	6%

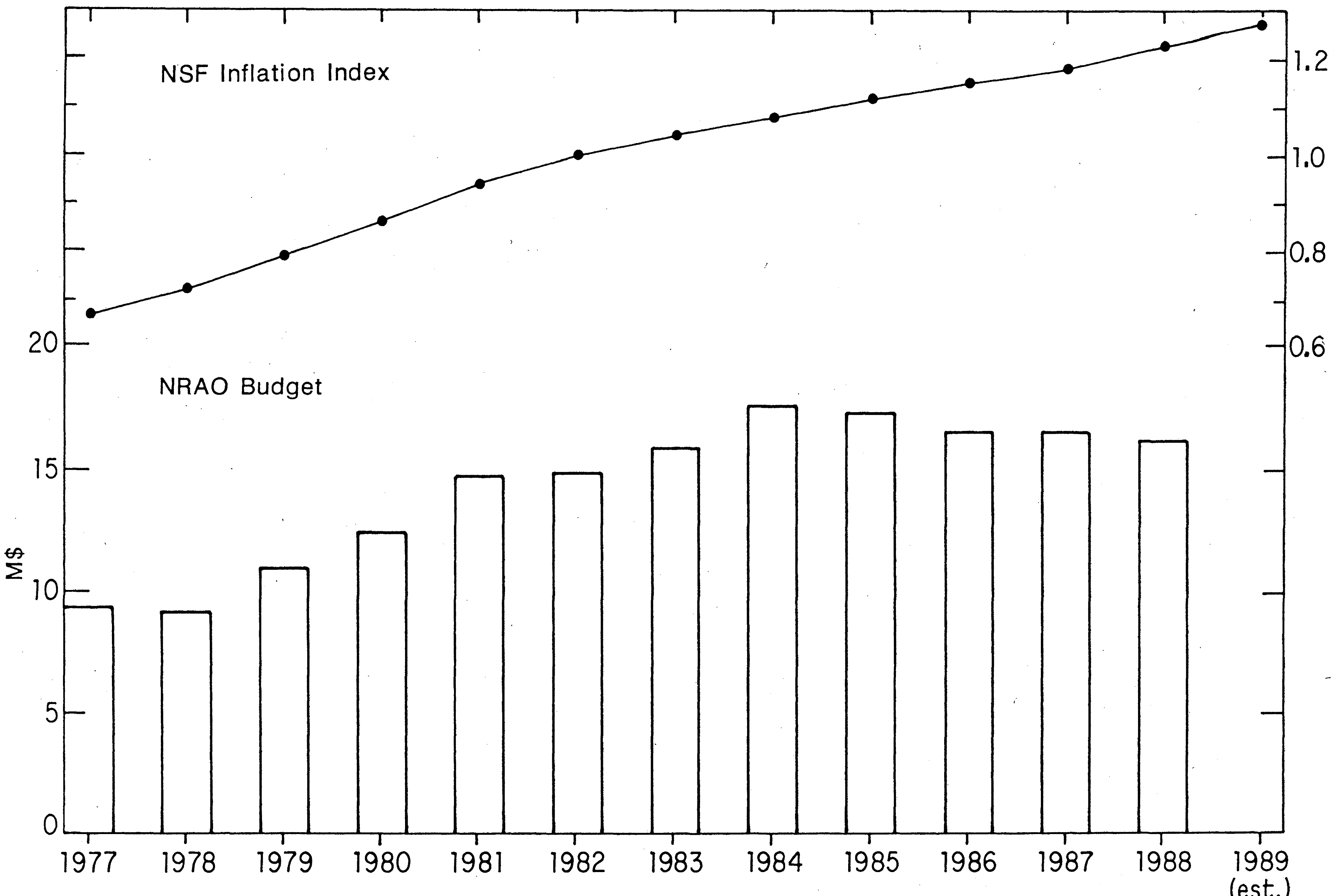


Figure 6. The history of NRAO funding for operations and equipment (exclusive of construction funds for the VLA and the VLBA) over the last decade. Note that the VLA was dedicated and in full operation in 1981; the VLBA began interim operation (one antenna) in 1987. The annual budgets are the amounts received from NSF in that year. The NSF inflation index is shown as the solid line.

operations in 1978. Note that the VLA did not begin full operation until 1981. Thus, the NRAO is now taking virtually the entire cost of operating the VLA from an Observatory funding level no larger than was available prior to the existence of the VLA.

This would be an achievement to celebrate if the long-term consequences for radio astronomy could be ignored. Unfortunately, the following cannot be ignored:

- The staff is overburdened and underpaid;
- Investment in future instrumentation is at an unprecedented low level (see Figure 7);
- Deferred maintenance threatens the vitality of major facilities;
- Urgent computing needs remain unaddressed;
- The operational needs of the VLBA are not being met;
- The technology development program that has been so important to the success of radio astronomy in the U.S. is in danger of being lost altogether.

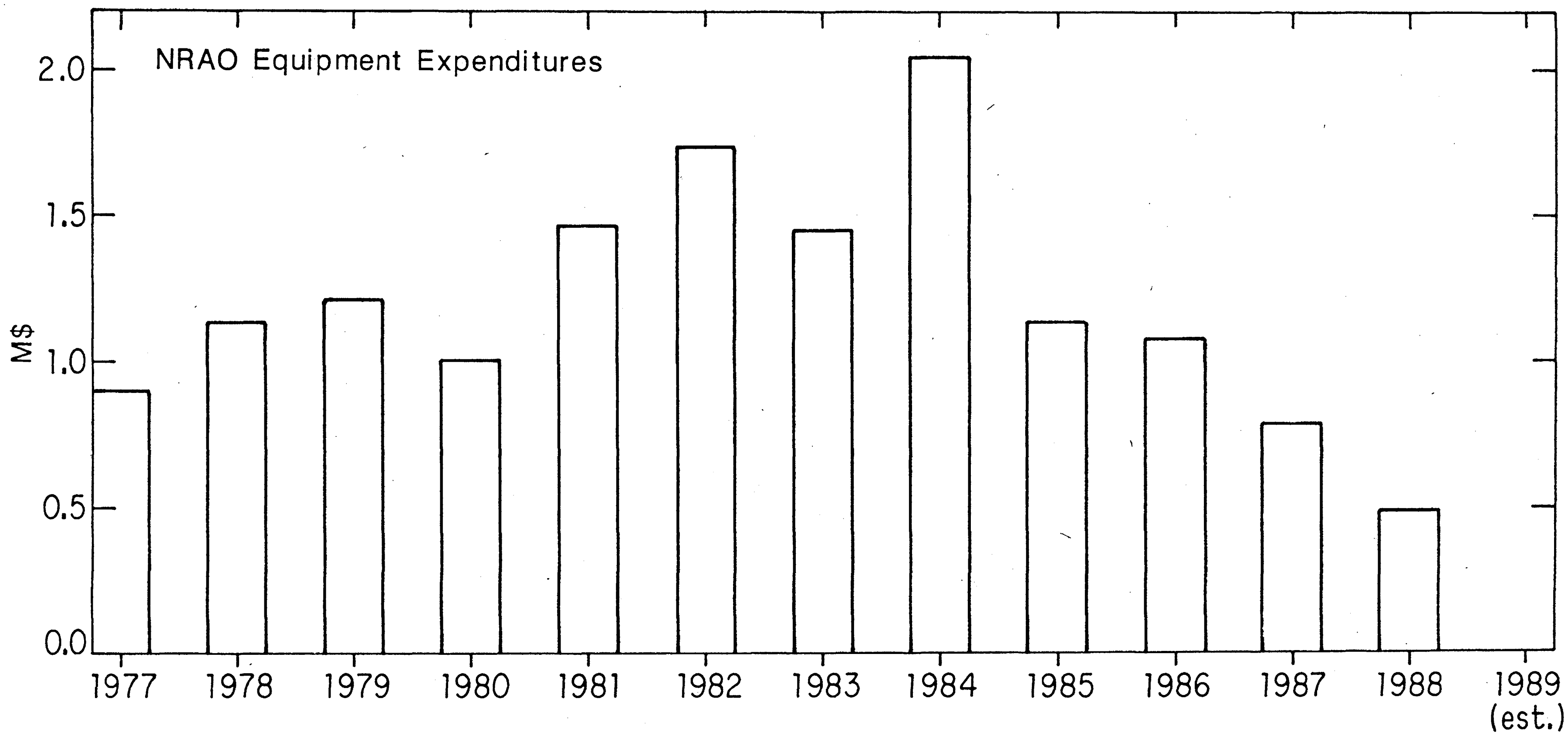


Figure 7. The history of expenditures for new instrumentation at the NRAO. This includes only equipment expenditures, not personnel costs.

NATIONAL RADIO ASTRONOMY OBSERVATORY
ORGANIZATION CHART
1 APRIL 1988

- **AUI**
  - Chairman of Board–M. Kuschner
  - President–R.E. Hughes
  - V.P.–Corporate Affairs–T.J. Davin
  - V.P.–Programmatic Affairs–J. Hudis
  - Secretary–J. Hudis
  - General Counsel–T.J. Davin
  - NRAO VISITING COMMITTEE
- **NRAO**
  - Director–P.A. Vanden Bout
  - Associate Director–R.L. Brown
  - Associate Director–J.L. Desmond
  - USERS' COMMITTEE

SOCORRO OPERATIONS
- Assistant Director W.M. Goss
- Deputy Site Manager R.A. Sramek
  - SCIENTIFIC SERVICES
  - ARRAY OPERATIONS – R.C. Bignell
  - COMPUTER – G.C. Hunt
  - ADMINISTRATIVE SERVICES – M.E. Dinius
  - ELECTRONICS – J.A. Campbell
  - ANTENNA & SERVICES – W. Del Giudice

GREEN BANK OPERATIONS
- Assistant Director G.A. Seielstad
  - SCIENTIFIC SERVICES
  - TELESCOPE SERVICES – J.F. Crews
  - ADMINISTRATIVE SERVICES – R.L. Fleming
  - PLANT MAINTENANCE – L.E. Howell
  - ELECTRONICS – R.D. Norrod

TUCSON OPERATIONS
- Assistant Director D.T. Emerson
- Deputy Site Manager P.R. Jewell
  - TELESCOPE OPERATIONS – D.A. Chase
  - BUSINESS – D.A. Webb
  - ELECTRONICS – J.M. Payne

CHARLOTTESVILLE OPERATIONS
- Associate Director R.L. Brown
  - OSBSERVATORY SERVICES – R.J. Havlen
  - COMPUTER – W.R. Burns

RESEARCH STAFF

TECHNICAL DEVELOPMENT
- Assistant Director M. Balister*
  - CENTRAL DEVELOPMENT LAB. & SPECIAL PROJECTS – M. Balister

ADMINISTRATION
- Associate Director J.L. Desmond
  - BUSINESS – J.P. Lagoyda
  - CONTRACTS – J.L. Desmond
  - PERSONNEL – M.E. Petty
  - FISCAL – J.R. Gibb

VLBA PROJECT
- Assistant Director & Project Manager P.J. Napier
- Deputy Project Manager A.R. Thompson
  - ELECTRONICS – A.R. Thompson
  - BUSINESS – W.H. Porter
  - SITE DEVELOPMENT – C.M. Wade
  - ANTENNAS – L.J. King
  - DATA PROCESSING – W.D. Cotton
  - CORRELATOR – J.D. Romney
  - MONITOR & CONTROL – B.G. Clark

*Acting

T H E

T H E 1 4 0 - F O O T T E L E S C O P E

Prepared for the Radio Facilities Panel
Division of Astronomical Sciences
National Science Foundation
by the National Radio Astronomy Observatory
March 1988

I. INTRODUCTION

The 140-foot radio telescope was designed and built to provide astronomers with a versatile instrument of reasonable aperture that could be adapted in conventional and unconventional ways to a wide range of astronomical investigations. The wisdom of this approach was rewarded shortly after the telescope began routine operation with the first discovery of a polyatomic organic molecule in the interstellar medium, formaldehyde. The instrumental capability of the 140-foot system exploited to advantage in this discovery--the ability to observe at a "non-standard" radio frequency with sufficient sensitivity--is precisely the same capability that led to the discovery nineteen years later, in 1988, of the cyanomethyl radical CH_2CN. In the intervening years the science progressed and dozens of other discoveries, large and small, were reported. There are larger telescopes than the 140-foot--there were larger telecopes in 1969 when formaldehyde was discovered--but there is no other which has contributed so much in so many different areas to centimeter-wave astronomy. With its constantly improving sensitivity, its versatility, adaptability, and reliability, the 140-foot has been, and continues to be, a unique research tool.

The characteristics of the 140-foot telescope most distinctive and most in demand by astronomers are:

- Frequency coverage. In 1987, research programs were conducted on the 140-foot telescope at frequencies from 25 MHz to 25 GHz. With very few gaps, sensitive state-of-the-art receivers are available throughout this frequency range. Often the Green Bank receivers define the state-of-the-art in radio astronomy.

- Stable spectral baselines. Detection of broad, weak, spectral features may be limited by instabilities in the RF/IF systems to a greater extent than by receiver noise. Exceptional care is taken to minimize these effects.

- The telescope is accessible. The 140-foot telescope is dedicated full-time to radio astronomical research. Astronomers are encouraged to bring their own instrumentation and/or to experiment with unconventional observing techniques. The now "standard" spectroscopic observing procedures at the 140-foot--e.g., total power, nutating dual-beam--all resulted from users' experiments and experience.

II. TELESCOPE AND INSTRUMENTATION

TELESCOPE SPECIFICATIONS

Diameter: 140 feet (43 m)
Pointing Accuracy: 7"
Sky Coverage: -46° to 90° declination.
Fully steerable. Tracking time is 2 hours or greater at all declinations.

Sensitivity: 0.26 K Jy^{-1}
Surface Accuracy: 0.7 mm (rms)

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

RECEIVERS

Frequency Range (GHz)	Amplifier	System Temperatures (K)
0.025- 0.088	Transistor	300
0.110- 0.250	Transistor	250
0.250- 1.0	Cooled upconverter/GaAsFET	45-85
1.0 - 1.45	Cooled GaAsFET	35
1.30 - 1.80	Cooled HEMT	18-23
2.90 - 3.50	Cooled GaAsFET	25-35
4.47 - 5.05	Cooled GaAsFET	25-35
4.70 - 7.20	Upconverter/Maser	30-50
7.60 -11.20	Upconverter/Maser	35-80
12.0 -16.2	Upconverter/Maser	50-80
18.2 -25.2	Maser	35-60

Note: All receivers are dual polarization. The prime focus receivers, those at frequencies below 5 GHz, are shared with the 300-foot telescope.

III. SCIENTIFIC PROGRAM

THE ROLE OF THE 140-FOOT TELESCOPE - The 140-foot telescope provides visiting astronomers with a combination of sensitivity and frequency versatility that is unique in astronomy. One can choose to observe at nearly any frequency in the range 1-25 GHz with the 140-foot and obtain instrumentation which will provide a system temperature that is usually less than 50 K: the L-band range is particularly noteworthy here with $T_{sys} < 20$ K. No other telescope in the world, of any diameter, provides such complete, low-noise, instrumentation.

Spectroscopy in general, but molecular spectroscopy and astrochemistry in particular, are the principle beneficiaries of the 140-foot telescope's sensitivity and frequency agility.

Unlike most other scientific areas which utilize well chosen but specific molecular lines as probes of the physical conditions in dense clouds, the study of chemistry requires maximum frequency coverage. This is because the most important transitions of different types of molecules, under differing physical conditions, occur at wavelengths ranging from the centimeter to the submillimeter. This dependence of spectral features on molecular structure and physical conditions is most easily illustrated for linear molecules; non-linear molecules do not behave very differently, but they are more difficult to treat.

The integrated brightness temperature of a given molecular line is proportional to the square of the frequency of the line, multiplied by the population of the initial energy level involved in the transition. For a linear molecule in thermal equilibrium among its rotational energy levels, these two factors result in a transition frequency ν_{max} of maximum intensity, where

$$\nu_{max} \propto \sqrt{BT}.$$

Here, B, the rotation constant, is roughly proportional to the inverse cube of the number of heavy (non-hydrogen) atoms in the linear molecule. The frequency of the most intense spectral feature of a linear molecule is proportional to $\sqrt{B}$, or to $1/\sqrt{N^3}$, where N is the number of heavy atoms. Larger molecules will have their strong spectral features at lower frequencies, viz., in the centimeter range, whereas smaller molecules will have their stronger features toward the millimeter and even the submillimeter range.

A glance at the above equation reveals that as temperature increases so does ν_{max}. The result is that the study of the emission of a given molecule at higher frequencies is a means of specifically probing regions of higher temperature. For example, a change in temperature from the 10 K which is typical of a quiescent cloud to 20 K characteristic of an excited region will increase ν_{max} by a factor of $\sqrt{2}$. Thus the study of even a single molecule in a heterogeneous source requires significant frequency versatility.

The need for centimeter-wave molecular spectroscopy is becoming increasingly important as (1) observations at millimeter wavelengths from the new generation of millimeter-wave telescopes require confirming or complementary work at centimeter waves, and (2) we recognize that the chemistry in the interstellar medium varies markedly from one environment to another.

While emphasizing frequency versatility, we should not lose sight of the need for sensitivity. Here there are two points to make. First, frequency coverage means the astronomer can observe at a frequency chosen by astronomical considerations and not limited artificially by the telescope instrumentation. Detection of the feature of interest thereafter depends on the strength of the line and the sensitivity of the telescope system. Second, a sensitive broadband instrument provides the opportunity for the astronomer to search not just for the expected but for the unexpected as well. Figure 1 is one 20 MHz slice of a frequency survey across 2000 MHz of bandwidth toward TMC-1 recently conducted by Irvine and his collaborators. The seven unidentified lines seen in this one spectrum are indicative of the spectral richness at K-band.

The sensitivity of the 140-foot telescope has a different meaning for those astronomers interested in detecting broad, weak features toward bright continuum sources. Here the emphasis is on control of systematic instrumental errors throughout the RF/IF/spectrometer system. The detection of ^{3}He noted below illustrates the excellence of the 140-foot telescope system in this respect.

Finally, some research done with the telescope requires a survey of an enormous region of sky. Burton's survey of several steradians mentioned below is such an example. The time consuming nature of observations such as these is a burden relieved of the astronomer by the Green Bank support staff: the observations can be made, as Burton's were, without the astronomer in residence.

Below are a few examples of recent research on the 140-foot telescope that illustrate its capabilities and rôle in contemporary radio astronomy. However, it would be unfortunate to communicate the impression via such examples that these things, important though they are, is "all" the telescope does. Rather, the diversity of science on the 140-foot is remarkable in and of itself. Recently astronomers have used the 140-foot to:

- Monitor OH emission in comets as a function of heliocentric distance;

- Measure low-frequency recombination line emission from the Galactic plane at frequencies 25-150 MHz;

- Obtain "zero-spacing" maps of Fornax A, M31, the Sun, and the Rosette to be used in combination with VLA data to create a complete image;

- Estimate the opacity of the Galaxy at high latitudes to soft X-rays from determinations of the HI column density;

- Determine the HI content of southern galaxies ($\delta < -19°$);

- Map the kinematics of the Galactic center region using recombination line observations;

- Participate in all NUG and EVN/NUG VLBI programs.

