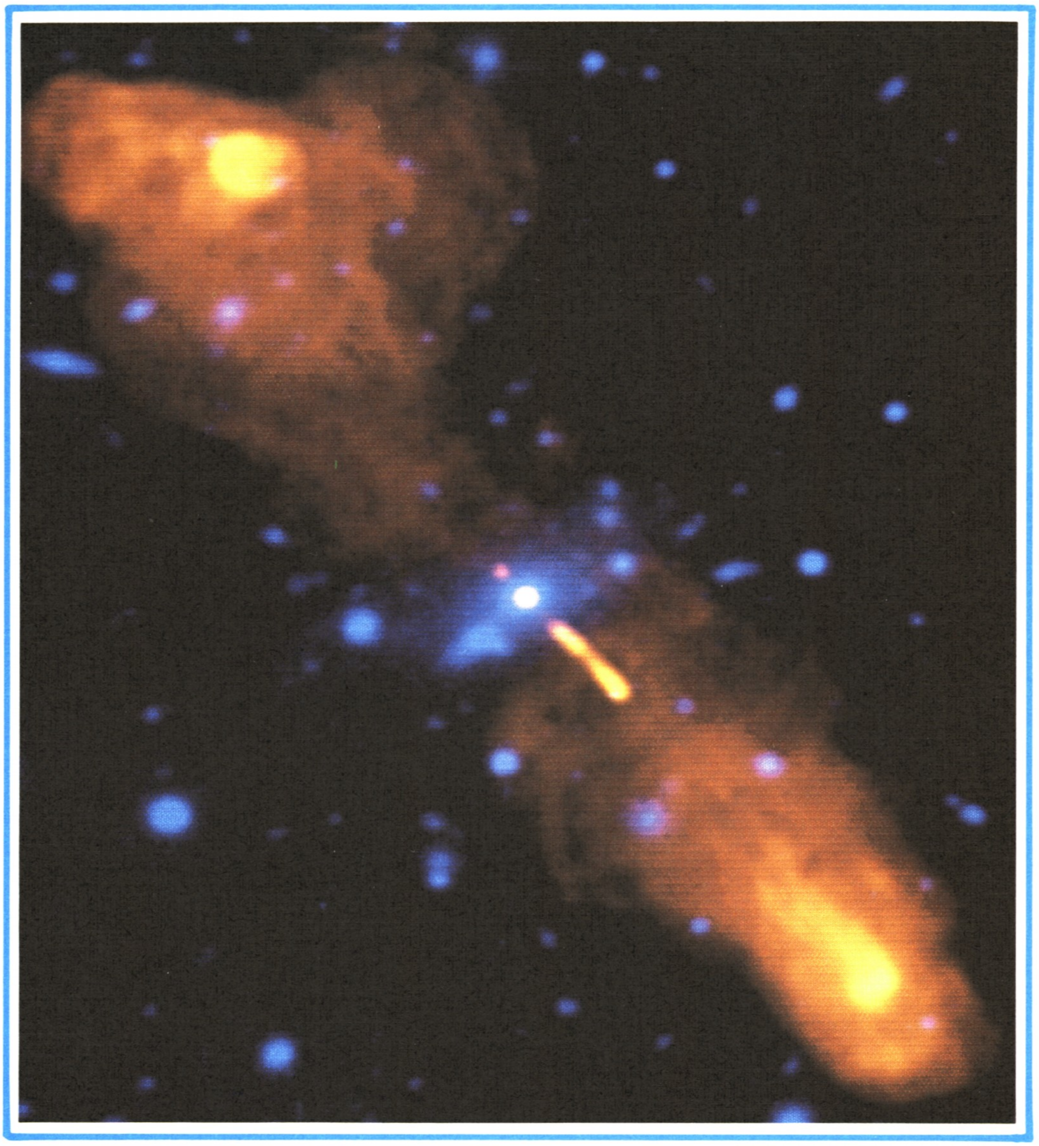


# LONG RANGE PLAN
# 1995 - 2000

NRAO

## NATIONAL RADIO ASTRONOMY OBSERVATORY

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

# NATIONAL RADIO ASTRONOMY OBSERVATORY

# LONG RANGE PLAN

# 1995 - 2000

## TABLE OF CONTENTS

# I. OVERVIEW

The long range plan of the NRAO is to provide forefront observing facilities for research in radio astronomy for this and subsequent generations of scientists. The NRAO plan, described in the following sections, recognizes the need to operate and maintain the telescopes, instrumentation, and computing capabilities of today. It also recognizes the need to plan for tomorrow's research facilities and to participate in the training of the students and scholars who will use that equipment to further their research endeavors.