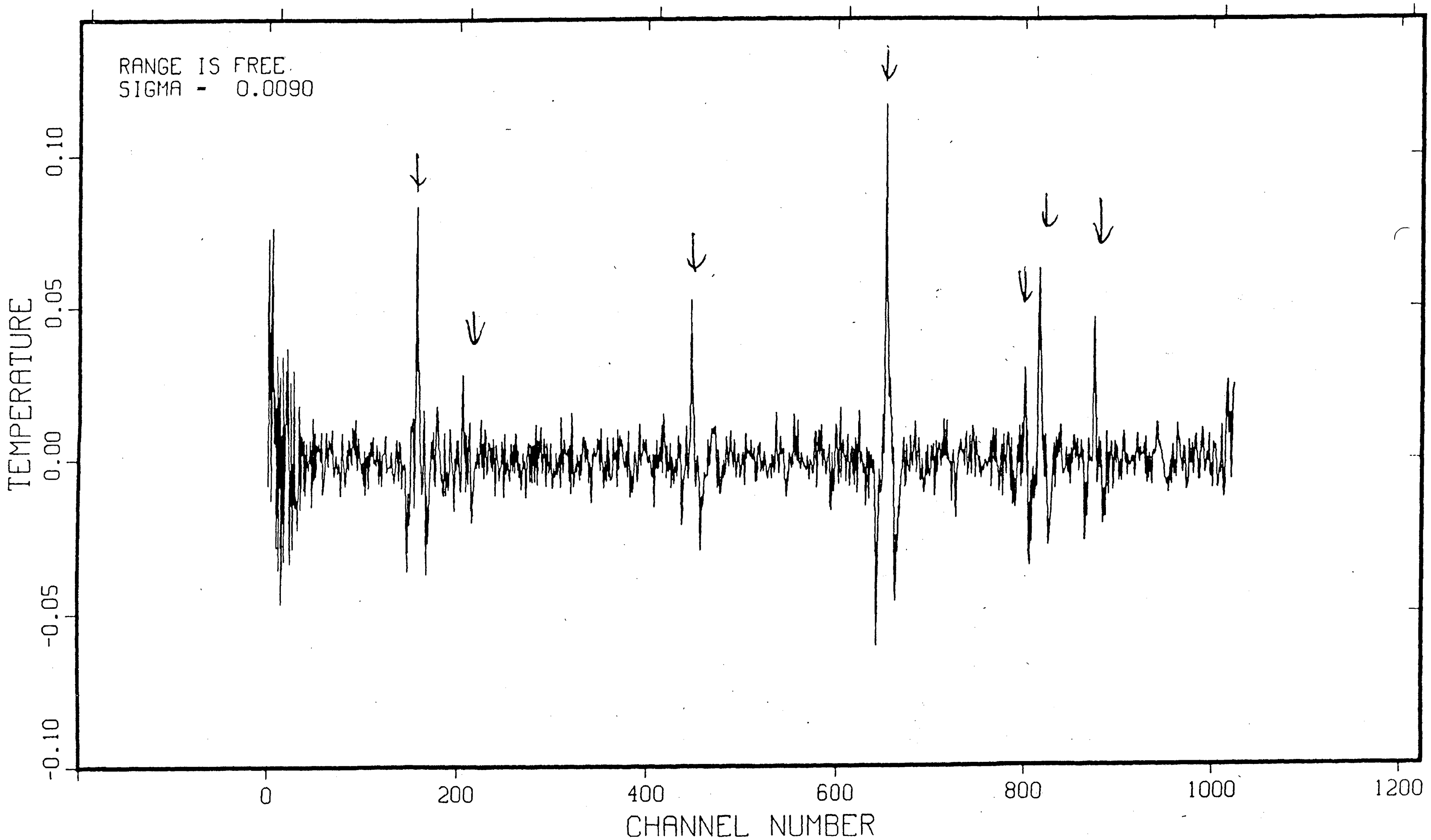


Figure 1. One 20 MHz piece of a K-band frequency survey of 2000 MHz total band width toward TMC-1. Note that there are seven unidentified spectral lines in this one spectrum.

<u>C_3H_2: THE FIRST INTERSTELLAR HYDROCARBON RING</u> - Interstellar chemistry is a field that is in many ways still in its infancy. Despite the detection of more than 70 molecular species, there are still major uncertainties about formation mechanisms, environment, and evolution within molecular clouds. One puzzle, the apparent lack of molecular ring molecules in the interstellar environment, was removed (but certainly not resolved!) with the detection of the ring C_3H_2.

In the course of a search for interstellar ethynamine, Matthews and his collaborators surveyed 200 MHz of the microwave spectrum of several galactic sources on the 140-foot telescope. Although ethynamine was not found, they covered the frequency of a previously unidentified spectral line (18343 MHz) originally discovered in IRC+10°216. It quickly became apparent that this transition is easily detectable in a wide range of objects throughout the Galaxy. Subsequently, the line was identified as the 1_{10}-1_{01} transition of the three-member ring molecule cyclopropenylidene (C_3H_2). Matthews <u>et al</u>. noted: *"As [this line] ... is one of the strongest known interstellar lines at short centimetric wavelengths, it promises to provide a very useful probe of the interstellar medium."*

Indeed, the molecule is so ubiquitous that it was readily detected on the 140-foot telescope in the dark band across the nucleus of the radio galaxy Centaurus A (NGC 5128) at an abundance not noticeably different from that in our own galaxy.

This molecule is so widespread that the physical circumstances conducive to its formation and excitation must be very common in interstellar space. However, it is such a highly reactive radical that it is not expected to be a dominant molecule in clouds with a stable environment and a mature chemistry. The molecule was recently discovered to be common in high latitude IRAS "cirrus" clouds, another feature which suggests that it traces a distinct regime, one in which the chemistry might not be anywhere near equilibrium. Besides its place as the only interstellar ring molecule (which may give theorists insight into the preference for linear chains rather than rings in interstellar space), the great abundance of C_3H_2 is its most interesting feature, and one which may make it useful as a general probe of molecular gas.

<u>EXTRAORDINARILY LUMINOUS METHANOL MASERS</u> - For more than ten years the source in Orion was known to exhibit weak maser action in the rotational lines of the E torsional symmetry of CH_3OH. Recently, Wilson and his collaborators from the Max Planck Institute fur Radioastronomie in Bonn reported additional methanol masers in W3 and NGC 7538 in the A torsional symmetry species. However, these were again weak masers and toward some sources the 9_2-10_1 line (23.1 GHz) was seen in absorption. The surprising variation of the behavior of the line, maser emission to absorption, called for observations of additional transitions at non-standard frequencies. To obtain observations at the necessary frequencies, they used the 140-foot telescope.

Observing the 2_0-3_{-1} line at 12.1 GHz, Batrla and his MPIfR and HIA colleagues not only detected methanol but showed this transition to be an extraordinarily luminous maser: flux densities of a few tens to thousands of janskys were reported. Toward W3, the photon luminosity in the CH_3OH 2_0-3_{-1} E line is higher by a factor of 2 than the luminosity of the OH 1665 maser line. That suggests that the abundance of methanol is as great as that of OH and that the pump mechanism is at least as efficient. Understanding such large methanol abundances is a problem almost as challenging as understanding the maser pump.

This is an example of an unexpected discovery made at the 140-foot telescope rather than elsewhere owing to the frequency coverage available but not relying on the sensitivity of the telescope. By way of a postscript here, it is noteworthy that this discovery, recognized in Australia, has already altered construction plans for receivers on the Australia Telescope. Receivers at 12 GHz are being installed for synthesis observations of the methanol maser line.

<u>THE DETECTION AND MEASUREMENT OF INTERSTELLAR ^{3}He</u> - A determination of the ^{3}He abundance in the interstellar medium can be used to test theories of cosmology, stellar evolution, and the chemical evolution of the Milky Way galaxy. In principle, measurement of the primordial ^{3}He abundance coupled with estimates of the primordial deuterium and ^{4}He abundances would enable one to determine both the baryon to photon ratio and also the number of equivalent neutrino flavors.

Singly ionized ^{3}He has a hyperfine transition at 8.7 GHz, analogous to the hyperfine line of HI at 21 cm. It should be detectable in emission in HII regions, where nearly all of the helium is singly ionized. The line formation and transfer is simple and well understood; the lines are optically thin and collisionally excited. The only difficulties in measuring ^{3}He are instrumental:

- The frequency of the ^{3}He line, 8.7 GHz, is not one of the "standard" frequencies of radio astronomy. The frequency is not in one of the protected bands.

- Because the abundance of ^{3}He is $< 10^{-4}$ that of hydrogen, the ^{3}He emission lines are very weak. The experiment requires a low-noise receiver and a system that performs well in very long integrations.

- The lines will be observed against a strong nebular continuum, so the line-to-continuum ratio is very low. To detect ^{3}He, a telescope must be capable of measuring a line that is $\lesssim 10^{-5}$ of the total system temperature. The experiment requires a system with excellent baseline stability, freedom from spurious effects such as reflections, mismatches in the IF, and so on. Many observers have noted that systematic effects which produce nonrandom frequency structure in the instrumental baselines dominate the radiometer noise and ultimately limit the detectability of weak (~ 2-3 mK), wide (~ 1 MHz) spectral lines.

- A large bandwidth spectrometer is needed so that many recombination lines of various strength can be observed simultaneously with the ^{3}He line to control systematic errors.

The first claimed detection of ^{3}He from observations on the 100-meter telescope at Effelsberg was not convincing, even to the discoverers. The line was seen in only one HII region at a low signal-to-noise ratio, and systematic effects were not under control or understood. The first unambiguous detections of ^{3}He, in several nebulae, were made at the 140-foot telescope by Rood and his collaborators, who explained:

> *"With a new microwave upconverter maser receiver and autocorrelation spectrometer, the smaller telescope at Green Bank is competitive with the 100-meter telescope at 8.7 GHz. Beyond the low noise temperature of the receiver, the wide bandwidth of both the autocorrelator and receiver make it possible to estimate instrumental baseline and other systematic errors with more confidence than ever before. For our measurements, such errors are more crucial than the signal-to-noise ratio; it is our belief that errors of this type have been seriously underestimated in earlier experiments."* (Ap. J. 280, 629)

There are now published results for 17 HII regions observed with the 140-foot telescope, either detections of ^{3}He or significant upper limits. These are probably the weakest lines ever measured in radio astronomy. Some have peak temperatures as low as 1 mK. From these observations we learn: (1) There are definite variations in the (^{3}He/H) ratio from one source to the next, but there is no large galactic abundance gradient. (2) The variation in ^{3}He between sources implies substantial chemical evolution of the Galaxy. (3) The lowest value of the ^{3}He abundance limits the primordial nucleon to photon ratio which, for a standard big bang model, limits the critical density contributed by nucleons to $0.025 \lesssim \Omega_N \lesssim 0.139$.

The 140-foot telescope is the only radio telescope, anywhere, that has reliably measured the ^{3}He line. Recently, i.e., since the last ^{3}He measurements were made, a second channel has been added to the receiver, doubling the system sensitivity. As shown in Figure 2, the noise continues to decrease as $t^{-1/2}$ for periods of up to 400 hours, and to rms noise levels $\lesssim 400\ \mu$K. (This is about 100 μJy per beam area in an 80 kHz band.) Bania, Rood, and Wilson (MPIFR) have applied to continue their observations at the 140-foot telescope with the expectation that many more sources will have detectable ^{3}He.

GALACTIC HI STUDIES - While it might seem that by now the galactic HI sky should have been exhaustively studied, the truth is that the data, and our understanding of them, are far from complete. For example, the only modern all-sky HI survey with beamwidth < 1° was made at Hat Creek and has an rms noise in each channel of ~ 1 K. In contrast, a moderately sensitive UV or optical spectrum taken toward a distant star or quasar can detect lines which originate in clouds with $N_H \lesssim 10^{18}$ cm^{-2}, which, for a line width of 10 km/s, implies that the cloud's 21 cm emission is < 50 mK

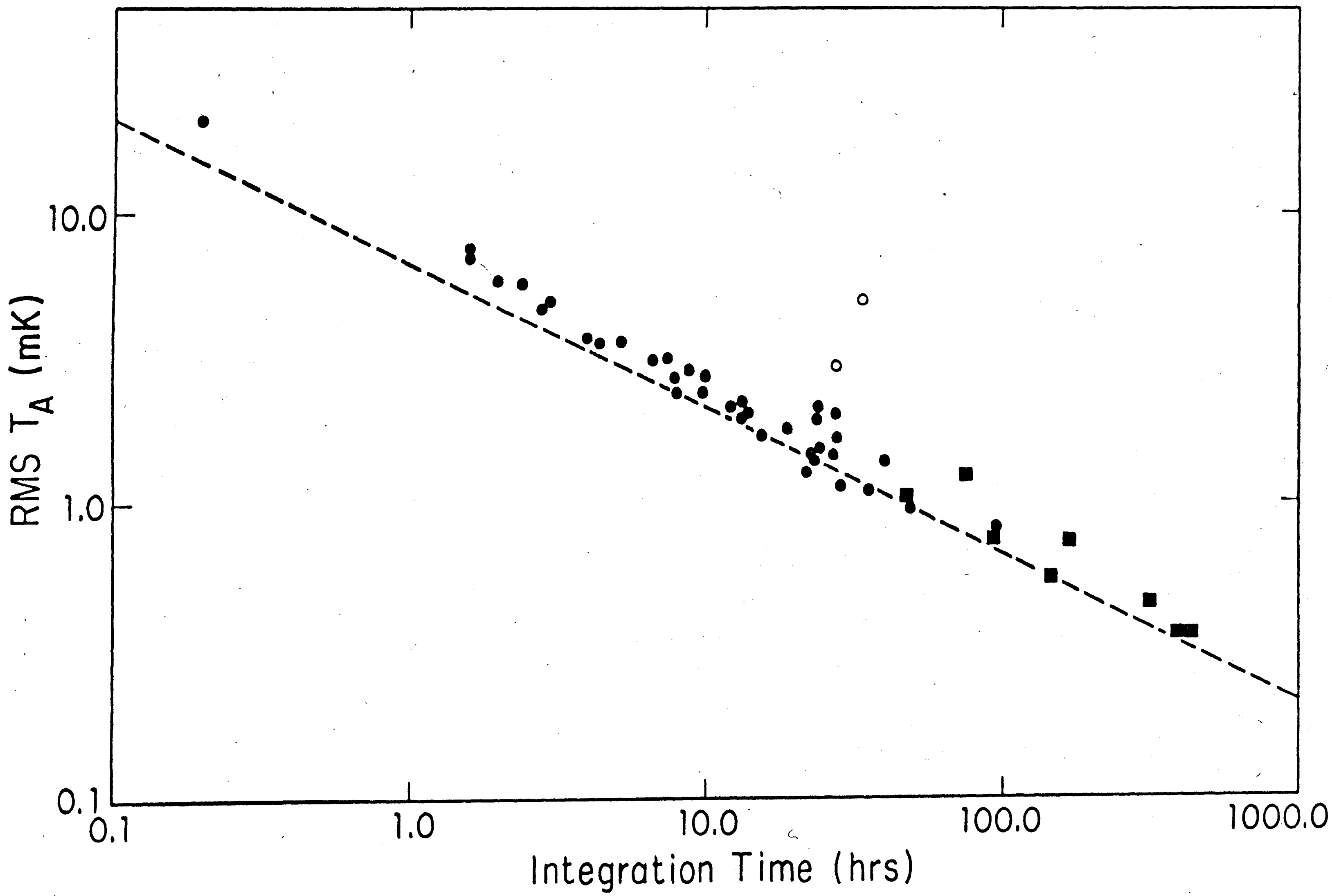


Figure 2. RMS noise, per 80 kHz channel, as a function of integration time. These data were taken as part of the search for the ^3He at 8.7 GHz. The total spectral bandwidth is 80 MHz.

at the line peak. There is a continuing need for high quality, 21 cm, HI spectra at an angular resolution of 10-20′.

In recent years the 140-foot telescope has been used for many HI studies. A very large survey of the galactic disk was done by Burton and collaborators. The motivation for undertaking this observing program was the desire for 21 cm data which would support investigations of the flare and warp of the outer-galaxy hydrogen, the high-velocity gas in the outskirts of the Galaxy, and the macroscopic optical-depth characteristics of the hydrogen layer which must be understood before the total galactic HI content can be measured. Although these investigations involve quite different aspects of galactic structure, the same sort of data are required. The main requirements are sensitivity to low intensities, broad velocity coverage, and as wide coverage as possible in position, especially in latitude.

These requirements are met with the sensitive L-band system on the 140-foot telescope. It is so sensitive that very short integrations ($\leq$ 1 min) still give low noise spectra, so a large piece of the sky can be mapped in a reasonable time. Moreover, the 140-foot telescope is so reliable that once a routine has been established the observer can take data "remotely." For most of Burton's survey he was not actually at the telescope. The telescope operators carried out the program and observations were made unattended by an astronomer. The excellent system stability, the low level of interference, and the reliability of telescope, equipment, and personnel ensured good results.

The body of Burton's survey is only now being analyzed. It will be of great value in comparative studies, e.g., in studying the association of infrared emission with HI and in determining the kinematics of gas in the most distant parts of the galactic warp.

A second kind of HI observing now being done frequently on the 140-foot telescope seeks to combine a very high sensitivity with a very high dynamic range. However, the current 21 cm receivers at Green Bank are so sensitive that in many directions of the sky the observations are not limited by noise but by a form of "scattered light" known as "stray radiation." Radio telescopes have weak sidelobes that cover the entire sky. Neutral hydrogen emission entering these sidelobes adds to emission detected via the main beam. When the main beam lies on an area of weak HI while the sidelobes cover bright emission from the Galactic plane, the "stray" component can comprise half of the observed signal. The stray signal mimics a smooth low-level component of interstellar HI, and it effectively limits the dynamic range of measurements. A method of removing ~90 percent of the stray component of 140-foot HI spectra by bootstrapping them to low-resolution data taken with a "clean" horn antenna having little sidelobe contamination was developed by Lockman and his collaborators at the University of Wisconsin and is now being used to provide highly sensitive HI spectra in special directions, e.g., toward quasars, distant stars, etc.

<u>PULSAR TIMING OBSERVATIONS</u> - Although in the past the 140-foot telescope had not been used for pulsar observations nearly as much as the 300-foot telescope, this situation is now changing. One reason is that there are several interesting pulsars which lie outside of the declination range of the 300-foot telescope but can be observed with the 140-foot telescope since it reaches declinations as far south as -46°: one can observe more than 85 percent of the sky. These factors came into the recent (and ongoing) observations of PSR 1821-24, a millisecond pulsar located in a globular cluster located at $\delta \approx -24°$.

Observations using the 140-foot L-band system were made on 6 days spread over three observing sessions and have been used to determine the period derivative (the "slow-down") of this pulsar. While the observed P is somewhat larger than expected (it implies a pulsar spin-down age of only 30 Myr, much less than the age of the cluster), it is consistent with models in which all pulsars with P < 30 ms are recycled pulsars which have been spun up by accretion. There is no evidence that this pulsar has a companion.

This pulsar is a probe of the mass distribution in the globular cluster. The apparent second period derivative of PSR 1821-24 will probably be dominated by the effects of cluster dynamics. With the present level of timing accuracy, the expected dynamical contribution to P should be detectable within 2 or 3 years. On a similar time scale, continued timing observations should yield the pulsar's proper motion (or useful upper limits), thereby revealing its transverse motion and providing unambiguous information on gravitational interactions in the cluster environment. Timing observations on this and other southern pulsars will continue for years.

<u>ISOTROPY IN THE COSMIC MICROWAVE BACKGROUND</u> - Continuum sensitivity presents a particular challenge to a single-dish radio telescope, and no observation is more demanding than the search for anisotropies in the microwave background. Demanding because we may be measuring zero--whatever the instrument sensitivity is, it always must be better.

The most recent series of observations, made at 19 GHz by Uson and Wilkinson (both in the physics department at Princeton when the work began), have produced the most stringent limits on fluctuations in the microwave background to date. At the 95 percent confidence level, they find $\Delta T_{rms}/T < 2.1 \times 10^{-5}$ on angular scales ~4'. The rms noise in these data is only 39 μK, or about 10 μJy/beam. While the physical interpretation of these results requires a model for the nature of the underlying fluctuations, this limit conflicts with those models in which the initial fluctuations are adiabatic and dominated by baryonic matter.

Uson and Wilkinson comment as follows (Nature <u>312</u>, 427): *"As a remnant of the early Universe, the cosmic microwave background provides unique information on the initial conditions from which matter has evolved to form the structures we see today. ... limits set on possible underlying fluctuations restrict the range of physical models for perturbations of the density in the early Universe."*

"It is hard to measure small-scale anisotropy in the microwave background at the level of 10^{-5}. These measurements require the use of large telescopes in order to obtain the wanted narrow beams. The main experimental problems are ... atmospheric emission at $\lambda < 1$ cm, ground radiation at all wavelengths, interference and variable instrumental effects... Besides these sources of systematic errors, one again has to deal with Johnson noise from the receiver." "The 140-foot telescope of the US National Radio Astronomy Observatory, with the K-band maser receiver mounted at the Cassegrain focus, is an excellent instrument for high-sensitivity continuum observations. ... it is exceedingly stable for long integrations and consistently reaches a sensitivity of $T_{rms} = 10^{-4}$K (antenna temperature) for 2^h of observation in the best weather conditions." "We thank C. Brockway and R. Fisher for their continuous improvements of the telescope, receiver and data acquisition system, and all the NRAO-Green Bank staff for their help and constant vigilance."