The NRAO operates radio telescopes with which astronomers may observe at frequencies across the electromagnetic spectrum from frequencies as low as permitted by transmission of the ionosphere, about 75 MHz, to frequencies as high as 300 GHz, above which terrestrial water and oxygen lines increasingly render the atmosphere opaque. Astronomers may choose to observe very faint sources aided by the large collecting area of the 140 Foot Telescope in Green Bank, WV, or the Very Large Array (VLA) near Socorro, NM, or they may choose to image the radio sky with the VLA or with the milli-arcsecond resolution provided by the Very Long Baseline Array (VLBA). Finally, for those observations that depend on access to millimeter wave radiation, astronomers may use the NRAO 12-meter millimeter-wave telescope on Kitt Peak, AZ. In sum, more than 850 astronomers and students use one or more of the NRAO facilities annually. These individuals come from research-oriented universities, from teaching colleges, from government laboratories, and from industry.

Observations sensitive to faint radio emission, imaging with high angular resolution and access to these two capabilities from meter-waves to millimeter-waves, these are the observational requirements needed by radio astronomy today and in the foreseeable future. Taken together, satisfaction of these needs defines the outline of the NRAO Long Range Plan for the period 1995-2000.

Figure 1 is a presentation of the complementary capabilities of the VLA, the Green Bank Telescope (GBT), and the Millimeter Array (MMA) as they will exist upon completion of the initiatives in this Long Range Plan. The VLA and MMA are synthesis imaging telescopes that may be physically reconfigured to provide variable angular resolution at each frequency. This allows the astronomer to tailor the resolution to the angular scale of the detail present in the source. The four VLA configurations are shown in Figure 1 as parallel lines, and the angular resolution between the longest and most compact configurations (shown shaded green) is achieved by weighting the data suitably in the imaging software. A similar characteristic holds for the Millimeter Array (shown as a coral shade), except that in the case of the MMA even the single array antennas may be used as part of the image construction process. Note that the angular scale covered by the VLA and the MMA is essentially the same, and each array achieves a resolution less than $0\overset{''}{.}1$ at its highest frequency and longest baseline. Together the VLA and the MMA give the astronomer access to common angular resolution across the radio portion of the electromagnetic spectrum.

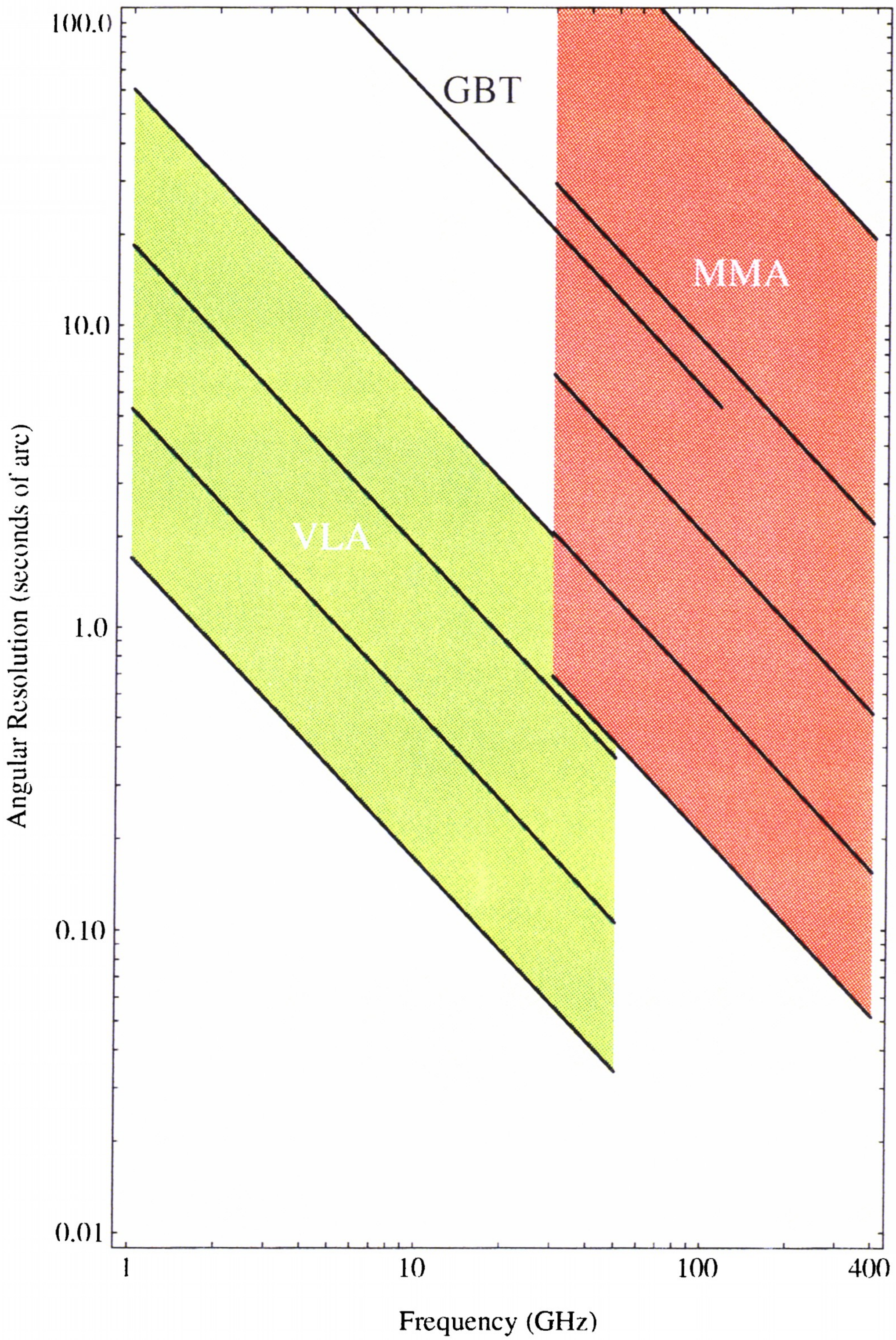



Figure 1. Angular resolution plotted against frequency for the VLA, GBT, and MMA.

The sensitivity of the VLA comes from its large collecting area, 13,000 square meters, which is approached by that of the similarly sensitive GBT with 10,000 square meters surface area. The sensitivity of the MMA comes from its collecting area, 2000 square meters, from its ability to observe thermal emission sources at short wavelengths where all such sources become increasingly brighter and from its capability of exploiting large observing bandwidths at millimeter-wave frequencies.

The central capability of the VLBA of interest to astronomers is its exceptional angular resolving power. With the addition of the 86 GHz receivers called for in the Long Range Plan, the VLBA will image astronomical sources with a resolution finer than 0.1 milli-arcsecond. This is one thousand times finer than the resolving power of the Hubble Space Telescope or the stand-alone VLA or MMA. In addition to providing images with a level of detail unique in astronomy, the VLBA angular resolution, converted to a time-scale for observable change occurring at the speed of light, will permit astronomers to view directly changes in cosmic sources in the "immutable" heavens occurring at the following rates: For:

| | | |
|---|---|---|
| Stars visiting in the night sky | - | 20 seconds |
| Stars throughout the Milky Way | - | 10 minutes |
| Nearby galaxies | - | 2 days |
| Most distant objects in the universe | - | $5/\Gamma$ years |

(Here $\Gamma$ is a measure of the bulk relativistic flow in active nuclei and quasars, $\Gamma \sim 2\text{-}20$). We can expect VLBA "movies" of the evolution of cosmic radio sources made possible by the extraordinary angular resolution of the telescope and the fact that it is made available full-time for high-resolution astronomical imaging.