IV. FUTURE PLANS

FURTHER IMPROVEMENTS IN RECEIVER SENSITIVITY - The fundamental amplification of the 140-foot Cassegrain receivers is a K-band maser tunable from 18-25 GHz. Frequencies between 5-18 GHz are converted in frequency to K-band by one of three parametric upconverters that proceeds the maser. While giving wide bandwidth and frequency flexibility, the upconverters introduce a source of noise (and instability) that it would be advantageous to eliminate. Heretofore, no competitive wideband, lower noise alternative was available. However, with the successful development of HEMT amplifiers at the NRAO Central Development Laboratory, we have the opportunity to replace the 5-18 GHz upconverter portion of the Cassegrain receivers with wideband HEMT receivers operating at the signal frequency. Since the CDL HEMTs have a receiver temperature of approximately 1 K/GHz, these amplifiers are superior to the upconverter/maser receivers but they are inferior to the maser itself at its K-band signal frequency.

We plan to replace the upconverter receivers with HEMTs over the next few years, retaining the maser receivers. The present system temperature of the 140-foot Cassegrain receivers is shown as the solid line in Figure 3; the expected improvement with HEMT receivers at 5-18 GHz is shown by the dashed lines.

IMPROVEMENTS TO THE TELESCOPE OPTICS - In August 1987, the first steps were taken to improve the 140-foot optics when a detailed holographic map was made of the primary mirror and, on the basis of this map, the surface panels were reset. At high frequencies the increased aperture efficiency (from 18 to 28 percent at 24 GHz) was reassuring. Further improvements in aperture efficiency will result when the figure of the secondary and tertiary mirrors are improved. More work on the feeds will reduce spillover, as well as the noise contribution of the feeds and waveguide. (At L-band more than half the total system noise of 18 K is a result of the feed and spillover.)

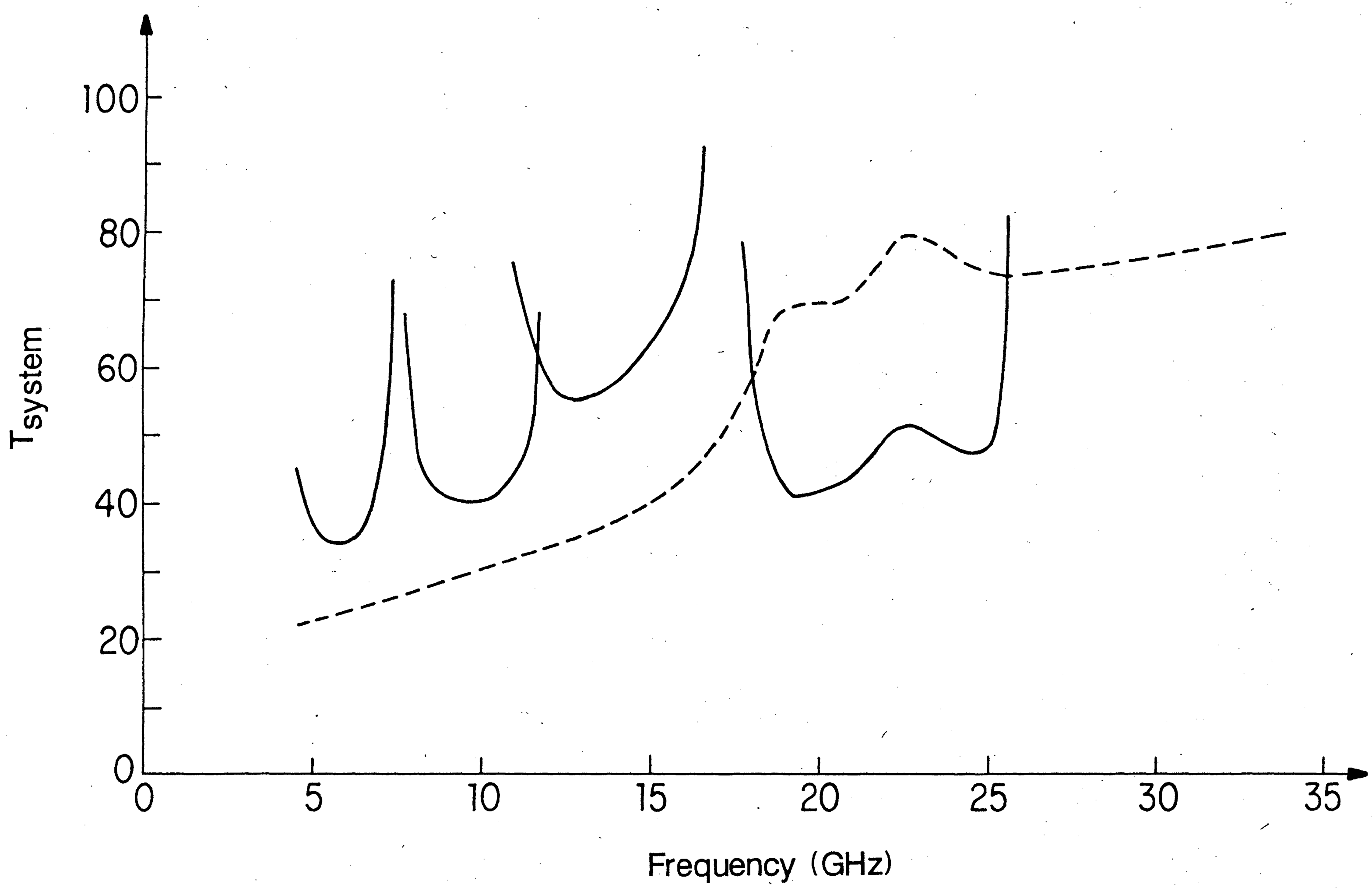


Figure 3. System temperature of one of the Cassegrain receivers on the 140-foot. The solid curves show the present performance with the upconverter/maser receiver. The dashed line is the expected system temperature with HEMT amplifiers at all frequencies.

The more precise setting of the telescope primary mirror achieved in August suggests that it may be possible to extend the useful frequency range of the 140-foot to the atmospheric window at 32 GHz. If so, measurements of the microwave background anisotropy and the Sunyaev-Zeldovich effect stand to be the principal beneficiaries, although an increased frequency range for spectroscopy also could be exploited. Figure 3 illustrates the system temperature which appears feasible with a HEMT amplifier at 25-32 GHz (dashed line).

V. USER INFORMATION

A BRIEF PROFILE OF THE 140-FOOT TELESCOPE USAGE - During the 1983-87 period an average of 47 proposals per year (55 in 1987) have been submitted to use the 140-foot telescope. This does not include the proposals submitted to the Network Users Group (NUG) for VLBI usage of the instrument. The non-VLB proposals for a typical year have involved 90 individual scientists (including students and NRAO staff), representing 58 different institutions. Approximately 87 percent of the non-VLB time requested by a typical proposal was scheduled for observation (includes both rejections and reductions). At any given time, however, depending on the requested frequency, proposals had to wait between six and nine months in the scheduling queue before the observations were made.

Since 1983, the 140-foot telescope has been scheduled for astronomical observing an average of 80 percent of the available time, consisting of 66 percent for visitors (including students) and 14 percent for NRAO staff. The balance of the time has been devoted to testing, calibration, maintenance, and instrument installation. Most recently, for example, telescope time was taken for holographic surface tests and panel readjustments. During scheduled astronomical observing, the time lost due to equipment failure, weather, and interference averaged 5.8 percent.

STUDENTS - An average of 26 graduate students per year have observed with the 140-foot telescope during the past five years (includes VLB programs). Examples of outstanding recent Ph.D. theses produced by students using the 140-foot telescope include:

- L. Danly, 1987, U. Wisconsin, "The Kinematics of Milky Way Halo Gas"
- J. A. Biretta, 1986 (VLB), Caltech, "Investigations of Radio Jets in M87, 3C 273, and 3C 345"
- A. G. Nash, 1986, U. Wisconsin, "Observations of Molecular Clouds in the Direction of Galactic and Extragalactic Radio Sources"
- J. E. Wadiak, 1986, U. Virginia, "Formaldehyde Observations of Molecular Clouds"
- K. Jahoda, 1986, U. Wisconsin, "HI Structure and the Soft X-Ray Background"

- L. A. Molnar, 1985 (VLB), Harvard, "Multiwavelength Studies of Cygnus X-3"

<u>PUBLICATIONS</u> - An average of 20 papers based on 140-foot telescope observations have been published per year in the last five years. An additional 16 papers per year reported on VLB experiments carried out on the telescope.

VI. OPERATING COSTS OF THE 140-FOOT TELESCOPE: EXPENSES IN CALENDAR YEAR 1987

OPERATIONS	
Telescope Operations and Maintenance	\$ 508k
50 Percent of Site Maintenance & Administration	\$ 475k
50 Percent of Pro-rata Share of Observatory Administrative Costs	\$ 392k
INSTRUMENTATION	
Jansky Laboratory Development and Maintenance	\$ 400k
Central Development Laboratory	\$ 70k
Research Equipment	\$ 100k
RESEARCH SUPPORT	
Site Support	\$ 235k
50 Percent of Green Bank Pro-rata Share of Observatory Support	\$ 327k
TOTAL: TELESCOPE AND SITE	\$1618k
TOTAL: OBSERVATORY SUPPORT	\$ 889k

T H E

T H E 3 0 0 - F O O T T E L E S C O P E

Prepared for the Radio Facilities Panel
Division of Astronomical Sciences
National Science Foundation
by the National Radio Astronomy Observatory
March 1988

I. INTRODUCTION

In September 1987 the 300-foot telescope celebrated its twenty-fifth year of continuous operation, dedicated wholly to astronomical research. Constructed to provide U. S. astronomers with an aperture as large as that available elsewhere in the world for operation to wavelengths (originally) only as short as 21 cm, the characteristics of the 300-foot telescope most important to its astronomical uses now are:

- The large aperture yields high sensitivity ($\approx$ 1 K/Jy) and resolution as fine as 3 arcminutes at 5 GHz.

- This transit telescope can reach sources over a wide declination range ($-19° < \delta < +90°$) but with limited tracking in hour angle (4^m sec δ at high frequencies, 30^m sec δ at low frequencies). It is most efficiently utilized by survey programs covering many sources or large areas of the sky.

- Sensitive receivers provide continuous frequency coverage from 30 MHz to 5 GHz, the upper frequency limit of the telescope. The 1.3-1.7 GHz receiver (for HI and OH observations) is the most sensitive receiver on any radio telescope in the world.

- The 300-foot telescope in Green Bank is located in the National Radio Quiet Zone (NRQZ). Interference from fixed transmitters in the NRQZ is regulated by the FCC. An additional West Virginia statute even protects against electrical interference generated within some tens of miles of the Observatory, for example, motors or welders. Protection from man-made interference permits observations at frequencies outside of bands allocated to radio astronomy (observations of high-redshift spectral lines, for example) or with very wide continuum bandwidth.

II. TELESCOPE AND INSTRUMENTATION

TELESCOPE SPECIFICATIONS

Diameter: 300 feet (91 m)
Pointing Accuracy: 10"
Sky Coverage: -19° to 90° declination
Sensitivity: 1.1 K Jy^{-1}

TELESCOPE OPTICS - Two receivers can be mounted simultaneously on the telescope, both at prime focus. One receiver is fixed on-axis in a focusing feed mount while the other is mounted on a traveling feed which tracks position to increase the hour angle coverage available.

RECEIVERS

Frequency Range (MHz)	Amplifier	System Temperature (K)
Single Beam, Dual Polarization		
25- 88	Transistor	300
110- 250	Transistor	250
250-1000	Cooled Upconverter/ GaAsFET	45-85
1000-1450	Cooled GaAsFET	35
1300-1800	Cooled HEMT	18-23
2900-3500	Cooled GaAsFET	25-35
4470-5050	Cooled GaAsFET	25-35
Multi-beam Receivers		
1300-1500	4-channel GaAsFET	90
2640-2750	4-channel GaAsFET	130
4600-5100	14-channel Cooled GaAsFET	60

Note: All these receivers are shared with the 140-foot telescope.

III. SCIENTIFIC PROGRAM

THE 300-FOOT TELESCOPE IN PERSPECTIVE - The role of the 300-foot telescope in astronomy worldwide is affected by its relationship to aperture-synthesis telescopes, especially the VLA. Many properties of the aperture "synthesized" by an interferometer and the "real" aperture of a single dish are similar in principle. For example, the sensitivity of either is proportional to its total surface area. In practice, however, single-dish telescopes and interferometers are sufficiently different that one or the other is usually the better choice for any particular observational problem. The angular resolution and position accuracy of an interferometer are determined by the length of its baselines and their electrical stability, while the resolving power and pointing accuracy of a single dish are limited by its diameter and mechanical stability, respectively. Observing programs needing resolution finer than about 1 arcminute or pointing errors smaller than a few arcseconds can be done only with interferometers. An interferometer maps an area that may be as large as the primary beam of its individual telescopes, but often much smaller--the effective field of view of the VLBA is much too small for finding sources by surveying the sky. The interferometer's high resolution reduces "confusion" by background sources so that extremely weak continuum features can be detected and mapped reliably.

Interferometers usually perform close to their theoretical sensitivity limits because they are insensitive to man-made interference and small receiver gain fluctuations. Thus, almost all mapping of moderately compact sources is done with interferometers.

On the other hand, interferometers are insensitive to sources with large angular sizes ($\geq$ 10 arcmin in the case of the VLA). Extended sources with low surface brightnesses (e.g., HI emission from external galaxies) require very long integration times to observe with interferometers because their flux density per synthesized beam is low. The inherent complexity of modern aperture-synthesis instruments also tends to limit their frequency coverage, instantaneous bandwidth, time resolution, and sensitivity. A single, exotic, expensive, or difficult-to-maintain receiver (e.g., a helium-cooled maser) can be used on a single dish to obtain the best possible performance, while interferometer receivers must trade off sensitivity for low cost, reliability, and conservative design. A new state-of-the-art receiver can be built and installed quickly on a single dish, but installation on the VLA takes a few years (the cycle time for all of the antennas to be brought into the telescope assembly building for their periodic maintenance). Finally, the computing time required to produce aperture-synthesis maps restricts the number of maps and consequently the sky area that can be covered, so that most large-scale surveys are made with single dishes.

The effects of these practical differences are so large that both single-dish and aperture synthesis telescopes are often used to complement each other in a single program. A good illustration is the radio search for gravitational lenses, intervening galaxies that split the point image of a quasar into three or more components separated by several arcseconds. Only about one quasar in a thousand should be lensed, so a radio survey covering thousands of square degrees is necessary to detect enough candidate sources. Such a survey was made at λ = 6 cm with the 300-foot telescope, and 10^4 sources were detected. But no single-dish telescope has either the resolving power to distinguish a gravitationally lensed source from a point source or the pointing accuracy needed to make unambiguous optical identifications with faint quasistellar objects. Thus the VLA made high-resolution "snapshot" maps of the candidates found by the 300-foot telescope, and only those sources with appropriate radio morphology and optical identifications are being followed up with optical spectroscopy. So far, at least three (of the seven known) gravitational lenses have been discovered by this program. The complementary relationship between the 300-foot and the VLA is analogous to that of the 48-inch Schmidt and the 200-inch telescope at Palomar. The former is used primarily to survey the sky and discover interesting classes of objects, the latter to study individual objects in greater detail.

RECENT SCIENTIFIC PROGRAMS ON THE 300-FOOT TELESCOPE

Continuum Sky Maps - The entire declination band $-5° < \delta < +82°$ was mapped with $\approx$ 12 arcmin resolution at 1400 MHz by Condon and Broderick. The resulting sky maps (Figure 1) are confusion limited (that is, the receiver noise is smaller than the map background fluctuations from faint sources too numerous to be resolved) and contain ≈ 2 x 10^4 clearly detected sources. These maps are available as both digital images on a FITS tape and as a printed contour atlas. With these tapes, astronomers can often undertake large observing programs without having to submit proposals, use the telescope, and reduce data. For example, the 1400 MHz maps have been used to select those 4C sources with very steep spectra as the first step in a search for millisecond pulsar candidates.

In 1986 and 1987, the new 7-feed, 14-channel receiver was used to cover $0° < \delta < +75°$ at 4.85 GHz with ≈ 3 arcmin resolution. The survey required about one month of telescope time and yielded maps with less than 10 arcsec rms position uncertainties and $\sigma \approx 1$ mJy confusion limit. The maps are already sensitive enough to reveal 10^5 sources in 6 sr, about the number of extragalactic sources expected in the new 60 μm IRAS Faint Source Survey or the planned ROSAT X-ray survey. The new 5 GHz maps will also be made available as a service to the astronomical community.

<u>HI Line Surveys of Nearby Galaxies and Clusters of Galaxies</u> - With its exceptionally sensitive L-band receiver ($T_s < 20$ K on the sky), the 300-foot telescope has become an efficient "redshift machine" out to $z \approx 0.03$. HI $\lambda = 21$ cm spectra of thousands of spiral galaxies have been obtained in several major long-term programs. Astronomical uses of these spectra include:

- Mapping superclusters and filaments of galaxies in three dimensions. Haynes and her colleagues, for example, recently mapped the distribution of galaxies in the Pisces-Perseus supercluster north of $\delta = +38°$, the Arecibo declination limit, on the 300-foot. HI surveys can even be used to follow these structures through the galactic zone of avoidance that obscures some 20 percent of the sky optically. Kerr and his students have begun an unbiased HI search for spiral galaxies with the 300-foot telescope, and several searches for HI emission from IRAS galaxies in the zone of avoidance have been made.

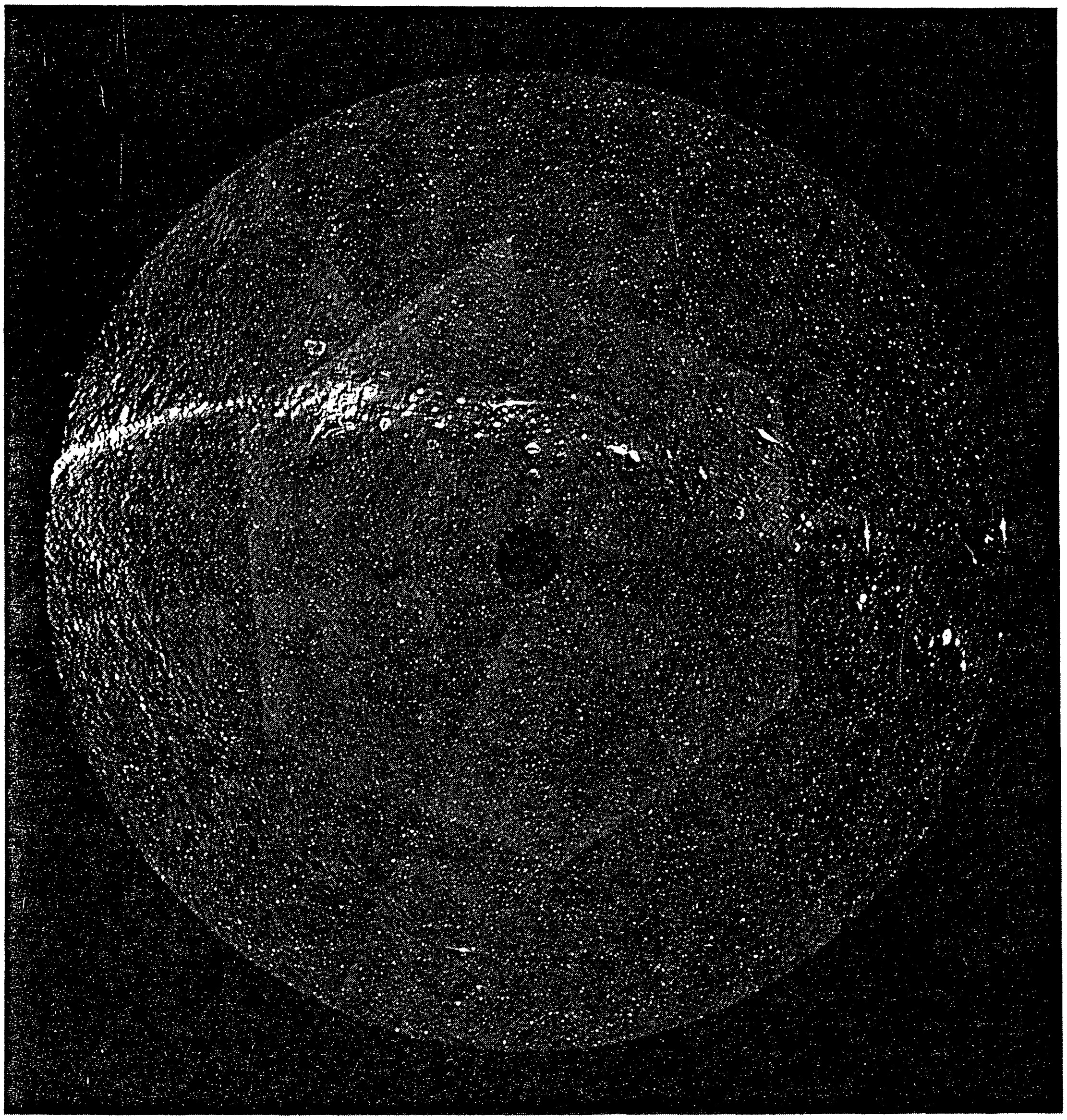
- Global HI masses and kinematic evidence for interactions were recently obtained for a sample of morphologically distorted galaxies as part of an investigation into the effects of interaction on star formation rates.