The Long Range Plan to accomplish the NRAO goals in the years 1995-2000 includes full realization of the observational capabilities mentioned above, namely:

- Construction of the Millimeter Array;
- Instrument upgrade of the VLA receiving and data correlation system;
- Completion of the initial instrumentation for the GBT;
- Implementation of an 86 GHz system on the VLBA.

In addition, software to support multi-beam mapping on the 12 Meter Telescope will be completed and verified, ultimately to be used also for the MMA. The user-oriented imaging software AIPS++ will be brought into full use on all the telescopes. The involvement of students is an important aspect of the various instrument development activities both because it provides a real-world complement to a student's academic education and because the new instruments are precisely those instruments on which present-day students will, as professional astronomers, depend on as their research tools.

## II. THE VERY LARGE ARRAY

Construction of the VLA, began in 1973, was completed in 1981. As each antenna was completed it was added to the array and very useful scientific observations were begun with the first few antennas as early as 1978. Since that initial phase the VLA has become enormously productive. More than 600 astronomers and students use the instrument annually in their research. However, the VLA antennas are now fifteen years old on average and much of the signal transmission and digital correlation electronics is even older than that. The VLA has now matured to the point where the long-life capital equipment has entered the phase where maintenance needs can be described as "life-cycle" needs — maintenance done on a regular schedule for the life of the VLA — and the technical instrumentation which has a finite useful life needs to be replaced with technology at the current state-of-the-art.

### VLA Maintenance

The critical "infrastructure restoration" needs of the VLA related to the rapid deterioration of the rail system and the power distribution system were given national attention in the pages of the National Research Council decade review of astronomy and astrophysics, the "Bahcall Report," and reprinted elsewhere as well. Both these critical problems had their genesis in the construction phase of the VLA and for both a one-time restoration action was needed.

In the case of the electric power cables, the type of cable insulation used on the VLA cable was that used at the time for buried cable by the electric power industry. Unbeknownst to either the power industry or the NRAO, the extruded polyethylene cable insulation had a manufacturing flaw that caused the insulation to break down after ten years or so of use in the ground. Cable shorts became increasingly frequent at the VLA, requiring that all the cable be replaced. Similar action was required of electric companies throughout the United States, and thousands of miles of buried electric transmission cable were and are being replaced. At the VLA 618,000 feet (117 miles) of cable needed replacement. A long-term program to install new cable will be completed in 1994. The new cable is expected to last a very long time. This particular problem is now of historical interest only, it is not a continuing or recurring maintenance expense.

Table II-1
**Replacement of Electric Power Cable**

| | 1992 | 1993 | 1994 |
|---|---|---|---|
| Installed During Year (1000's of feet) | 288 | 105 | 74 |
| Cumulative Percent of Total Project | 71% | 88% | 100% |

A related maintenance item requiring a one-time restoration measure is the replacement of the concrete access ways leading to underground waveguide connections along the arms of the VLA wye configuration. The waveguide access ways were made during VLA construction by the practical expedient of stacking rectangular concrete shells. Over time the sides of the shells have buckled and cracked as the soil shifted. The concrete access ways are being replaced by galvanized steel structures, with the work done by the VLA site crew. Replacement work will continue to completion in the time period of the present Long Range Plan on the following schedule.

Table II-2
**Replacement of Waveguide Access Ways**

| | 1992 | 1993 | 1994 | 1995 | 1996 |
|---|---|---|---|---|---|
| Number Repaired in Year | 12 | 11 | 29 | 29 | 29 |
| Cumulative Percent of Total Project | 10% | 19% | 52% | 68% | 100% |

Maintenance of the VLA rail system had both a need for two corrective measures, eliminating a large number of defective cross-ties and rebuilding the 72 perpendicular track intersections at the antenna stations. There is a continuing need to replace worn out ties, rework the track ballast, correct drainage and erosion problems, and level and align the track.

The problem with the VLA rail system that was highlighted in the Bahcall Report, and reproduced in other forms, was the large number of cross-ties that were installed during construction but deteriorated rapidly soon thereafter. These particular ties had been used in wet regions of the country and were obtained as government surplus at the time of VLA construction. Exposed to the dry New Mexico air these particular ties lost their structural integrity. They had to be replaced. Aided by NSF funds specifically directed to restoring the infrastructure of the NRAO, and aided by the availability of surplus military heavy equipment that we were able to acquire at no cost, the most seriously defective ties were replaced. The work was done by seasonal in-house workers.

There are approximately 280,000 ties in the VLA rail system. Transport of the VLA antennas gives the ties only light, occasional loading. Nevertheless, wooden ties will decay over time. In the desert southwest the useful lifetime of a rail tie is about 50 years. Even with such a long life, replacement of the ties must be done at a sustainable rate of 280,000 ties/50 years = 5600 ties per year. At a cost of $24 per tie, the annual materials cost for the tie replacement is $134,000; add to this the cost of labor to do the replacement and the routine VLA cross-tie maintenance cost is nearly $200k annually. This cost will continue as long as the VLA operates.

There are other maintenance needs of the VLA rail system mentioned above, all of which will be done by the same NRAO rail crew but none of which involves a large materials cost. The other major activity involving the rail system occurring during the present Long Range Plan is completion of the project to rebuild the rail intersections at each of the 72 antenna stations. Past and anticipated progress is shown below.

Table II-3
**Refurbishment of Rail Intersections**

| | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|
| Rebuilt During Year | 3 | 2 | 8 | 3 |
| Overhauled During Year | 20 | 9 | 20 | 7 |
| Cumulative Percent of Total Project | 32% | 47% | 86% | 100% |

As can be seen from the tables above, virtually all work on the rail system, the rail intersections, the waveguide access ways, and the array electric power distribution system will either be complete by 1995-96 or it will settle into a routine maintenance program that will continue indefinitely. Stated another way, these aspects of the VLA physical plant have reached operational maturity. This is not true of the VLA antenna maintenance.

Throughout the fifteen years that the VLA antennas have been operational, they have received regular in-the-field maintenance that includes lubrication of the gears and moving parts, replacement of failed equipment, and so forth. In addition, at regular intervals, separated by approximately 30 months, each antenna receives major refurbishment in the antenna assembly building. It is on these occasions that major new equipment is installed or operational modifications made. Up to this point it has not been necessary to paint the entire antenna structures because the comparatively dry New Mexico climate tends to age the paint only slowly. Only spot painting has been done, where necessary, at the time major antenna refurbishments are scheduled. However, by now the oldest antennas need to be repainted, and we plan to begin a painting program in 1994 that will evolve to a routine phase of array maintenance.

In 1994 we plan to experiment with painting removal and application techniques. We will seek advice from painting consultants to define our procedures. Once defined, the antennas will be painted at the rate of three antennas per year by an in-house crew that will be trained for that purpose. In all likelihood the same individuals who previously worked to install the electric power cable will be re-trained as painters: no new staff are anticipated to handle antenna painting. At the rate of three antennas painted per year, each antenna will be repainted every nine to ten years, basically a stable rate equal to the needs in the desert southwest. The specialty paint used for the antennas has the property that it diffuses light at visual and infrared wavelengths while neither scattering nor absorbing light at radio wavelengths. These properties are needed to allow the VLA to observe at and near the sun. The paint is expensive; the process of stripping the old paint and applying the new primer and paint is time consuming. The cost to paint a single antenna, materials and work time, is anticipated to be $200k - $250k. Such a cost, for three antennas per year, is incorporated in the NRAO budget for VLA operations in the Long Range Plan for 1995 and each year beyond that. Painting, like rail system maintenance, is a continuing expense incumbent on us as long as the VLA operates.