- HI spectra obtained at the 300-foot telescope are being used to measure the Hubble constant via the Tully-Fisher relation between HI line width and optical or infrared luminosity.

- "Stripping" of gas from galaxies in clusters is studied by comparing the HI masses of cluster and field galaxies.

- Galaxies selected from the IRAS catalogs are observed to obtain distances and spectroscopic evidence of tidal interactions.

The L-band receiver covers the $\lambda = 18$ cm lines of OH as well. It has been used at the 300-foot telescope to discover many of the known OH



1400 MHz SKY SURVEY

"megamaser" galaxies--galaxies experiencing enormous bursts of star formation in their nuclei.

Pulsars - Most pulsar observations are made with large single dishes because sensitivity with high time resolution is needed, confusion by steady sources can be rejected, and pulsars are such compact objects that even the largest interferometer cannot resolve them. They have very steep spectra, so they are easiest to observe at low frequencies ($\nu \leq 1.4$ GHz) where interference is common. The 300-foot telescope was used to discover the Crab pulsar almost 20 years ago. It has since made a number of general surveys of pulsars to determine their birth rate, age distribution, evolution, and spatial distribution in the galaxy. The most recently completed search for fast pulsars with the 300-foot telescope found 20 new pulsars with a period distribution consistent with two pulsar populations--slow pulsars and fast "recycled" pulsars. Timing measurements of these pulsars are being made with the 300-foot telescope to yield estimates of their dipole magnetic field strengths and to reveal binary systems. Searches for new millisecond pulsars are also being made.

Variable and Transient Sources - Many long-term programs to detect or monitor variable radio sources are running on the 300-foot telescope. Cyg X-3 and SS 433 are well known examples of the class of galactic radio sources whose flux densities change significantly on time scales of hours or days. Most have been found in other wavebands (e.g., X-rays), but now a systematic radio search for them is being made with the 300-foot telescope by Gregory and his students. It is possible to detect even quite faint variable sources in the presence of the galactic background by comparing maps made on successive days and looking for sources which appear or disappear.

The radio "light curves" of extragalactic variables are being monitored over a wide range of frequencies. Above $\nu \approx 1$ GHz, the observed long-term (months to years) variations are intrinsic, and they contain information about synchrotron radiation outbursts in the nuclei of active galaxies and quasars. The rapid flickering discovered and studied at the 300-foot telescope may be caused by refractive interstellar scintillations (RISS) in the interstellar medium of our galaxy. Most low-frequency ($\nu < 1$ GHz) variability of extragalactic sources observed with the 300-foot telescope may also be caused by RISS. This hypothesis receives support from a program on the 300-foot telescope that monitored the low-frequency flux densities of pulsars (since they are point sources) with a wide range of dispersion measures. Since pulsars with very long RISS time scales appear to have intrinsically steady luminosities on time scales of days to weeks, the slow flux-density variations seen in most other pulsars must be caused by RISS.

Observations at Very Low or Unprotected Frequencies - Green Bank is in the National Radio Quiet Zone, where it is protected from man-made interference--an often fatal problem for observations at very low frequencies. Recently the 300-foot telescope observed recombination lines from highly excited neutral carbon atoms at frequencies as low as $\nu \approx 30$ MHz. These atoms have Bohr radii $r \approx 0.003$ cm, making them the largest ever studied in any environment. The lines are pressure broadened and their excitation temperature is nearly equal to the gas kinetic temperature, so they provide a new diagnostic for studying cool gas in the interstellar medium.

If primordial galaxies or "pancakes" exist at redshifts $z \approx 5$, they may be detectable in HI emission at $\nu = 1420/(1+z) \approx 240$ MHz. A search for such emission is in progress at the 300-foot telescope.

The 300-foot telescope has frequently been used to observe highly redshifted HI absorption lines since the discovery of the $z = 0.692$ system in the QSO 3C 286.

IV. FUTURE INSTRUMENTATION

PULSAR PROCESSOR/FFT SPECTROMETER - A spectral processor is being built for the 300-foot telescope, with completion scheduled for early 1989. For spectroscopy, it will provide a maximum bandwidth of 40 MHz, 2048 channels, and 8 IF inputs. It will offer flexible configuration, e.g., two simultaneous 40 MHz IFs with 1024 channels for each. The timing circuitry involved in its autocorrelation can also be used for pulsar studies. An accumulator can average data synchronously with a pulsar's period. Furthermore, pulsar signals can be de-dispersed and their Faraday rotation removed. The processor will be able to recognize and reject RFI with a time resolution of ≥ 12.8 microsec. The primary scientific projects driving the need for a spectral processor are (1) redshifted hydrogen studies of external galaxies and (2) detailed studies of pulsar physics and the intervening medium that modifies pulsar signals.

PHASED ARRAY RECEIVER - A second project intended to enhance the usefulness of the 300-foot telescope is the construction of a focal-plane array of receivers. This is one project that could have been completed in 1988, but which has been stretched over the next two years because of insufficient equipment funds. The intent is to increase the effective hour-angle coverage of this "transit" telescope by continuously varying the amplitude and phase illumination. By mounting a 2 x 8 phased array of receivers on a structure which can track hour angle, the effective daily observing time may be tripled with high aperture efficiency and low coma. This is so advantageous that the array in progress may be only the first of several, each needed to cover a different frequency band. The first is designed to cover the band 400-500 MHz, with instantaneous bandwidths of 10 MHz. Presently, a source can be tracked for (10 sec δ) minutes on either side of transit before the telescope gain falls by half. With the focal plane array, that increases to $\pm$(30 sec δ) minutes/day. The major scientific objectives are (1) redshifted ($z = 1.8$-2.5) neutral hydrogen absorption studies in quasars and (2) pulsars whose steep spectra favor low frequencies.

HI OBSERVATIONS WITH AN UNBLOCKED APERTURE - HI column densities and line profiles are most severely limited not by receiver sensitivity but by corruption from "stray radiation," i.e., emission coherent at the feed but which does not come in the main beam. Stray radiation is power in the far telescope sidelobes which are themselves the results of imperfections in the illuminated aperture attributable mostly to reflections off the feed legs. The solution to these problems is to observe with an inherently "clean" telescope. Fortunately, because the 300-foot telescope has only two feed support legs, there are large areas of the aperture unblocked to the east and west of the main axis. Experiments have shown that we can illuminate these parts of the dish and achieve a truly "clean" beam. (Beam efficiencies greater than 98.7 percent were demonstrated by observations at 5 GHz with an offset feed.)

Construction has begun on an off-axis, 21-cm feed to illuminate one unblocked portion of the antenna. When complete, a sky survey will be undertaken of the galactic HI north of -19°. Such a survey will characterize the distribution of Galactic HI, and Galactic kinematics, with an angular resolution, velocity resolution, sensitivity, and discrimination against spurious features which is unprecedented. It will be a time consuming survey: at 40 seconds integration per beam the telescope time required is 600/n days, with n being the number of feeds.

V. USER INFORMATION

A BRIEF PROFILE OF 300-FOOT TELESCOPE USAGE - During the 1983-87 period an average of 14 proposals per year have been submitted to use the 300-foot telescope. This clearly illustrates the major strength of the telescope, as it is primarily devoted to survey work and the accumulation of extremely large data bases of fundamental importance to long-term studies. In a typical year these projects have involved 57 individual scientists (including students and NRAO staff), representing 23 different institutions. Virtually all of the observing time requested for each proposal was granted. At any given time, however, the backlog of pending proposals translated into an approximate six-month waiting period in the scheduling queue before the time was assigned.

Since 1983, the 300-foot telescope has been scheduled for astronomical observing an average of 69 percent of the available time, consisting of 55 percent for visitors (including students) and 14 percent for NRAO staff. The balance of the time has been devoted to testing, calibration, maintenance, and instrument installation. Major telescope upgrades, such as the addition of N-S motion to the feed carriage, the installation and shakedown of the seven-feed receiver, and installation of a new control/data-taking computer, have been performed. During scheduled astronomical observations, however, the downtime attributed to equipment failure, weather, and interference averaged only 3 percent.

STUDENTS - An average of 13 graduate students per year have observed with the 300-foot telescope during the past five years. Examples of outstanding theses produced by students using the 300-foot telescope include:

- G. H. Stokes, 1985, Princeton, "A Search for Short Period Pulsars and Its Implication for the Period Distribution of Pulsars"
- R. J. Dewey, 1984, Princeton, "A Search for Low Luminosity Pulsars and Its Implications for the Pulsar Luminosity Function"
- C. R. Lawrence, 1983, MIT, "Weak Extragalactic Radio Sources"
- M. Damashek, 1983, U. Massachusetts, "A Search for Radio Pulsars in the Northern Sky: Discovery of a Pulsar in a Unique Binary System"

PUBLICATIONS - An average of 20 publications per year have been based on 300-foot telescope observations during the 1983-87 period. This is only a slight decrease from the 24 published in the 1973/74 period.

VI. OPERATING COSTS OF THE 300-FOOT TELESCOPE: EXPENSES IN CALENDAR YEAR 1987

OPERATIONS	
Telescope Operations and Maintenance	$ 408k
50 Percent of Site Maintenance & Administration	$ 475k
50 Percent of Green Bank Pro-rata Share of Observatory Administrative Costs	$ 392k
INSTRUMENTATION	
Jansky Laboratory Development and Maintenance	$ 475k
Central Development Laboratory	$ 70k
Research Equipment	$ 150k
RESEARCH SUPPORT	
Site Support	$ 235k
50 Percent of Green Bank Pro-rata Share of Observatory Support	$ 327k
TOTAL: TELESCOPE AND SITE	$1593k
TOTAL: OBSERVATORY SUPPORT	$ 939k

THE

12-METER MILLIMETER-WAVE TELESCOPE

Prepared for the Radio Facilities Panel
Division of Astronomical Sciences
National Science Foundation
by the National Radio Astronomy Observatory
March 1988

I. INTRODUCTION

The NRAO 12-meter telescope began as the 36-ft telescope, and the 36-ft telescope is where millimeter-wavelength molecular astronomy began. Following a period of explosive growth in this new area of astronomical research, during which most of the dozens of molecular species known to exist in the interstellar medium were first detected at the 36-ft, the telescope's reflecting surface and surface support structure were replaced and the 36-ft was re-christened as the 12-meter (in 1984). Subsequently, the scientific program has evolved from one dominated by observing programs in astrochemistry to one with concentrations in molecular clouds and galactic star formation, evolved stars, and, more recently, studies of external galaxies as well. The 12-meter is the only millimeter-wavelength telescope operated full-time as a national facility; more than 145 visitors make use of the telescope annually. It offers users flexibility and the opportunity to respond quickly to new scientific developments: low-noise receiving systems at a wide range of frequencies are maintained and operational reliability throughout is emphasized. The development of multi-beam receivers has inaugurated a new era of high speed source mapping on angular scales complementary to those of the millimeter-wave interferometers.

II. TELESCOPE AND INSTRUMENTATION

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

TELESCOPE SPECIFICATIONS

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

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

Receivers

Freq. Range (GHz)	Mixer	SSB Receiver Temperature (K) (per channel)
70-115	Schottky	350-500
90-115	SIS	80-150
200-240	Schottky	500-700
240-270	Schottky	1200
270-310	Schottky	1200-1500
330-360	Schottky	1800-2200
Eight-beam Receiver		
220-240	8-Schottky	500-700

Note: All single beam receivers have 2 orthogonal polarization channels. Receiver temperatures include all receiver optics.

Spectrometers

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

Resolution (kHz) per channel	Number of channels	Number of filter banks
25	256	1
30	128	1
100	256	1
250	256	1
500	256	1
1000	256	2
2000	256	2

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

Hybrid Spectrometer - To increase further the flexibility, frequency resolution agility and to accommodate the 8-beam receiver, a hybrid filter bank/autocorrelator is under construction. It will be on the telescope in the fall of 1988. Its instrumental parameters are as follows:

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

  1 x 2400 MHz
  2 x 1200 MHz
  4 x 600 MHz
  8 x 300 MHz

- frequency resolution (per channel): variable in steps of 2 continuously between 1.56 MHz and 24 kHz.

One of the assets of the 12-meter telescope is access to work done at the NRAO Central Development Laboratory (CDL) in collaboration with the semi-conductor devices laboratory at the University of Virginia. The CDL develops components which are built into telescope systems by the Tucson engineering staff. Figure 1 illustrates the improvement during the history of millimeter-wave astronomy of 115 GHz mixers produced by the CDL.

III. SCIENTIFIC PROGRAM

ROLE OF THE 12-METER IN MILLIMETER-WAVE SCIENCE - As the only national millimeter-wave telescope operated full-time for visiting astronomers, the first priority for the telescope is to support the diversity of millimeter-wave science. The 145 annual users of the telescope not only seek to observe galactic clouds using very narrow spectral bandwidths but they also observe galaxies using broad spectral bandwidths. They study the fractionization of deuterium using lines of DCO^+ at 70 GHz, and they study ion-molecule chemistry from observations of lines of HCO^+ at 356 GHz. Continuum observations of thermal emission from dust are important. Large areas of the sky are mapped. VLBI observations are supported.

The 12-meter telescope attempts to provide the full range of capabilities needed from a single dish by millimeter-wave astronomers. The needs change, of course, as new scientific opportunities are presented and as new facilities become available. In response to this evolution, priorities at the 12-meter telescope are refined and new techniques and capabilities are developed. Two examples illustrate this point.

- The success of the OVRO and Hat Creek millimeter-wave interferometers in mapping small regions brings with it the need to have available large-scale maps, to put the interferometer results in context, to provide necessary "zero-spacing" data, and to identify scientifically interesting regions for future interferometric work. The 8-beam, 220-240 GHz receiver and hybrid filterbank/autocorrelator at the 12-meter is a response to this need.

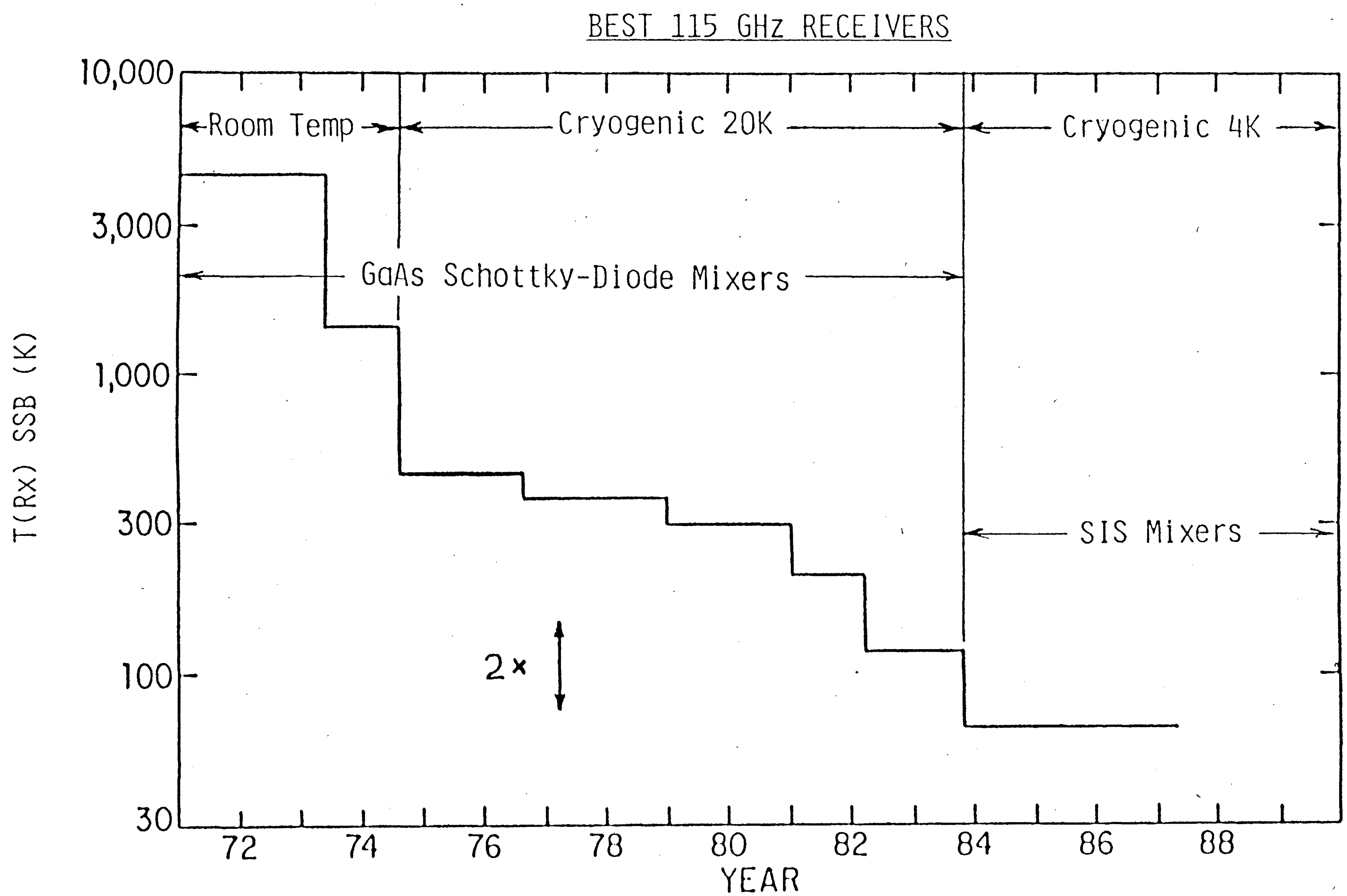


Figure 1. The history of 115 GHz receiver temperature (SSB) at the 36-foot/12-meter telescope.

- The submillimeter telescopes on Mauna Kea, the CSO and JCMT, can focus their efforts at the highest frequencies, > 400 GHz, where they are truly unique if other facilities are available for the "lower" frequency complementary work. A sound 200-360 GHz capability at the 12-meter is one asset in this respect which is receiving increased emphasis.

Presently, the capabilities of the 12-meter telescope that are most important to its users are the following:

- The low-noise 3 mm SIS receiver and dual-beam sky subtraction technique provide stable baselines to temperatures less than 1 mK. CO emission from cosmologically distant galaxies and tenuous circumstellar envelopes is detectable at this level.