**VLA Electronics Upgrade**

Unlike the case for the physical plant of the VLA for which a routine maintenance schedule can be established and followed rigorously year by year, improvement of the array electronics system should occur in those intervals when technological developments cross major thresholds. Several important such thresholds have been crossed in the twenty years since the VLA electronics system was designed. The three most important for improvement of the VLA are these:

- Transmission of wideband data can be done with optical fibers having an accessible bandwidth of 1-10 GHz. Waveguide signal transmission such as used at the VLA is narrowband and is now an obsolete technology;
- Digital samplers are commercially available with speeds of 2-4 Gsps. This makes possible a correlator of bandwidth at least as large as 1 GHz, twenty times greater than the bandwidth presently processed by the VLA correlator;
- Simple heterostructure field effect transistor (HFET) amplifiers have been developed largely through the commercial interest of the communications industry. At cryogenic temperatures the HFET amplifiers provide wide bandwidths and low noise suitable for radio astronomy applications.

As an upgrade to the VLA, we plan to incorporate all three of these developments. After another twenty years or so we can anticipate the opportunity to make still another VLA technical upgrade.

The current proposed VLA upgrade to begin in the period 1995-2000 has three components:

- Replace most of the VLA receivers to achieve lower noise temperatures and wider bandwidths. Two new observing bands will also be added. These receivers will provide 1 GHz of IF bandwidth in each polarization. This is a factor of ten increase over the 100 MHz per polarization now available on the VLA.
- Replace the buried waveguide with a fiber optic system to send the wide bandwidth signals to the correlator.

- Construct a new VLA correlator to both process the wide bandwidth signals for continuum observations and provide improved resolution and flexibility for spectral line work.

This upgrade plan emphasizes improvements to the high-frequency performance of the VLA. Upgrades to the low-frequency performance can be done with relatively little cost and could be done as part of an ongoing retrofit program. A major exception to this is the project of placing a 800-1200 MHz prime focus system on the VLA. This would require extensive mechanical alterations to the antenna quadrupod and the focus/rotation mount. An upgrade plan for VLA operation below 1250 MHz and for mechanical changes to the antennas needs further study as an additive alternate to the plan.

**A Technical Summary of the VLA Upgrade**

The three parts of the upgrade are: receiver improvements, a fiber optic data transmission system, and a new wide bandwidth correlator. Although there are many aspects of the design that have yet to be worked out, it is useful to have a concept for the purpose of estimating the costs and time schedule. The general scope of the concept presented here is realistic, although the details will certainly change.

The working design has the 2 GHz of instantaneous bandwidth broken into two pairs of oppositely polarized IF-channels, each 500 MHz wide. These four IF channels need not be contiguous. At higher frequencies, where much more than 1 GHz of receiver tuning range is available, four different frequencies can be observed simultaneously. For full flexibility, this scheme will require four synthesizers per IF conversion in each antenna and will return four independent IF channels to the correlator.

The location of the samplers (antenna or control building), the number of frequency conversions, and the method of lobe rotation have yet to be decided. Baseband filtering could be done either digitally or with analog filters. The correlator could be of a lag or FX design.

It is likely that several of the VLA systems can be used with little or no change. For example, the antenna drive and the monitor and control systems could be adopted with little change. The time-keeping equipment should not require upgrade. The only change in the infrastructure would be installing the fiber optic cable and abandoning the waveguide. The required cryogenic capacity is already in place.

**Antenna and Receiver Improvements**

At the antennas, the upgrade involves improving receivers for the current observing bands, adding new observing bands, and modifying the antenna structure for improved operation. Table II-4 shows a possible restructuring of the VLA high-frequency observing bands.