- Dual-beam continuum mapping effectively cancels sky fluctuations and permits maps to be made of very extended objects. This is especially useful for mapping thermal dust emission at 1 mm.

- Continuous frequency coverage from 200-360 GHz with sensitive receivers is exploited by astronomers interested in astrochemistry.

- Receivers at several frequency bands (as many as four receivers) are available on the telescope. Nearly simultaneous observations at 3 mm and 1 mm, for example, may be made with a change-over time of a few minutes. Observations of continuum sources and maser sources benefit by such flexibility.

- The telescope is accessible to user-supplied instrumentation. In the past year visiting scientists have brought the following instruments to the 12-meter, installed them on the telescope, and made successful observations: (1) a Fourier-transform spectrometer; (2) a 345 GHz SIS receiver; (3) a multibeam bolometer; and (4) a continuum polarimeter.

The scientific thrusts of the work currently being done on the 12-meter telescope highlight these capabilities.

<u>Studies of Objects at Large (10,000 km/s) Redshift</u> - The introduction of a low-noise SIS receiver for use at the 12-meter telescope in the 3-mm window has allowed users to measure the CO, and by inference the molecular gas content, of a number of galaxies with redshifts (cz) of up to 23,000 km/s. The galaxies studied have in general been selected because of their high infrared luminosity. A current working hypothesis is that these objects are extremely "active" galaxies that are comprised of two galactic systems interacting or actually merging. The large amounts of molecular gas typically found in the systems may serve as the fuel to power a putative compact, energetic, active galactic nucleus.

The recent detection of the extraordinarily luminous object IRAS 14348-1447 by Sanders and his colleagues (Figure 2) offers the possibility of a connection between the luminous IR/CO galaxies and quasars. The CO is found at a redshift of 24,700 km/s (a frequency of approximately 106 GHz). The inferred total molecular mass is 6×10^{10} solar masses, comparable with the largest amount of HI observed in any spiral galaxy. At first sight the galaxy is similar to many of the other IR/CO objects and shows not only a double nucleus but also a warped disk; it is plausibly two systems merging. However, it is also as luminous as many optical quasars, although almost all of the energy is radiated in the infrared. IRAS 14348-1447 may thus be a dust-enshrouded quasar which in time will evolve to resemble its traditional optically-bright counterparts.

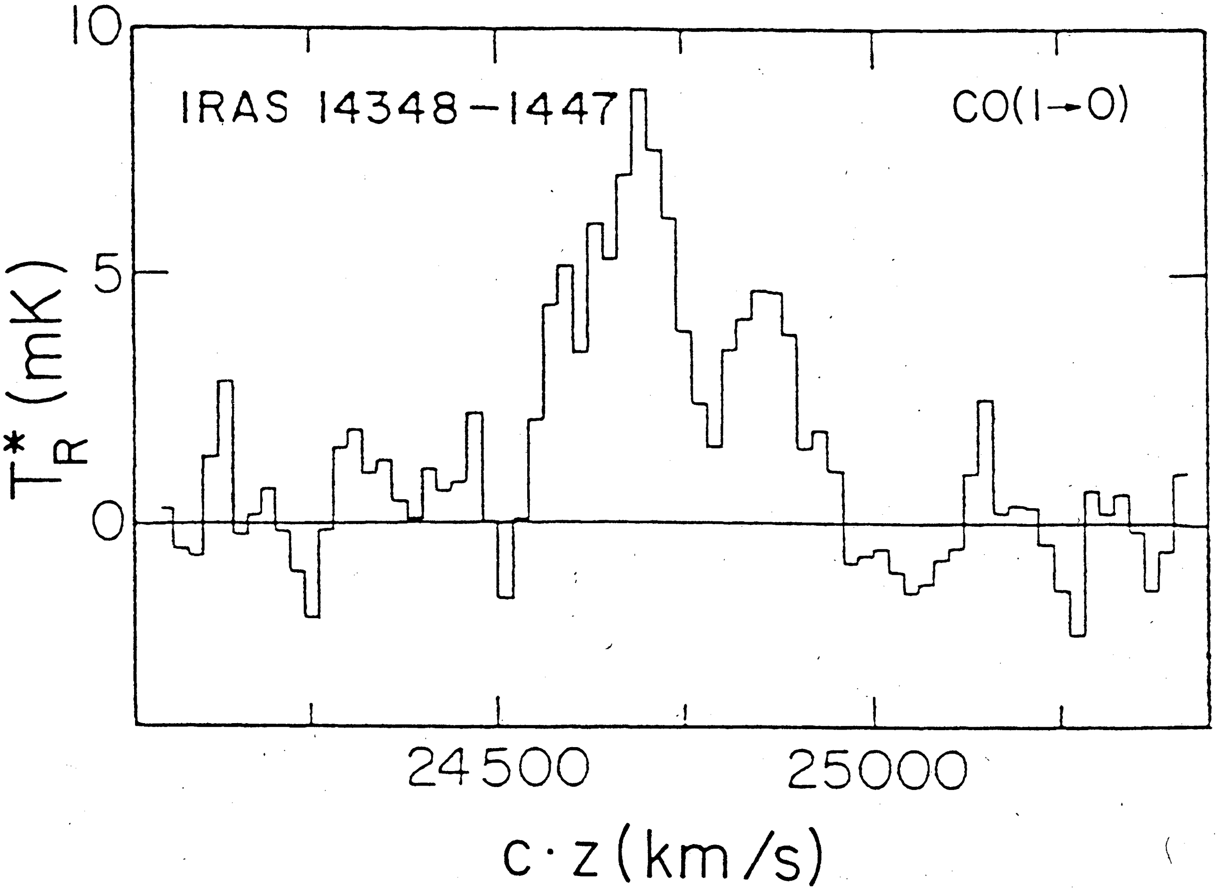
Observations such as that of IRAS 2438-1447 severely test the entire observing system. Broad, weak lines require much more than a low noise receiver: long integrations also require a stable IF, a reliable spectrometer, and a procedure for cancelling atmospheric noise. The baseline shown in Figure 2 is the raw baseline with an rms less than 2 mK; it was achieved by an observing technique, refined at the 12-meter, of rapid ON-OFF switching using the nutating subreflector.

The field of high redshift molecular line observations is obviously in a very early stage of development. Progress will depend upon extending the CO observations to other infrared objects at even greater distances. Of most importance will be the improved high-sensitivity receivers at the principal CO transitions that are now envisioned in the program of ongoing development of the 12-meter facility. The multibeam receivers will be of less impact since these objects are of small angular extent.

<u>Studies of Evolved Stars</u> - The sensitivity and frequency coverage of 12-meter receivers and spectrometers have produced a number of important, new results in the study of evolved stars and circumstellar envelopes. Recently, the 12-meter has been used to detect CO from tens of stars first identified with IRAS. A study of the outflow momentum in this large sample illustrated that more than one physical mechanism is responsible for the mass ejection.

The large mass loss rates of many evolved stars may have an important effect on the formation of planetary nebulae. Currently, we know of about 15 planetary nebulae that have CO envelopes. The envelopes are probably remnants from the red giant stage; of the 15, all but one were first detected with the 12-meter. The 12-meter detections include two of the best known planetary nebulae, the Helix and the Ring nebula. A map of CO in the planetary NGC 2346 has shown that a thick band of CO is responsible for the "bow tie" morphology of the nebula seen at optical wavelengths.

The study of circumstellar envelopes is another example of research facilitated by sensitive receivers covering many frequency bands. For example, during a recent four-day observing run, the 12-meter was used to study SiO maser emission in three rotational transitions ranging in frequency from 86 GHz to 258 GHz. Since maser emission characteristics



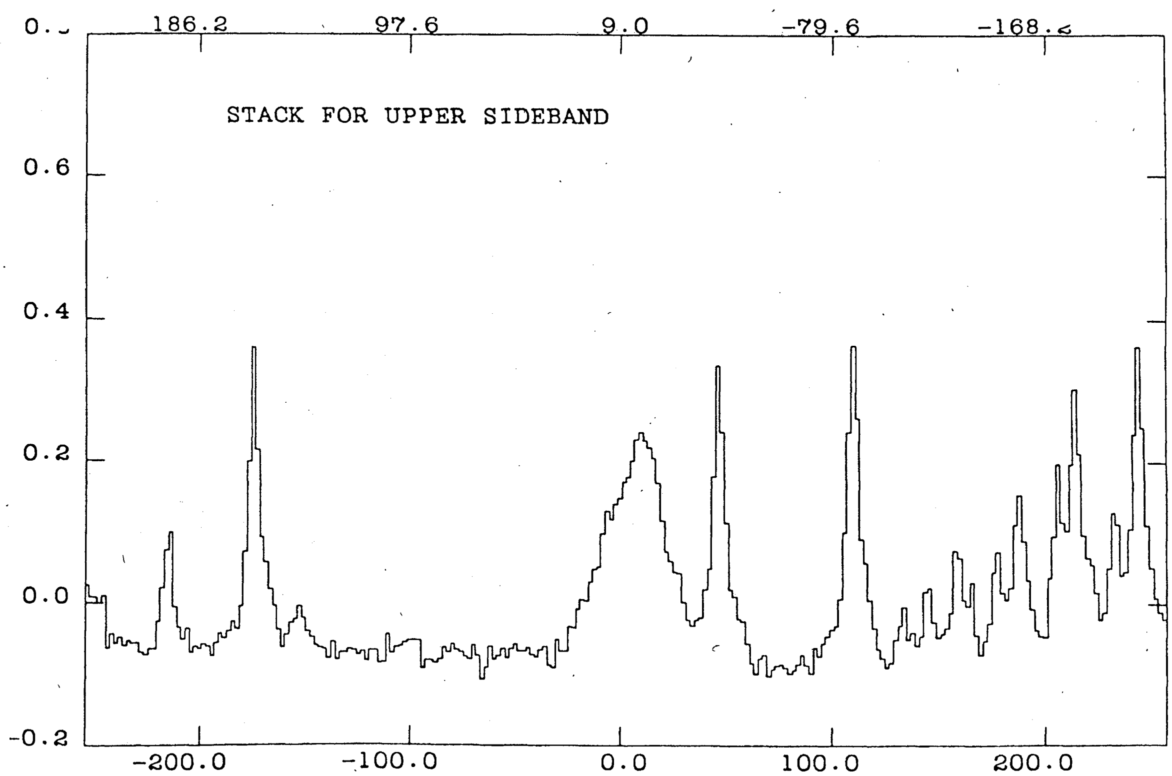


Figure 2. (*Top*) The CO emission toward IRAS 14348-1447, the most distant galaxy in which CO has been detected.

Figure 3. (*Bottom*) One 500 MHz piece of a submillimeter frequency survey of OMC-1 that is complete from 330.5 to 360 GHz.

vary with time, one needs to measure several transitions at the same time to properly constrain pumping models. The 12-meter facility for switching rapidly between 3 mm and 1 mm receivers made this work possible. In the coming few years, the 12-meter will have sensitive SIS receivers covering all the millimeter wave atmospheric windows accessible from Kitt Peak. A multifrequency capability, which will allow two or more frequency bands to be observed simultaneously, will also be developed. A sensitive, frequency-agile system will benefit observations of thermal and maser emission as well as continuum emission from circumstellar dust.

Studies in Astrochemistry - The 12-meter telescope has played the major role in the discovery of interstellar molecules; its contributions led to the birth of a new discipline, astrochemistry. Although rapid growth of this field has stimulated the creation of new facilities in chemistry and astronomy, observations done with the 12-meter telescope continue to play a pivotal role. New species recently detected include PN, SO+, acetone, and, tentatively, H_3O^+ and $H_2{}^{18}O$ which bear on the formation of water.

Although notoriously difficult to observe, water is among the most important interstellar molecules, particularly through its role as a coolant in clouds. Recent efforts at the 12-meter have provided the data to put, for the first time, water chemistry in the interstellar medium on a quantitative basis. First, two independent groups discovered a line which may derive from H_3O^+, the most important ion in water chemistry and direct precursor to the creation of water. Very recently, Jacq and his colleagues have detected the lines of the ^{18}O isotope of water in several sources. Since oxygen fractionation should not severely affect water, these observations provide the first inkling of the true abundance of interstellar water. The sensitivity, frequency coverage, and atmospheric transparency of the site were the most important assets available at the 12-meter which contributed to this success.

Most molecular emission, arising in widespread cool gas, is rotationally excited. But in intense radiation fields or in very dense regions, vibrationally excited material may be found, as demonstrated by the discovery of vibrationally excited emission from HCN, HCO^+, CS and SiS. The three detected states of vibrationally excited HCN observed near IRC2 in OMC1 measure the radiation field near this very young star, and trace the enormous abundance of HCN in the near-stellar environment where radiation from the star sublimates grain mantles. Vibrationally excited CS and SIS probe the innermost zone of the envelope of the carbon star IRC+10216 where the envelope is accelerated. The high sensitivity of the 12-meter is a critical asset for investigation of these very weak lines.

One of the most interesting problems to face astrophysicists is that of the origin of the elements. A crucial key to solution of this problem is a determination of the isotopic abundances of the elements. Over most of our galaxy and in all external galaxies, the only way to determine abundances is through molecular observations at millimeter wavelengths. Most of this research has been performed on the 12-meter telescope, taking advantage of its frequency coverage and sensitivity. The microscopic aspect of the question was recently attacked by Wannier and Sahai, using 12-meter spectra, who found that the observed enrichment in the scarce ^{17}O isotope in evolved stars cannot be reconciled with predictions for CNO nuclide production. On the macroscopic side of the question, dealing with the chemical evolution of galaxies, the nucleosynthesis and galactic evolution of the oxygen isotopes is the outstanding problem to be solved.

Finally, access to the submillimeter, to frequencies as high as 365 GHz, is becoming an increasing asset at the 12-meter to studies of "light" molecules, vibrationally excited molecules, and the higher transitions of molecules in warm environments. The spectroscopic richness between 330.5 and 360.0 GHz is readily apparent from a spectral survey recently completed across this entire 30 GHz band in OMC-1. One 512 MHz region of the survey is shown in Figure 3.

<u>Continuum Studies</u> - Continuum observations at millimeter wavelengths are limited by fluctuations in the sky brightness. The 12-meter telescope uses a nutating subreflector to remove these fluctuations but the beam throw, 4 arcminutes, conventionally limits the angular extent of the source which can be observed. However, by driving the telescope over a much larger region, the dual-beam difference is related to the differential source brightness: the total source brightness can be restored from the differential measure. Software at the 12-meter is available for astronomers to make this restoration; now very large regions are mapped routinely.

The availability of the new continuum hardware and software, coupled with rapid advances in infrared astronomy have spurred renewed interest in the use of the 12-meter telescope for the study of the continuum emission of dust. The most basic measurement is of the continuum flux of the dust at millimeter wavelengths where the optical depth of the dust is low. Comparison of the millimeter flux with the corresponding quantity at various infrared wavelengths enables the characteristics of the dust, such as grain emissivity and temperature, to be inferred. At this time only a few of the brightest HII regions have been studied because mapping large regions with good sensitivity is inherently a time-consuming project. Most of the regions that have been studied appear to have grains of similar properties. However, in one region, OMC-1, the grains are relatively hot, with a peculiar emissivity function.

There are a number of important questions about the grains in regions of recent star formation which could be addressed by more complete millimeter-wave data and complementary data from the infrared. It is important to find out how the color temperature of grains varies with the excitation parameter (or the hardness of the uv flux) of the ionizing radiation in the region, and how the temperature varies with galactocentric distance. We would like to determine if the grain emissivities are a function of color temperature, in order to explore the possibility that grains in hot regions have been partially evaporated. Finally, estimates of the mass of dust would have great value in the discussion of the dynamics of HII regions and the evolution of molecular clouds.

Such studies inevitably are of a statistical nature and rely upon measurements of a large number of objects spanning a wide range of physical conditions. To complete such studies will require a much "faster" telescope. For the 12-meter, we expect the increased speed will be achieved by the introduction both of improved receivers and of the multibeam 220-240 GHz system.

SPECTROSCOPIC MAPPING - Since so many objects of interest are large compared to the beam, a multi-beam mapping receiver increases the telescope throughput by the number of receivers. The 8-beam, 220-240 GHz receiver at the 12-meter is a response to this opportunity. But the receiver is just one part of the system: also needed is a multi-port spectrometer. At the National Observatory the spectrometer must have bandwidth flexibility since visiting astronomers may want to map galaxies with broad lines or molecular clouds with very narrow lines. The hybrid filterbank/autocorrelator at the 12-meter is designed to meet this need. Below are examples of types of observations being conducted at the 12-meter that will benefit from the 230 GHz multibeam capability.

Nearby Galaxies. Nearby external galaxies present significant challenges to the observer: molecular emission is widespread, weak and broad. The challenge is met by the 12-meter telescope, located on a dry site, equipped with sensitive stable receivers, good pointing, and a very clean beam. The thrust of current research in this area is to define the role of the gas and dust, and of star formation in spiral galaxies.

In M31, the first complete survey of GMCs in an external galaxy are being carried out. Here the 100 pc resolution of the 12-meter ensures good sensitivity to individual GMCs as well as to features in the interarm region. Interestingly, the integrated CO intensity in the arm is dominated by individual features on a broad, weak line profile. The discrete features are emission from individual GMCs; in the transition to the interarm region they vanish, leaving behind the broad, weak profile, presumably emission from a background ensemble of smaller clouds. Although some GMCs may be located from optical photographs through association with HII regions, for example, many can only be located through sensitive CO mapping.

The center of galaxies hold special interest, as much of the activity related to the "starburst" phenomenon appears to be concentrated there. A type of molecular cloud different from disk GMCs inhabits some galactic centers; these clouds appear to be characterized by warmer than average temperatures, i.e., temperatures of 30-40 K as indicated by infrared dust measurements rather than the 20 K or so extrapolated from measurement of Milky Way clouds. The properties of this warm gas are most effectively gauged through observations of the J=3-2 line of CO, recently mapped in IC 342 by Ho and his collaborators, and in four additional galaxies. In IC 342, for example, clouds maintaining a temperature of 38 K over a 350x150 pc extent have been found, which Ho et al. believe may relate to strong star-forming activity associated with the nuclear gas bar. These 12-meter data constitute the only data on J=3-2 CO emission in external galaxies yet available; the observations underscore the importance of the dry 12-meter site and the utility of sensitive, reliable, receivers. A new shaped subreflector has considerably improved the beam and the sensitivity of the 12-meter at 345 GHz, a very important advantage when one needs to compare data at high but very different frequencies, such as 230 and 345 GHz.

Molecular Clouds and Star Formation - A theoretically unexpected but observationally ubiquitous aspect of star formation is the phenomenon of bipolar flow. Because these flows generally involve large cloud areas, because they occur so commonly, and because their (often) bipolar signature aids identification of the flow source, they provide a good diagnostic for locating and characterizing young stellar objects in clouds. For example, Margulis, for his recent Ph.D. thesis research, used the 12-meter to map the extensive Mon OB1 molecular cloud, and he found 10 percent of its area to show high velocity emission, most associated with nine distinct sources. Considerable debate has occurred over the state of the wind powering the flow in young, low mass stars: is it ionized or is it neutral? In a very sensitive integration toward the outflow source SVS13 (which is responsible for HH7-11), Lizano and her colleagues discovered that the neutral stellar wind arising from the protostellar surface appears to power the flow. Eventually, these powerful mass loss episodes disrupt the cloud core from which the young star formed, an effect which has been graphically illustrated by 12-meter observations of the L43 system. The disruption also perturbs the cloud chemistry.

But a star cannot form by losing mass--what of the earlier stages? Partly owing to its striking flow, a protostellar source, IRAS 16293-2422, has been identified in Ophiuchus, which is apparently losing mass in a bipolar flow while accreting mass, presumably equatorially onto its protostellar disk. The evidence for accretion arises from intercomparison and modelling of numerous CS and $C^{34}S$ lines. Emission components of these profiles arise in heated, accreted background gas, and absorption components arise in cooler, yet-to-be accreted foreground gas. Sensitive, observations like these which cover a large area and a wide frequency range facilitate determination of the structure and dynamics of dense star-forming molecular cloud cores.