Table II-4
**Proposed Cassegrain Observing Bands for the Upgraded VLA**

| Band | Freq. Low (GHz) | Freq. High (GHz) | BW (GHz) | BW Ratio | |
|---|---|---|---|---|---|
| L | 1.25 | 1.75 | 0.50 | 1.40 | Keep |
| S | 2.13 | 2.70 | 0.57 | 1.27 | New |
| C | 4.80 | 6.70 | 1.90 | 1.40 | New |
| X | 8.00 | 9.10 | 1.10 | 1.14 | Keep |
| Ku | 12.00 | 15.40 | 3.40 | 1.28 | New |
| K | 18.00 | 26.50 | 8.50 | 1.47 | New |
| Ka | 26.50 | 40.00 | 13.50 | 1.51 | New |
| Q | 40.00 | 50.00 | 10.00 | 1.25 | 20 More |

**Improved Low Noise Receivers.** A slow upgrade to the VLA receiver systems has been going on since the early 1980s. For several years this involved installing better low-noise amplifiers in the existing receivers. More recently, a new style receiver was introduced using the VLBA design in which the receiver is attached directly to the feed and the polarizer is cooled in the cryogenic dewar. This reduced the noise contribution from the polarizer and eliminated long ambient temperature waveguide runs that added to the system temperature.

The VLBA-style receivers are now used at 1.4 GHz, 8.5 GHz, and for the ten antennas operating at 45 GHz. These receivers will remain with perhaps only minor modification. The greatest improvement in system temperature can be made at the 5 GHz, 15 GHz, and 22 GHz bands using the VLBA-style receivers and modern HFET amplifiers. Completely new receivers will be built for these bands. Implementation of such receivers will halve the system temperature.

The new receivers will provide the 1 GHz per polarization bandwidth needed for continuum sensitivity. They will also tune a wider frequency range to permit the study of new spectral lines, such as methanol, that were unknown when the VLA was first built. The frequency range in the 5 GHz, 15 GHz, and 22 GHz bands will be extended. A redesign of the 20 cm feed may be done to permit observations at lower frequencies.

At present, only ten VLA antennas are outfitted for 45 GHz operation. This band will be made available on all antennas as part of the upgrade.

**New Observing Bands.** Two new receiver systems for the 2.5 GHz and 33 GHz bands will be added at the Cassegrain focus. These will open new molecular line observations to the VLA, improve rotation measure studies, and permit the VLA to participate in bistatic planetary radar observations with the Arecibo Observatory.

**Antenna Modifications.** Adding the two new observing bands will require rearranging the feeds on the VLA feed ring and installing a new feed enclosure. Since the high-frequency receivers will be mounted very close to the Cassegrain focus, a structure more like the VLBA feed cone probably will be needed.

When 45 GHz receivers were first installed on the VLA, the ten antennas with the best surface accuracy were chosen to get these receivers. The VLA upgrade proposes putting 45 GHz on the remaining 18 antennas. This will require some effort to improve the performance of the worst antennas.

**New LO/IF Transmission System**

In order to transmit 2 GHz of bandwidth from each antenna, this proposal includes a fiber optic link to all of the VLA stations and is expandable to include links to the nearby VLBA antennas and possible new antennas intermediate between the VLA and present VLBA stations. Separate fibers will carry the LO reference signal and the wideband IF signal. Between four and six single-mode fibers will run to each antenna station. Although low temperature coefficient fiber will be used on runs exposed to ambient temperature, a round-trip phase correction system will probably be needed.

It is not yet decided whether to send the IF back as a digital signal that is generated by samplers located at the antennas or to send an analog signal to the central electronics room.

**New Correlator**

The current VLA correlator is limited to a bandwidth of 4 x 50 MHz. A new correlator is needed to process the 2 GHz of bandwidth and to achieve the increase in sensitivity. Moreover, the current correlator limits the type of science which can be done due to its limited spectral resolution at wide bandwidths. At 50 MHz bandwidth, the VLA can produce only eight spectral channels. Wide-field imaging at low frequency and spectral line searches for redshifted spectral lines are very inefficient with the current correlator.

The specifications for the new correlator are still under discussion. The working design has a minimum of 512 channels in each of the four IF channels being returned from the antennas. The bandwidth of each channel would be adjustable in factors of two over a wide range, allowing widely variable spectral resolution. Full polarization will be available at all bandwidths.

The new correlator will be capable of processing data from 32 antennas. These 32 could be some combination of the 27 VLA antennas plus the 2 nearby VLBA antennas (Pie Town and Los Alamos), plus up to 4 new antennas intermediate between the VLA and current VLBA stations.