Clearly, many star formation studies require a sensitive mapping capability. The multibeam system will address this need within the next year. Sensitivity and frequency flexibility, already reliable features of the 12-meter operation, will be further improved as SIS detectors are incorporated into the multibeam receiver, and as their operation is extended to higher frequency where the finer beam necessitates faster mapping.

IV. FUTURE INSTRUMENTATION

MULTIBEAM MAPPING CAPABILITY - The 8-beam 220-240 GHz Schottky receiver has been tested on the telescope and performs perfectly. It provides two rows of four 30" beams separated by 80". The beam shape for all beams is diffraction limited, the telescope illumination is complete, and the sensitivity is as expected from the receiver noise.

Full implementation of the multibeam receiver awaits completion of the hybrid filterbank/autocorrelator now expected in the fall of 1988.

The eight receivers are all Schottky mixers. Upgrade to SIS mixers from the NRAO Central Development Laboratory is anticipated once the SIS devices and 4K cryostats can be fabricated.

On a somewhat larger time scale, we are working toward an array of 32 independent SIS receivers at 230 GHz on the 12-meter. Development of a flexible and inexpensive spectrometer is crucial to this initiative.

SUBMILLIMETER CAPABILITY - Observational experience at frequencies greater than 300 GHz has been most favorable throughout the winter of 1988. Nine submillimeter programs, involving 18 astronomers and 27 days, have been scheduled on the telescope this winter. With a new subreflector shaped for the 12-meter at the University of Texas using holographic maps of the 12-meter surface, the aperture efficiency at 345 GHz has been improved by at least 50 percent. The Kitt Peak site appears to be adequate for submillimeter observations four months a year. The combination of telescope improvements, operational ease, and successful operation in 1988 promotes submillimeter astronomy at the 12-meter. Receiver performance will be addressed in the near future, with a change to SIS mixers expected.

INSTRUMENT DEVELOPMENT FOR THE MILLIMETER ARRAY - As planning for the national millimeter-wave array progresses, the number of instrumental problems and opportunities that must be addressed is increasing. Currently, work is beginning on very wideband quasi-optical SIS mixers, computer controlled local oscillators, and varactor tuning techniques. As these and similar devices become available they will be installed on the 12-meter and used to further the astronomical research programs of visiting astronomers. In addition to providing astronomers with new capabilities, the observational experience will permit each of the new instruments to be evaluated in the most demanding environment.

Through prototyping and evaluation, observations with the 12-meter will be indispensible for the timely development of instrumentation for the millimeter-wave array.

V. USER INFORMATION

A BRIEF PROFILE OF THE 12-METER TELESCOPE USAGE - The table below reflects the schedule statistics for proposals submitted for the 1986 and 1987 observing seasons combined. Proposals to the 12-meter cannot accumulate. If a proposal is not selected in two calendar quarters following submission, it is returned to the proposer.

Proposals submitted	220
Proposals rejected	69
Proposals scheduled	151
(hours granted/requested)	82%

Each year the scheduled projects have involved an average of 145 individual scientists (including students and NRAO staff) representing 54 different institutions.

Since the telescope reflecting surface and backup structure was replaced, the 12-meter telescope has been scheduled for astronomical observing 83 percent of the available time outside of the summer shutdown period. Visitors (including students) have shared the observing time in a 70:13 proportion with NRAO staff. The balance of the time has been devoted to testing, calibration, maintenance, and instrument installation. Downtime due to equipment failure, weather, and interference has averaged 15 percent.

Students - An average of 21 graduate students per year have observed with the 12-meter telescope since 1985. Examples of outstanding recent Ph.D. theses produced by students using the 12-meter telescope include:

- L. A. Magnani, 1987, U. Maryland, "Molecular Clouds at High Galactic Latitudes"
- M. Margulis, 1987, U. Arizona, "Star Formation in the Monoceros OB1 Dark Cloud"
- M. S. Schenewerk, 1986, U. Illinois, "New Molecular Probes of Astronomical Sources"
- K. N. Mead, 1986, RPI, "Molecular Clouds in the Outer Galaxy"
- R. Sahai, 1985, Caltech, "Circumstellar Shells of Late-Type Stars"

Publications - The 1983-87 period has seen an average of 30 papers per year published as a result of 12-meter telescope observations. The longer term average back to 1973 has not deviated significantly from that number.

VI. OPERATING COSTS OF THE 12-METER TELESCOPE: EXPENSES IN CALENDAR YEAR 1987

OPERATIONS

12-meter Telescope Operations and Maintenance	$ 435k
Site Maintenance and Administration	$ 319k
Pro-rata Share of Observatory Administrative Costs	$ 302k

INSTRUMENTATION

Site Development and Maintenance	$ 668k
Central Development Laboratory	$ 422k
Research Equipment	$ 200k

RESEARCH SUPPORT

Site Support	$ 197k
Pro-rata Share of Observatory Support	$ 291k

TOTAL: TELESCOPE AND SITE	$1619k
TOTAL: OBSERVATORY SUPPORT	$1215k

THE
VERY LARGE ARRAY

Prepared for the Radio Facilities Panel
Division of Astronomical Sciences
National Science Foundation
by the National Radio Astronomy Observatory
March 1988

I. INTRODUCTION

The Very Large Array realizes the need for an imaging radio telescope that can provide radio "pictures" with a resolution similar to those obtained from optical telescopes. Recognition of this need is recognition as well that contemporary astronomical research has no wavelength boundaries but benefits from concerted work at all wavelengths. Thus, we expect the VLA to make important contributions to all the astronomical disciplines and this expectation is being abundantly fulfilled. More than 650 astronomers from 165 institutions use the VLA annually for their research on everything from the sun and planets to stars, galaxies, and quasars. The combination of VLA sensitivity, together with its angular resolution, multi-frequency capability, and flexibility to reconfigure, enables the VLA to reveal the full diversity of the radio sky. Future joint VLA/VLBA observations offer the prospects of a further increase in the quality of radio images and thus in our understanding of the physics of the radio sky.

II. INSTRUMENTAL CAPABILITIES

The VLA consists of twenty-seven 25-meter antennas arranged in a wye-configuration, nine antennas on each arm of the wye. The antennas are transportable along double rail track and may be positioned at any of 72 possible stations. In practice the antennas are rotated among four standard configurations which provide a maximum baseline along each arm of 0.59, 1.95, 6.39, and 21.0 km, respectively. Reconfigurability provides the VLA with variable resolution at fixed frequency.

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

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

In addition, two new frequency bands have been installed.

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

- 327 MHz prime focus FET receivers were installed.

Table 1 summarizes the parameters of the VLA receiver system.

TABLE 1. VLA RECEIVING SYSTEM

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

The VLA receives two IFs with full polarization capability in continuum bandwidths ranging from 50 MHz to 97 kHz. 512-channel spectroscopy is supported in all bands.

III. SCIENTIFIC PROGRAM

Nearly 400 distinct observational programs are run on the VLA annually. The diversity of this research shows the role of the VLA in contemporary astronomy.

EXTRAGALACTIC NONTHERMAL SOURCES - The VLA has made fundamental contributions to the study of energy transport and energy deposition in radio galaxies and quasars. The high angular resolution, dynamic range, speed, re-configurability, and multi-frequency polarimetric capabilities of the VLA all contribute to this work in essential ways. The speed permits studies of large samples of sources even in polarized intensity, the reconfigurability allows multi-frequency imaging at fixed angular resolution, and the combination of high angular resolution together with great sensitivity and dynamic range has revealed qualitatively new structural features of many sources.

Population Studies - An important example of the results obtained from representative samples has been the elucidation of the occurrence rates, symmetries, magnetic properties, and spreading rates of radio jets in extragalactic sources. The discovery that jets are detected easily and often in weak radio galaxies and also in powerful radio quasars elevated "beam" models of energy transport in active galaxies to the status of dogma. Detailed imaging of sources with jets has shown further that the kiloparsec and larger scale jets come in two main "flavors": prominent, symmetric, rapidly spreading jets dominated by perpendicular magnetic field components; and less prominent, asymmetric, highly collimated jets dominated by parallel field components. The jets in edge-darkened, low power sources are overwhelmingly of the first kind; those in powerful, edge brightened "classical doubles" are of the second kind. These characteristics appear to correspond to two principal regimes of supersonic jet propagation through an ambient medium that are distinguished primarily by the Mach number and the density contrast of the jet flow relative to the medium.

A second example is the discovery that the apparently one-sided jets in powerful sources are systematically on the side of the source that depolarizes more between 20 and 6 cm. The simplest interpretation of this effect is that the depolarization measures, to first order, the path length through a clumpy magnetoionic medium surrounding the source. The "one-sided" jets are thus systematically on the side of the source that faces the observer. This simple geometrical interpretation of the depolarization asymmetry strongly supports the view that jet sidedness in the powerful sources results from Doppler boosting of the approaching side of an intrinsically bipolar relativistic flow.

A third example is the discovery that the extended radio structures are more distorted, the jets are more curved, and the core prominence more variable, in quasars at $z > 1.5$ than in those at lower redshifts. This suggests that the radio structures of these high redshift quasars are distorted by interactions with an ambient medium whose pressure was significantly greater at earlier cosmic times, although other interpretations, such as gravitational lensing or orientation bias, cannot yet be excluded entirely.

A fourth example is the correlation of detailed radio structure distortions and depolarization with morphology of extended extra-nuclear optical line emitting gas in nearby radio galaxies. Although the detailed phenomena vary from source to source, it is now clear that the large-scale outflows associated with the radio source production entrain, compress, and ionize ambient material which may then be detected spectroscopically. In the case of NGC 541, the action of such an outflow on a nearby galaxy (Minkowski's Object) may have induced a burst of star formation.

The above, together with observations of radio "trail" sources and "wide angle tails" argue that the synchrotron radio sources strongly interact with ambient gas in a variety of environments. Increasingly, the VLA will be used as a tool for probing the environmental variables as our understanding of source dynamics becomes more secure.

<u>Radiometry and Polarimetry at Fixed Resolution</u> - Detailed multi-frequency studies of radio sources at high angular resolution with the VLA have given us both insight and surprise.

- The extremely high rotation measure gradients in the lobes of Cygnus A are evidence for interaction between the expanding lobes and a dense magnetized medium surrounding them. Smaller, well organized, RM gradients accompanied by low depolarizations have been detected across M84, M87, 3C 66, and NGC 6251. These fluctuations are much larger than expected from the foreground Faraday screen of our Galaxy and show instead that the media the sources are interacting with is circumgalactic gas with a significant ordered magnetic field as well as an appreciable density and pressure.

- Spectral age estimates for the lobes of powerful sources based on imaging at four frequencies have shown how lobe separation (hot spot advance) speeds increase with increasing radio power, an important constraint for source models.

High Fidelity Imaging of Individual Sources - Qualitatively new features have been found in the lobes of the brightest 3C sources imaged with the VLA. The lobes of Cygnus A, Virgo A, and Fornax A contain complexes of tangled filaments with magnetic fields that are preferentially aligned along the filaments. Similar, though less well delineated, features are being found in the lobes of many other sources.

The radio jets in two of the nearest radio galaxies, Centaurus A and Virgo A, contain edge-brightened fine structure that strongly suggests that the emission is dominated by phenomena on the jet boundary layer rather than by fluctuations pervading the body of the jets. The brightness distributions over the outer segment of the jet in Cygnus A, and over several parts of the jet in Virgo A, resemble a twisted double helix. These results challenge the conventional description of how the parameters in the outflow from an active galaxy determine the synchrotron emissivity of radio jets, and thus cast doubt on how to characterize the flow properties from observations of the radio emission.

The large scale structures of many core-dominated radio sources have been detected by high dynamic range imaging. These results contradict the suggestion that core-dominated sources are Doppler boosted emission from relativistic jets in a parent population that is drawn from the radio-quiet quasars. Instead, they encourage the class of "unified" models in which these sources are interpreted as favorably aligned relativistic jets drawn from an ensemble of lobe dominated radio galaxies and quasars involving all radio powers and structure types.

COSMOLOGICAL STUDIES - When the VLA was first proposed in the early 1960's, one of the most important anticipated experiments was to image the radio sky at the faintest possible levels. From the detection of weak point sources, with their optical identifications, one might determine the evolution of sources and the cosmology of space with more success than with the use of quasars. New classes of objects, not previously detected, might be seen at these weak levels--peculiar stars or nearby galaxies. Extended emission or absorption might also be observed, due to fluctuations of the Cosmic Background Radiation, to absorption of this radiation by hot cluster gas, or to clouds of emission from our own galaxy. Over the last six years VLA deep integrations have, indeed, been fruitful.

The best statistics on the nature of weak, discrete radio sources at the tens of microjansky level come from 1.5 GHz VLA observations. The faintest radio sources are preferentially associated with late, blue spiral galaxies rather than with the giant elliptical galaxies and quasars associated with the strongest radio sources. Most of the emission is confined to the nucleus of these galaxies and has a flatter spectral index than that determined from samples of sources brighter than 1 millijansky. These galaxies may be related to the starburst galaxies. Such sources have more predictable intrinsic properties than the quasars and giant radio galaxies and, thus, may be better probes of cosmological evolution. About 10 percent of the sample are Galactic stars, possibly flare stars at the peak of their intensity.

Integrations of over 60 hours on several regions of sky have been made with the VLA at 4.9 GHz, where it is most sensitive. Because the area of sky that can be sampled at 4.9 GHz is less than at 1.5 GHz, the number of sources detected at the higher frequency is smaller. However, these observations confirm the results about the discrete sources. The rms noise level of 5 microjansky after about 60 hours of integration time, at 30 arcsec resolution, corresponds to a brightness temperature sensitivity of about 1/10000 K. Several experiments have determined limits to possible fluctuations in the Cosmic Background Radiation of $5x10^{-5}$ of the 2.7 K at angular scales between 15 and 60 seconds of arc. These limits are as good as those obtained from large antennas at higher frequencies and are uncomfortably small. Where are the fluctuations? Are they washed out by gravitational lensing?

Similar observational methods have been used to measure the absorption of the 2.7 K CBR by hot gas in rich clusters. These observations show that the gas is more extended than the cluster population as a whole. With an increase in sensitivity by about a factor of five, quantitative information about the density of hot matter in clusters can be obtained--a result which may be important in determining how much non-luminous matter is contained in the halo of clusters.

The concentration of dark matter in the universe is effectively probed by searches for gravitational lenses. Here the sub-arcsecond resolution of the VLA is used to identify those objects which are likely lens candidates. Confirmation of the lens phenomena, of course, rests on optical spectroscopy. Discovery of gravitational lenses is a tedious process involving (1) single dish radio surveys to provide positions of strong sources; (2) VLA snapshot images to isolate those sources with symmetrical structure, and (3) optical spectroscopy. Tedious though it may be, it is the only way to measure the gravitational potential of non-luminous material in the universe. It leads to some spectacular images, such as that of MG 1131+0456 which may be an "Einstein Ring."

NEUTRAL HYDROGEN IN GALAXIES - Recent concerted efforts to optimize the spectroscopic capability of the VLA have made the telescope comparable in sensitivity to the best single dish telescopes, but it is very much faster: from each D-array observation, one obtains an image of a square degree of sky with 40 arcsec resolution.

HI in Clusters of Galaxies - The effect of the cluster environment on the evolution of member galaxies is readily observable from HI observations in a volume-limited survey. The large field of view means that many galaxies (even tens of galaxies) are imaged simultaneously.

HI in Elliptical Galaxies - A significant fraction of nearby early-type elliptical galaxies are known from infrared observations to have an interstellar medium rich in dust. VLA searches for the HI gas accompanying the dust in these ISM have been fruitful. In general, the galactic HI mass is approximately what would be expected from the mass of dust inferred from the infrared luminosity. On the other hand, the VLA images often show the distribution of gas (and presumably dust as well) in ellipticals to be disturbed. This morphology together with the observed decoupling between the specific angular momentum of the stars and the gas both suggest that the HI has its origin in conditions external to the elliptical itself. Tidal effects are important.

Extended Low Surface Brightness HI - Studies of the faint HI envelopes surrounding otherwise normal galaxies are needed for an understanding of tidal interactions and of quasar absorption lines. Spectacular examples of HI plumes extending 100 kpc or more from the parent galaxy are found in Mk 348 and Arp 143, among others. In all cases the HI traces the gravitational trajectory of a galaxy-galaxy interaction and chronicles the event in a manner that is useful for modeling and analysis.

Galaxy Kinematics and Dark Matter - Since the HI distribution in spirals, ellipticals, and SO galaxies extends well beyond the luminous material, the HI provides an ideal probe of the kinematics of these galaxies at large radii. The search for gravitational effects of dark matter is one important application of the observations which has been pursued especially vigorously in galaxies such as NGC 5666 in which VLA observations show the HI to extend to 20 times the half-light radius. However, the question of the existence and distribution of dark matter is not to be settled by one or a few observations. Rather, statistically sound samples of galaxies and their kinematics are needed. Here the snapshot mode of the VLA, which can provide high quality rotation curves for as many as 20 nearby spirals in a single day's observing, is invaluable.

SUPERNOVAE AND SUPERNOVA REMNANTS - Prior to the advent of the VLA the most sensitive radio interferometric searches for post-outburst supernovae and historical extragalactic supernova remnants were, with a single exception, negative. These results had important consequences because they implied that the relativistic electrons so characteristic of evolved supernova remnants were generated decades to centuries following the outburst. All this changed with the VLA.

Guided by optical supernova searches and identifications, observers using the VLA have detected radio emission from more than one post-outburst supernova each year. Both Type I and Type II supernovae are detectable as radio sources. In all cases, the radio "light-curve" increases to maximum rapidly, with the radio maximum occurring occasionally earlier than, but more often later than, the optical maximum. The subsequent decline follows a power law with time which is somewhat steeper for Type I supernovae than for Type II. The evolution of the radio light curve taken together with the optical light curve and spectroscopic determination of the expansion velocity, provides information on the stellar wind of the progenitor star and on the interstellar environment in the vicinity of the supernova. These observations require not only the sensitivity of the VLA but also its angular resolution and multi-frequency flexibility. Moreover, future VLBA observations of the angular size of radio supernovae should provide a measure of the distance to the host galaxy.

Given the knowledge that individual supernovae are detectable, evolving, radio sources, we can use VLA observations to verify and constrain models of "starburst" galaxies. Infrared observations provide a growing body of evidence that episodic bursts of massive star formation in some galaxies lead to periods of elevated galactic luminosity accompanied by supernova events from those stars that have reached the end of their evolution. Striking confirmation of this has been provided by VLA observations of the prototypical starburst galaxy M82. Many of the 40 discrete radio sources in M82, some of which have long been known to be unusual, show secular decreases in flux density over periods of months to years, reminiscent of the radio supernovae. As the luminosity of these sources is similar to typical supernovae, while the cumulative luminosity of the entire population of sources is comparable to that required to provide the luminosity of M82, these observations appear to validate the starburst concept. VLA observations of other starburst galaxies are progressing.

Radio supernovae are where one might expect to find them--in starburst galaxies and at the position of optical identifications. But they also may be where one doesn't expect to find them. Just such an identification was made in the course of VLA observations taken for M. Rupen's thesis research. Observing the edge-on galaxy NGC 891, Rupen noted a bright point source well displaced from the galactic nucleus. Archival VLA and WSRT data showed this source to have appeared in the last four years. HI absorption observations placed the object within NGC 891, and optical spectroscopy confirmed its identification as a supernova, albeit a very unusual Type V SN. Its radio luminosity vastly exceeds that of any known radio supernova. Were it at the distance of Cas A its 6 cm flux density would exceed 10^6 Jy! The imaging quality of the VLA permits discoveries, even serendipitous discoveries such as this, to be made.

Imaging the remnants of old supernovae also provides both insight and surprise. For more than a decade, the remnant Cas A provided the fundamental flux density calibration for (single dish) radio astronomy. Far from being a static "calibrator," under the high resolution provided by the VLA the remnant is seen to break up into an ensemble of tenuous clumps of ejecta. Comparison of radio images made over the course of four years reveals that individual clumps brighten and fade while moving radially outward. Some clumps puncture, from within, the decelerated SNR shell and swept-up ISM material. Observations such as this serve to focus theoretical work. Equally spectacular, and surprising, are the images of axially-symmetric and filamentary SNR such as G357.7-0.1 which may form over a long period of time.

STAR FORMATION - Star formation is a vexing phenomenon to understand owing to the complex interrelation between the various gaseous constituents of "typical" regions of star formation. A molecular cloud collapsing under its self-gravity will perhaps be rotating, will perhaps be associated with a larger complex of newly formed stars, and will perhaps be interacting with hot, ionized gas. Disentangling the various processes requires observations at visible, IR, millimeter-wave and radio frequencies. In this context, VLA observations are important because they can reveal the kinematics of molecular and ionized gas at high resolution.

Using NH_3 observations as a tracer of molecular kinematics, several VLA observers have shown that gravitational collapse is accompanied by cloud rotation. But if the final gravitational collapse can be inhibited in the cloud center by magnetic pressure, for instance, then formation of massive stars may occur coherently at the interface where infalling material meets the supported cloud core. Just such a rotating ring-like configuration was identified in W49A.

The multi-frequency imaging capability of the VLA at angular resolutions comparable to those of optical/IR observations has been important for studies of the composition and distribution of dust in star-forming regions, for example, those in M42 and M8. The spectroscopic imaging capability has led to such startling discoveries as the pronounced overabundance of helium in W3. Finally, the rapid imaging capability of the VLA has permitted imaging of all known regions of star formation in the Galactic anti-center.

STARS AND PULSARS - Somewhat unexpected is the role that the VLA has played in our understanding of the radio emitting properties of main sequence stars. Prior to the VLA, observations of the radio emission from stars were strongly confusion limited. The superior resolving power of the VLA effectively eliminates confusion problems, and the field of stellar radio astronomy has progressed rapidly since the dedication of the VLA.

Among the many important observations of stellar radio emission made with the VLA are (1) the detection of thermal emission from the massive, radiatively driven winds of O stars and the attendant nonthermal component due to electrons accelerated by shocks in the wind; (ii) the detection of thermal emission from the cool, slow-moving winds of red giants and supergiants; (iii) the detection of nonthermal radiation from the dipolar magnetospheres of magnetic A and B-type stars; (iv) the unexpected phenomenon of quiescent gyrosynchrotron emission from the coronas of dwarf M stars; and (v) the first dynamic spectra of microwave outbursts from flare stars.

The point source sensitivity and the polarization capability of the VLA have allowed observers to find pulsars since 1982. Up to the present only a few gated observations of pulsars have been carried out and most experiments have treated pulsars as conventional steady sources. In 1982, both the VLA and WSRT played an important role in sorting out the various continuum components of the galactic radio source 4C 21.53. The compact component was the remarkable 1.6 msec pulsar PSR 1937+214. This pulsar rotates about 20 times faster than the Crab pulsar and is now thought to be a "spun-up" neutron star. In 1985 a point source near the center of the globular cluster M28 was found with the VLA at 20 cm. Subsequent VLA observations identified the point source as a steep spectrum (spectral index -2.4) and highly polarized (35 percent) object. These latter properties provided strong evidence that the M28 source was a pulsar and subsequently a 3 msec pulsar was discovered at this position. Later, in 1987, a 11 msec pulsar was discovered near the globular cluster M4 at Jodrell Bank and subsequent VLA observations have shown that the pulsar indeed lies within the core of the cluster. This pulsar is in a low mass binary system, in contrast to the M28 pulsar. Finally, in 1987, a steep spectrum compact polarized source near the center of the peculiar galactic supernova remnant CTB 80 was discovered using the VLA at 20 cm. The detection of the point source required the resolution of the VLA in the A array of 1 arcsec to discriminate against the complex background of the supernova remnant. Subsequent observations at both Green Bank and Arecibo showed that this source is a 39.5 msec pulsar with a spin-down age of about 100,000 years.

SOLAR SYSTEM

The Sun - Although the VLA was not designed specifically to observe the Sun, it has proved of great value to solar radio astronomers as it is the only instrument capable of imaging the Sun in two dimensions with high angular resolution at radio wavelengths. As a consequence, it has led to several advances in our understanding of both active and quiet Sun phenomena.

In the early part of this decade, the Sun was near the peak of its eleven year activity cycle--solar flares were relatively frequent and observing was directed toward the flare phenomenon. Because the spectral peak of impulsive microwave burst emission from the Sun is typically between 5 and 10 GHz, the VLA is able to image both optically thick and optically thin components of a burst with a temporal resolution of seconds and arcsecond angular resolution. These unique capabilities made it possible to demonstrate that the source of microwave burst emission was typically confined to a compact region on a magnetic neutral line, i.e., at the top of a coronal magnetic loop.

As solar activity declined towards a minimum in late 1986, the VLA imaging and contemporaneous single dish data were used with maximum entropy-type image reconstruction algorithms to produce several full disk images of the Sun at 21 cm, a wavelength which probes the transition region and low corona. The maps were of the highest angular resolution and dynamic range yet obtained. They conclusively demonstrate global solar cycle modulation of the corona through coronal hole evolution and modulation of the thermal background component of the quiet Sun.

Synthetic Aperture Observations of the Planets - The X-band upgrade at the VLA provides the scientific community with a new method of examining the solar system: synthetic aperture radar reception. This method was first successfully demonstrated in June 1987 when the rings of Saturn were illuminated with the 350 kW Goldstone radar and the return echo was detected in both matched and mismatched polarization using ten antennas of the VLA. This technique offers the new dimension of unambiguous spatial resolution as well as Doppler-strip resolution and replaces current radar range-gate mapping techniques. In addition, the bi-static experiment provides an improvement in signal sensitivity by a factor of 5 over present mono-static radar observations and thus reduces the total required observation time.

The first experiment with this new method used the VLA in the D configuration, resulting in poor spatial resolution at Saturn. Nevertheless, the results confirm previous radar observations of Saturn's rings: The rings are the most highly reflective targets in the solar system and echo power is comparable in matched and mismatched polarizations. The observations also detected an anomalously high echo return at zero doppler shift which can be investigated by repeating the experiment with greater sensitivity and resolution.

Future synthetic aperture radar observations may show the greatest promise in studies of Venus, Mercury, Mars, the Galilean Satellites, Titan, and the larger asteroids. The primary advantage of using the VLA is the high spatial resolution that can be obtained on the surface of these objects. Using the array in its largest configuration will give the following resolution: Venus 38 km, Mars 69 km, Mercury 81 km, Galilean Satellites 555 km.

The Solar Wind - The high temporal and spatial resolution of the VLA has been used to test theories of radio wave scattering in the solar wind. A background radio source, 3C 279, was imaged with sub-arcsecond spatial resolution for integration times from 10 msec up to 10 minutes. At the shortest integration time, the existence of complete spatial coherence in the scattered radiation was demonstrated. At integration times of a few seconds, refractive scintillation similar to that now thought to be responsible for the low-frequency variability of extragalactic radio sources was seen. Finally, at integration times of several minutes, the observed scattering disk yielded information on the spectrum of electron-density fluctuations in the solar wind. The importance of this work is threefold: first, it tests the basic optics of the scattering process; second, it permits studying the solar wind close to the Sun's surface; and third, it tests the application of similar methods to interstellar scintillation where a spatial resolution of much better than a micro-arcsecond may be achievable.

IV. FUTURE PLANS FOR THE VLA

ELECTRONICS

75 MHz (4 m) System - Four VLA antennas have been outfitted with simple dipole feeds to explore the feasibility of VLA observing at 75 MHz, and initial tests with this system have been encouraging. Full use of this frequency will await the next solar minimum. Research programs will include the studies of steep-spectrum components of radio galaxies and quasars, the haloes of normal galaxies, the spectra of more compact sources, imaging of supernova remnants, searches for steep-spectrum galactic sources such as millisecond pulsars, studies of diffuse HII in absorption against the nonthermal background, flare stars, interstellar propagation effects, and solar system objects.

L-Band Sensitivity Improvements - Spectroscopic observations with the VLA at 21 cm are limited in sensitivity by the ten year old front end design, which provides 50-60 K system temperatures with all of the front ends in the same dewar. A more modern design based on HEMT amplifiers in independent dewars could shorten the input waveguide runs and allow cooling of the polarization splitters, reducing the system temperatures to about half their present values. This would reduce by a factor of four the observing time for 21 cm line observations of a given sensitivity. HI and OH spectroscopy of extragalactic objects will be the primary beneficiary of this improvement.

Increased Angular Resolution - Many types of radio sources have physically interesting structures that are barely resolved with the VLA but which do not require VLBI resolution. These include galactic circumstellar sources, compact HII regions, bipolar outflow sources, filaments and knots in supernova shells, filaments and knots in extragalactic jets and "hot spots" in the lobes of radio galaxies and quasars. For nonthermal sources one cannot simply increase the resolution by increasing the frequency, as brightness sensitivity is also essential. Studies of Faraday depth, or of radio spectra, must also be done at given frequencies to address given physical questions. The ability to vary the VLA's configuration to obtain "scaled arrays" has been vital to its success as an astrophysical instrument--but this capability is restricted to resolutions of 1 arcsecond or lower at 20 cm and to 5 arcseconds or lower at 90 cm. We can increase the angular resolution of the VLA by linking it to the Pie Town VLBA antenna over microwave or fiber optics links. The delay, fringe-rotation, and control systems for the VLA must also be expanded. In so doing, we will double the resolution of the VLA for northern sources, but the imaging quality at this resolution will be of low fidelity. True imaging requires the following further step.

Combined VLA-VLBA Imaging - The VLA and VLBA, used separately, only sparsely sample the spatial frequencies from 40 to 400 km, leaving a range of angular resolutions uncovered (with useful dynamic range) at any frequency. This "gap" is unfortunate because the most physically revealing observations of radio continuum sources of all kinds are those that determine how the Stokes parameters of the radiation vary with frequency over a wide frequency range at a fixed angular resolution. For example, wide-band spectral studies at fixed resolutions are required to understand electron transport in the sources. Faraday depth studies at fixed resolution are needed to assess thermal densities and magnetic field strengths. To explore the physics of any class of radio continuum source fully at 0.1 to 0.001 arcsecond resolution will require bridging this "gap" through combined VLA-VLBA imaging. It is planned to do this in three main stages: (a) linking the Pie Town VLBA antenna to the VLA as noted above; (b) providing additional VLBA backends at the VLA so that up to four VLA antennas can be used as the "inner elements" of the VLBA when the VLA is in its A configuration; (c) adding additional VLBA antennas in New Mexico and Arizona for use with either the VLA or the VLBA as appropriate for individual experiments. The long-term goal is to provide an array of at least 40 elements (27 VLA antennas, 10 VLBA antennas, plus three or more additional antennas) that can be divided into subarrays as required to obtain a "matched spatial filter" appropriate for each experiment that requires high resolution, wide field imaging. These ideas, of course, are not new: the VLBA configuration was centered on the VLA location specifically to allow synergy between the two instruments in the 1990's.

MAJOR MAINTENANCE

The VLA Rail Track System - The VLA rail track system consists of two standard gauge railroad tracks which run along each arm of the array. During operations the antennas rest on concrete foundations 100 feet from the main rail line. Each station is connected to the main line by a short spur rail line and a track interchange. There are about 80 miles of rail track in the system. The combined weight of the transporter plus the antenna is about 300 tons. With 24 wheels on four trucks, this gives a loading of 50,000 pounds on each of the 12 axles, not unusual for a railroad track.

The rail system currently has 800,000 feet of rail on the main line and 46,000 feet on the antenna spurs. There are 190,000 ties. The entire track system was constructed with used materials; the rail, for example, dates from 1902 to 1956.

Since the VLA began full operation in 1980, the rail system has received inspection and upkeep. Now, at roughly ten years of age for much of the system, more major maintenance is required. The main, but not the only, problem is a deterioration of groups of rail ties. This has become serious because the rate of deterioration has accelerated beyond what would normally be expected, because the system was built with used ties. Ties that came from wet regions of the U.S. are deteriorating rapidly in the dry conditions of New Mexico.

Other major maintenance items in the track system besides the ties are: replacement of clogged ballast; realigning, gauging, and upgrading antenna spur lines; replacing bad rail sections; and cleaning and dressing ballast.

The immediate goal is to bring the VLA rail system back to its original construction specifications. An updated estimate based on our detailed inspection is that this will cost about $2,850,000 spread over five years. A detailed technical report outlining the plan to restore the track system to specifications was submitted to the NSF in March 1987.

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

Polyethylene cable deteriorates with age owing to a process known as "treeing." A "tree" is a growing channel which propagates through the insulation, probably due to ion or electron bombardment. The number and size of trees in a cable is primarily a function of time in service, operating electric field strength, and the presence of manufacturing impurities. As treeing progresses, the dielectric strength of the insulation deteriorates until voltage surges due to switching transients or nearby lightning strikes break down the insulation and the resulting arcing produces a ground fault.

Prior to November 1985 the VLA had no cable failures. There have been twelve failures since then. If the failure rate follows industry experience, in a few years the deterioration of the cables will lead to a very serious disruption of VLA operations. The only solution is to replace the power cables. Steps to slow the cable degradation and minimize the disruption of operations will allow the cable to be replaced over several years. The total cost is estimated to be approximately $1.35M.

VLA/VLBA COMPUTING - Both the quality and the quantity of images produced by the VLA now greatly surpass the original goals, as Table 2 shows.

TABLE 2. DEVELOPMENT OF VLA IMAGING POWER

	Goal 1969	Achieved 1980	Achieved 1988
Speed (images per day)	3	200	200
Image Size - Routine (pixels)	128x128	512x512	1024x1024
Image Size - Maximum (pixels)	512x512	1024x1024	4096x4096
Spectral Line Channels (full array)	-	8	512
Dynamic Range - Routine	100:1	500:1	2,000:1
Dynamic Range - Maximum	100:1	2,000:1	100,000:1
Maximum Sensitivity (mJy)	0.1	0.05	0.005
Resolution (arc seconds)	1	0.1	0.07

Each increase shown in Table 2 has required computing resources beyond those originally anticipated. The growth in demand for computing resources has outstripped our ability to provide them within the annual operating budgets of NRAO. Only a small fraction of the exciting but exceptionally computer-intensive scientific investigations can now be supported. Useful observing capabilities that are designed into the array hardware are now withheld from users, solely to avoid overloading the data reduction computers.

In order to rectify this situation, the NRAO submitted to the NSF in September 1987 a proposal, "Array Telescope Computing Plan," which leverages the VLBA computing budget and creates a joint VLA/VLBA computing environment suitable for the needs of both arrays.

V. USER INFORMATION

A BRIEF PROFILE OF THE VLA TELESCOPE USAGE - During the 1983-87 period an average of 466 proposals per year have been submitted to use the VLA. On average, 382 of these proposals have been scheduled per year. These projects have involved 596 individual scientists (including students and NRAO staff), representing 140 different institutions (666 scientists from 165 institutions in 1987). The typical proposal that has been scheduled has received 55 percent of the time requested.

Since 1983, the VLA has been scheduled for astronomical observing an average of 75 percent of the available time, consisting of 64 percent for visitors (including students) and 11 percent for NRAO staff. The balance of the time has been devoted to testing, calibration, and maintenance. Downtime during this same period has averaged 6.9 percent.

Students - Since 1983, an average of 86 Ph.D. students per year have observed with the VLA. Of the more than 60 Ph.D. theses produced by students using NRAO facilities in the last five years, the following few examples are noteworthy representatives from the VLA:

- S. A. Baum, 1987, U. Maryland, "Extended Optical Emission Line Gas in Powerful Radio Galaxies"
- T. S. Bastian, 1987, U. Colorado, "Aperture Synthesis Observations of Solar and Stellar Radio Emission"
- F. Yusef-Zadeh, 1986, Columbia, "Radio Study of the Arc and the Sgr A Complex Near the Galactic Center"
- J. N. Hewitt, 1986, MIT, "A Search for Gravitational Lensing"
- J. R. Leahy, 1985, Cambridge, "The Polarization of Extragalactic Radio Sources"

- M. P. Ondrechen, 1985, U. Minnesota, "The Distribution of Kinematics of Neutral Hydrogen Gas and the Radio Continuum Emission in Barred Spiral Galaxies"
- C. P. O'Dea, 1984, U. Massachusetts, "Morphology and Energetics of Narrow Angle Tail Radio Sources"
- J. M. Wrobel, 1983, U. Toronto, "The Radio Continuum Properties of Bright E/SO Galaxies which Contain Compact Radio Core Sources"
- G. A. Garay, 1983, Harvard, "Aperture Synthesis Observations of Star Forming Regions: Compact HII Regions and Masers"

Publications - The number of publications based on VLA data during the past five years has steadily increased from 130 per year in 1983 and 1984 to over 200 per year in 1987.

VI. OPERATING COSTS OF THE VLA: CALENDAR YEAR 1987

OPERATIONS

Array Operations and Equipment Maintenance	$ 379k
Site Maintenance and Administration	$2840k
Pro-rata Share of Observatory Administrative Costs	$1186k

INSTRUMENTATION

Site Maintenance and Development	$1164k
Central Development Laboratory	$ 141k
Research Equipment	$ 300k

RESEARCH SUPPORT

Site Support	$1695k
Pro-rata Share of Observatory Support	$2199k

TOTAL: ARRAY AND SITE	$6078k
TOTAL: OBSERVATORY SUPPORT	$3826k

THE

VERY LONG BASELINE ARRAY

Prepared for the Radio Facilities Panel
Division of Astronomical Sciences
National Science Foundation
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I. INTRODUCTION

Many of the most exciting subjects of modern astrophysical research, including active galactic nuclei and quasars, pulsars, molecular masers and active stars such as SS 433, require high spatial resolution that can be achieved only by using radio arrays with dimensions of thousands of kilometers. The Very Long Baseline Array (VLBA) will exploit techniques which have been developed for the VLA and VLBI to give an imaging forming instrument with unprecedented angular resolution and image quality. At its shortest operating wavelength the resolution is a few tenths of a milli-arcsecond, corresponding to linear scales of an astronomical unit within the Galaxy to a few parsecs for the most distant quasars and radio galaxies.

Together with the VLA, the VLBA will provide a continuous range of brightness sensitivity and resolution from a few arc minutes (VLA D Array at 327 MHz) to 0.2 milli-arcseconds (VLBA at 43 GHz). The VLBA elements are located so as to optimize the image quality. The nine observing bands of the VLBA are designed to cover: the main spectral lines of interstellar masers; the radio astronomy continuum bands, to give a range of resolution, surface brightness sensitivity, and spectral information; as well as the DSN bands commonly used for a variety of world-wide geodetic experiments.

Each of the ten elements of the VLBA is being designed to work at wavelengths as short as 3.5 mm, although initially the shortest wavelength receivers will be at 7 mm. The VLBA playback facility will accommodate 20 inputs, so that up to 10 additional antennas located throughout the world can be used to further increase the sensitivity and resolution. It is anticipated that these external stations will adopt the VLBA recording standards, and that the VLBA Array Operations Center in New Mexico will become the coordinating center for much of the worldwide VLBI activity.

The operation of the VLBA will be under the control of an operator located at the Socorro Array Operations Center who will execute a preplanned program of observations based on proposals and review. Like the VLA, it is anticipated that the VLBA will be used by a wide range of individual scientists who do not have any particular expertise in radio interferometry. Individual observers will not need to be present at observing time or when the tapes are correlated, but may choose to monitor either activity from their home location via an external terminal and display. While this mode of observing has its well known advantages and disadvantages, it is particularly suitable for the VLBA as there is little opportunity for scientific interaction either at observing or correlating time. Since the observer need not be present, the daily observing program may be adjusted to match the weather conditions or to exploit unusual scientific opportunities.

Data reduction and analysis will be based on the extensively used AIPS package. The data reduction facilities will be combined with those of the VLA at the Socorro operating center, to exploit best the available hardware and software. The combined VLA/VLBA Operating Center will support all types of VLBA observing, including geodesy and geophysics, but it is anticipated that as in the case of the VLA, many users will choose to do most or all of their analysis at their home institution, and we do not plan to provide sufficient internal computing resources to process all of the VLBA observations.

II. PROJECT STATUS - MARCH 1988

SITE AND ANTENNAS - The following table gives the status of the ten antennas and associated sites.

Site	Status
Pie Town NM	operational
Kitt Peak AZ	antenna done; electronic outfitting 50% done
Los Alamos NM	antenna done; electronic outfitting beginning
Ft. Davis TX	antenna 75% done; electronics 50% built
North Liberty IA	site construction done; antenna assembly beginning
Brewster WA	site construction done; antenna under manufacture
Owens Valley CA	site development beginning; antenna authorized
St. Croix VI	site acquisition expected soon; antenna authorized
Mauna Kea HI	site acquisition in process
"Northeast"	site to be acquired - spring 1988

Manufacture of the last two antennas will be authorized in early 1989. Assembly of the last antenna on its site will begin in early 1990. No further changes are anticipated in the contract with Radiation Systems, Inc. for the antennas. All of the antennas will be completed by 1991, and full operation of the VLBA is expected by the end of 1992.

With the exception of a problem known as "azimuth-wobble," the Pie Town antenna meets specifications. Most important, the specification of the primary reflecting surface accuracy has been exceeded: the combination of panel surface and panel setting accuracy was specified to be less than 180 μm rms. The measured value is 145 μm rms. This means the goal of an array that can in principle function at 3 mm wavelength is possible. The "azimuth-wobble" is being diagnosed and appears to be caused by a combination of factors associated with the azimuth track: unevenness of the rail surface, grouting technique, and possibly other factors. Corrections will be made by the manufacturer in the early antennas, and succeeding antennas are not expected to show the problem.

RECEIVER SYSTEMS - The following table gives the measured amplifier noise temperatures and expected system noise temperatures for the nine receiving bands along with status comments.

VLBA FREQUENCY BANDS AND NOISE PERFORMANCE

Band	Tuning Range	Receiver Input Type	Receiver Input T(Phys)	$T(R_X)$	T(Sys)	Comment
330 MHz	0.312 - 0.342	GASFET	300	30	90	Production
610 MHz	0.580 - 0.640	GASFET	300	30	60	Production
1.5 GHz*	1.35 - 1.75	HEMT	15	7	27	Production
2.3 GHz	2.15 - 2.35	HEMT	15	8	28	Prototype
4.8 GHz*	4.6 - 5.1	HEMT	15	10	30	Production
8.4 GHz	8.0 - 8.8	HEMT	15	16	36	Production
10.7 GHz	10.2 - 11.2	HEMT	15	20	40	Pie Town only
15 GHz	14.4 - 15.4	HEMT	15	30	52	Production
23 GHz*	21.7 - 24.1	HEMT	15	60	92	Prototype
43 GHz	42.3 - 43.5	SIS	3	40	77	Development
43 GHz	42.3 - 43.5	HEMT	15	90	127	Development

* First set of receivers to be installed at each site; others installed later in construction schedule. All bands except 43 GHz have been installed at Pie Town.

These high-performance receivers are based on very reliable, cryogenically cooled, transistor-amplifier technology developed at the NRAO Central Development Laboratory. Each receiver is completely independent and self-contained, allowing for maintenance and repair at a central location by replacing entire receivers.

<u>HYDROGEN MASER CLOCKS</u> - Sigma Tau, Inc., has delivered four masers and delivery is expected soon on two more. The masers meet specifications (root Allen variance ≤ 2×10^{15} at 10^3-10^4 seconds, ≤ 1×10^{-13} at 1 second averaging time). Two masers are undergoing careful environmental tests at JPL to determine their long-term stability.

<u>RECORDER/PLAYBACK SYSTEMS</u> - Haystack Observatory has completed the first two recorder systems. One is being integrated into the control system hardware in the digital lab at the VLA prior to installation at Pie Town. The other is being held at Haystack for further system tests prior to shipment. Two more systems are being built as "pre-production" models before beginning production run manufacture of the remaining 18 systems. NRAO will build several major subsystems for these production units.

Haystack has begun a prototype of the first playback system. The correlator requires 24 of these for full capacity operation.

It is anticipated that the VLBA recorder/playback system and recording format will eventually become the world standard. To ensure a smooth transition, which is likely to take many years, from the present

MKIII standard, the VLBA recorders will be able to write MKIII tapes. However, there will be certain important limitations on bandwidth and number of channels for mixed-standard operations.

OTHER ELECTRONICS - One set of all associated electronics required at each site has been completed and installed at Pie Town. Equipment for succeeding sites is in routine production.

CORRELATOR/PROCESSOR - The correlator implements an FX, or spectral-domain, architecture. In October 1987 all aspects of the correlator were thoroughly reviewed, including the major hardware elements and control software, modes and performance tradeoffs, playback interface and data format, model tracking algorithms and accountability, expandability and future inclusion of data from orbiting antennas, subarray capabilities, cost, and construction schedule.

Design of the correlator is based on a dual-purpose VLSI chip using a specialized complex floating-point number representation. This chip functions as a radix-4 stage in the station-based FFT section, and also serves as a complex multiplier/accumulator in the baseline-forming section. An extensive preliminary chip design has been completed and analyzed through several simulations, and a request for proposals was recently issued for final design support, prototyping, and fabrication.

A subsection of the correlator, with seven station inputs out of the eventual twenty, and two of the final eight baseband channels, is expected to be completed and tested by mid-1990. At that point the subsection will be moved to Socorro and the initial subarray of VLBA antennas then complete will begin stand-alone operation. Replication of modules to expand the correlator to its final configuration will then continue in Socorro.

MONITOR AND CONTROL - Software governing local station functions is complete. Astronomical observing routines are logically complete and the software is being written and debugged. Software to communicate between stations and the Array Controller MicroVax exists in a rudimentary form; the Pie Town antenna has been controlled remotely from Socorro.

DATA PROCESSING - Much of the software required for imaging has already been developed and installed in AIPS. Development is proceeding on software to interface to the correlator and monitor data base for calibration and editing of data, and for the analysis of geometric data.

ARRAY OPERATIONS CENTER - Construction of the Array Operations Center is proceeding on schedule, with completion expected in summer/fall of 1988. This building will also house VLA operations staff whose presence is not required at the VLA site. The ability to house operations staff for both arrays in a common building is an important element in the operations plan.

III. SCIENTIFIC PROGRAMS

The VLBA will be used to attack a wide variety of astronomical problems covering essentially all areas of modern astronomical research from the solar system to the most distant parts of the universe.

GALACTIC RESEARCH - Within our own Galaxy there is a variety of very compact radio sources of solar system dimensions which are unresolved by conventional radio telescopes, but which can be studied with the VLBA.

Interstellar Masers - One of the most important problems in galactic astronomy is to understand the life cycle of stars. Interstellar maser clouds of OH, H_2O, and SiO are often found in regions where stars are formed and in the atmospheres of very old stars. High-resolution radio pictures made with the VLBA will be able to probe the dynamics and magnetic fields in these regions on a scale of 10^{13} to 10^{18} cm and give information at each end of the cycle of stellar evolution.

OH masers contain magnetic fields of the order of a few milli-gauss which cause the spectral features to exhibit Zeeman splitting. Observations of this splitting reveal the 3-dimensional magnetic field vectors throughout these regions, which give some insight into the manner in which the magnetic field affects cloud collapse and star formation.

Active Binaries - The milli-arcsecond imaging capabilities of the VLBA will be used to make the equivalent of movies of the variable radio structures known to exist in the merged magnetospheres of nearby active binary stars. For systems like Algol and the RS CVn binaries, this will allow detailed studies of plasma phenomena that are many orders of magnitude more energetic than the strongest ever seen in the magnetospheres of Jupiter and the Sun.

Galactic X-ray binaries such as SS 433 and Cyg X-3 will be observed with the VLBA to study the evolution of the time variable synchrotron-emitting jets and relativistic plasmoids that are commonly produced in these stellar systems.

Novae - The early phases of evolution of the structure of explosive ejecta in some novae, recurrent novae, and other interacting wind objects, which now can be resolved only when they reach VLA resolution scales of 0."1 will also be studied with the VLBA.

The Interstellar Medium - At frequencies below a few gigahertz, VLBA images of compact objects in the Galactic plane are distorted by scattering in the interstellar plasma. Such scattering can be used as a tool to study density irregularities in the ISM on small scales.

EXTRAGALACTIC RESEARCH - Perhaps the greatest impact so far of VLBI research has been in the study of the active compact cores of radio galaxies and quasars. Only at radio wavelengths is it possible to obtain high resolution images so close to the "central engine". The observed alignment of the parsec sized jets found in the radio nuclei with the more extended jet features observed with the VLA indicate a common axis in radio galaxies and quasars which is collimated on a scale of a parsec or less, is focused for distances up to megaparsecs, and remains fixed in space for up to millions of years. Of particular interest has been the study of rapid motions in nearly all of the several dozen sources which have been studied in detail with VLBI. In most cases the motion is super luminal apparently due to bulk relativistic motion of the emitting region. Because the radiation from an object moving at relativistic speed is focussed along the line of sight, a suitably oriented observer will observe an apparent enhancement of the radiated luminosity by up to a factor of a thousand or more, as well as apparent superluminal motion due to the differential signal propagation time from different parts of the moving source. These effects have important implications for the theory of AGN's, particularly, if the radiation in other parts of the spectrum also is enhanced by relativistic effects.

So far only a few relatively strong and relatively large compact sources have been observed in even moderate detail. The situation may be compared to that existing for the large scale structure of radio galaxies and quasars before the VLA and Westerbork. The VLBA will have greater sensitivity, resolution, and image quality which will allow the study of much larger samples in much more detail. In particular, it will make possible study of selected interesting objects, not just the strong sources, and to test the statistical inferences of the relativistic beaming models from dynamical studies of complete samples.

<u>SOLAR SYSTEM RESEARCH</u> - Solar radio flares often involve coherent emission processes which can produce very high brightness temperatures for short times in compact regions. The VLBA will be able to make movies with high time and spatial resolution of such flares, taking advantage of total power records, the after-the-fact correlation, and VLA snapshots to determine the location and time of the signals of interest.

The VLBA will be equipped with the frequencies used by deep space probes for communication. High angular resolution tracking of such spacecraft, relative to background radio sources or other spacecraft, can be used to improve planetary ephemerides and to aid in spacecraft navigation. It can also be used for unique projects such as a recent international experiment that used VLBI to study winds in the Venus atmosphere by tracking the motions of two balloons placed there by the Soviet VEGA spacecraft.

It will be possible to study small solar system objects, such as asteroids, by illuminating them with a powerful radar from a facility such as Goldstone and observing the reflected radiation with the VLBA. Accurate, three-dimensional, position information can be obtained in this manner and, with a resolution of less than 100 meters at an astronomical unit, structural information can be obtained as well. An observation of Saturn using this technique has already been done successfully with Goldstone and the VLA.

ASTROMETRY AND DISTANCE MEASUREMENTS - The high resolution of the VLBA will enable it to extend the range of direct distance measurements by trigonometric parallax. Observations of proper motions will be possible both throughout our galaxy and in other galaxies. This will open up an exciting range of astrometric solutions to the important problems of the structure and rotation of the Galaxy.

One type of H_2O maser source contains clusters of hundreds of bright spots whose relative motions are nearly random. The distance to such sources can be determined by statistical parallax methods. The distance to the maser sources in Orion and W51, 1,600 and 23,000 light years, respectively, has been measured using this technique with an accuracy of about 20 percent. With the VLBA it will be possible to make similar measurements on a much larger number of objects, including H_2O masers in nearby galaxies, thus extending this relatively direct distance measurement by a factor of about 100. This will have major implications to cosmology as knowledge of the correct scale of the universe will lead to a better understanding of its mass, energy content, age, and eventual evolution.

GEODESY AND GEOPHYSICS - Plans are being made to use the VLBA for a broad range of problems in geodesy and geophysics, as well as for astronomy and astrophysics. Because the spacing of the interferometer fringes depends on the separation of the antennas, precise analysis of the received signals enables one to measure the antenna separations with very high accuracy. This measurement has a variety of applications to geodesy and crustal dynamics (plate tectonics).

Already VLBI techniques have been used to measure transcontinental distances to an accuracy of about a centimeter. Systematic measurements made over years have been used to measure directly the relative motions of different pieces of the Earth's crust due to Plate Tectonics. Such motions are typically a few centimeters per year. While the motions have been measured, higher accuracy is required to constrain models of the details of tectonic motions. The VLBA should be able to provide such measurements, especially between the continental sites and the Hawaii and Virgin Islands sites which are on different plates. Plate tectonic motions are responsible for most large earthquakes, so a detailed understanding is of considerably more than academic interest.

Perhaps the most demanding geodetic measurements that will be attempted with the VLBA are observations of distortions, or lack thereof, within the North American Plate. To place interesting constraints on geophysical models will require accuracies of about a millimeter per year for any motion--a difficult goal but one which should be achieved with the carefully designed equipment of the VLBA.

Accurate measurements of the orientations of VLBA baselines relative to an inertial reference frame defined by distant quasars provides the best available data on the rotation rate and orientation of the Earth. The VLBA, with its full time observing and need for regular calibration, will provide suitable data in the future. Both the rotation and orientation of the axis of the Earth are variable on many time scales. The rotation is influenced by tidal drag and by changes in atmospheric motions and pressure. A detailed understanding of the Earth-atmosphere coupling requires both good atmospheric data and the high quality rotation data provided by the VLBA. Measurements of polar motion are also one of the most important constraints on the nature of the Earth's core and on the interface between the core and the mantle.

Geodetic VLBI observations worldwide will benefit from the VLBA's imaging capabilities. Source structure will soon limit the accuracy of geodetic observations, and such observations usually have neither enough stations nor enough data on each source to make decent maps. The VLBA can provide and monitor the source structures of a catalog of reference objects so that this particular source of error can be eliminated.

<u>FUNDAMENTAL PHYSICS</u> - The VLBA can also be used to measure with great accuracy the relativistic bending of radio signals as they pass close to the sun. Classical optical measurements of stars near the limb of the sun made during times of solar eclipses provided one of the first experimental demonstrations of general relativity. But even today it is difficult to measure the bending of starlight with an accuracy better than 10 percent. VLBI measurements have already given an order of magnitude improvement in accuracy, and the very much greater resolution of the VLBA will lead to even further improvements. Indeed, the sensitivity to relativistic effects will be so great that even position measurements made 90 degrees away from the sun will need to be routinely corrected for relativistic bending.

<u>LONG RANGE PROSPECTS</u> - As currently designed, the VLBA will give a vast improvement in sensitivity, resolution, image quality, frequency agility, spectral resolution, and time discrimination over current VLBI facilities. But even further improvements are possible.

<u>Intermediate Baselines</u> - By using the VLA and VLBA together it will be possible to partially bridge the gap between VLA and VLBA spacings. There are too few antennas to adequately cover this gap, but the location of the New Mexico and Arizona antennas has been carefully chosen so that the addition of three or four more antennas in New Mexico will give a well designed 40-41 element array with good (u,v) coverage from 40 meters to 8,000 km. This is discussed in more detail as part of the planned VLA expansion.

<u>Shorter Wavelengths</u> - Each of the ten elements of the VLBA are the most precise antennas of this size in the United States, and it is anticipated that they will work well at wavelengths as short as 3.5 mm. Successful VLBI observations have already been demonstrated at this wavelength, and by equipping the VLBA with 3.5 mm radiometers it will be possible to further improve the resolution by a factor of two. This is equivalent in optical astronomy of moving from a "good" site to a "superb" site. These radiometers are estimated to cost a total of $200k, but there may be other costs required to upgrade the subreflectors and antenna

pointing accuracy. It is too early in the project to evaluate these needs.

Space VLBI - Extension of the VLBA to 3.5 mm will give essentially the highest feasible resolution possible from the surface of the Earth. At shorter wavelengths, irregularities in the Earth's atmosphere cause deterioration of the images. To improve the resolution even further, it will be necessary to go into space. At least three space VLBI missions are being currently planned. These are:

the ESA QUASAT mission;
the Soviet RADIOASTRON mission; and
the Japanese VSOP mission.

Unfortunately, there is no comparable plan by the United States to exploit further the VLBI techniques which we have developed in this country. NRAO scientists are, however, involved in the planning of the ESA and Soviet missions and have been invited to contribute to their design and construction. It is hoped that funds will be available from NASA to support this work.

Space VLBI requires an extensive ground array to provide a distribution of Earth-Space baselines, and it is expected that all of the space missions will use the VLBA recording technology and that the VLBA will be used as the major ground support of the space VLBI programs. The VLBA correlator is the only large VLBI correlator being developed, and we have discussed its use in support of the space missions. Although the correlator is being designed to allow for a space-based element, some additional hardware will be needed at an estimated cost of about $500,000, which may be available from NASA.

SENSITIVITY - The sensitivity of the VLBA will be limited by the bandwidth of the tape recording system. However, this is a rapidly developing technology. It is likely that very significant improvements in the sensitivity will be possible in the future, but this will require replacing the entire recording and playback system.

IV. OPERATING PLAN

Operation of the VLBA presents a major challenge. The antennas are located at remote sites widely separated from each other but must operate in concert as a system comparable in complexity to the VLA. Achieving the high reliability of operation demanded by the investment in the array while at the same time keeping operations costs at a reasonable level is the goal of this plan. It has already had a profound effect on the design of the array.

Cost considerations require keeping the staff levels at each of the ten sites to a minimum. The goal is two technician-level personnel at each site for maintenance of continuous, daily 24-hour operation. It follows immediately that all subsystems must be modular. Units that fail will be exchanged for working units, with all repairs to be made at a central location.

Further economy of operation can be achieved if the operations teams at the central location, to the extent possible, have joint duties for both the VLA and VLBA. This is much of the rationale behind the choice of Socorro for the location of the VLB Array Operations Center (AOC). It is also the rationale behind the decision to make the AOC large enough to house all VLA staff whose physical presence is not required at the VLA site. The construction of a building larger than that required by VLBA needs alone was made possible by an appropriation of $3M from the State of New Mexico; the VLBA construction project is paying a matching $3M. We estimate the annual cost savings realized by joint operation of the VLA and VLBA in Socorro will be $1M annually.

The following table gives a summary of the annual operating costs of the VLBA in 1987 dollars. These costs are incremental to NRAO's existing operating budget.

Category	Cost ($1987)
Personnel (95 people)	$3.1M
Travel	0.2
Communications and Power	0.8
Materials and Supplies	1.2
Shipping	0.2
New Equipment	0.5
	$6.0M

The personnel estimates are based on the following plan and VLA experience.

	VLA Alone	VLA & VLBA Combined
VLBA Site Technicians	-	20
Electronics	28	51
Antennas	25	33
Array Operations	13	27
Business	28	36
Computing	17	28
Scientific Services/ Management	17	28
Total	128	223

Difference is 95 additional personnel needed to operate the VLBA jointly with the VLA.

Interim Operations - Full operation of the VLBA is not expected until 1992. Operations during construction are to follow this schedule:

- addition of antennas to operations of the ad hoc network of the VLBI consortium as they are completed;
- operation as a sub-array in late 1990;
- full operation of the 10-element array in 1992.

The funding schedule for interim operations was scheduled to be a roughly linear ramp up to $6M in 1992 from a very modest start in 1987. Actual funds available for VLBA operations have been $0.2M (1987) and $0.5M (1988). That means that the Kitt Peak and Los Alamos antennas will not be operated for the VLBI Consortium observing runs in 1988; only Pie Town is available to support these runs. While the regular operation of Pie Town in VLBI Consortium runs does check out one system in actual observing by users, revealing problems early for timely correction, the delay in using the other sites as they become available hurts VLB science and puts difficult dislocations in what was to be a smooth growth in staff and operations funding. Moreover, it will delay the testing of many of the new features of the VLBA.

V. USER INFORMATION

As with other NRAO instruments, the VLBA will be a user facility, open to all qualified scientists regardless of institutional affiliation or nationality. No particular expertise in radio interferometry will be required of users, and because of the wide range of astronomical problems which will require the VLBA the user community is expected to be very large, certainly much larger than the 200 or so dedicated scientists currently using the VLBI networks. Moreover, because of the extensive applications outside of normal astronomical research as well as the anticipated demands for the support of space VLBI, the pressure for observing time is expected to be unusually severe.