**Cost and Schedule**

The time scale for this project is uncertain since many parts of the system have yet to be defined. The amounts of work that will be contracted out and that will be done with NRAO staff are not yet decided. A fundamental requirement of the upgrade project is that the VLA should continue to function as a user instrument during the upgrade. The impact of this on cost and schedule is uncertain. Nonetheless, some estimates can be made.

The time scale of the project will probably be set by the need to move antennas through the antenna assembly building for overhaul. The tasks will include:

- New feed cone and receiver installation;
- Normal preventive maintenance and retrofits;
- One out of five antennas may need azimuth bearing replacements;
- Five weeks per year devoted to reconfiguration of the array.

If we allow four antennas to have an 8-week overhaul and one antenna to have a 12-week overhaul (for the azimuth bearing replacement), we will complete five antennas per year. This will be a tight schedule and will probably involve working two shifts per day. With 28 antennas, and adding a few months for startup and cleanup, the upgrade project will take six years. During that time there will often be two antennas out of the observing array for retrofits.

Six new cryogenic systems (includes finishing 45 GHz) will be added to the array. A total of 170 cryogenic receivers will need to be built. Even if design and prototyping can be done before the main project begins, we still need to fabricate about 30 cryogenic receivers per year. During the normal receiver retrofit program, we've built between 9 and 12 receivers per year. About 800 new LO/IF modules will have to be built.

Six years should be adequate time to complete the fiber optics system and the new correlator.

Considering that the normal VLA and VLBA maintenance and upkeep must be kept going, it will be desirable to add about 30 people to the Engineering Services and Electronics Divisions for the six-year duration of the project.

At a minimum, a two-year period of design and prototyping should precede the actual project start. If 1995 and 1996 are devoted to research and development, the VLA upgrade could be completed in 2002.

A tentative project budget is given in Table II-5.

Table II-5a
**VLA Upgrade Budget**

| | | M&S ($k) | Wages ($k) | New m-yr |
|---|---|---|---|---|
| 1. | Receivers | 6,150 | 2,300 | 50 |
| 1a. | Feeds | 1,050 | 50 | 2 |
| 2. | Ant. LO/IF | 3,000 | 1,750 | 60 |
| 3. | LO/IF Trans. | 2,400 | 100 | |
| 4. | Central LO/IF | 1,600 | 900 | 30 |
| 5. | Correlator | 5,600 | 1,000 | 20 |
| 6. | Hardware | 400 | 0 | 0 |
| 7. | Ant. Mechanical | 900 | 800 | 18 |
| 8. | Test Equipment | 150 | 0 | 0 |
| | | 21,250 | 6,900 | 182 |
| Employee Benefits (@30%) | | | 2,070 | |
| Contingency 10% (Wages and M&S) | | 2,100 | 680 | |
| | | 23,350 | 9,650 | |
| | TOTAL | $33,000 | | |

Table II-5b
**Annual Budget for the VLA Upgrade**

| | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | Total |
|---|---|---|---|---|---|---|---|---|
| Cost ($M) | 2.0 | 6.0 | 6.0 | 6.0 | 6.0 | 5.0 | 2.0 | 33.0 |
| Work-year | 18 | 30 | 30 | 30 | 30 | 24 | 20 | 182 |
| NRAO* | 6 | 10 | 10 | 15 | 15 | 15 | 15 | - |
| Subcontracted* | 12 | 20 | 20 | 18 | 15 | 9 | 5 | - |

* Breakdown of required manpower into temporary project hires and permanent NRAO employees.

# III. VERY LONG BASELINE ARRAY

## Present and Planned Instrumentation

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

The VLBA will become fully operational in 1994. All antennas were completed in 1993 and the correlator will be fully checked out by the end of 1994. The full complement of thin tapes will have been purchased and placed into use. Global VLBI Network sessions will continue and full-time VLBA observing will commence. In addition to straightforward VLBI observations, such as those of continuum and spectral line emission, some of the more advanced capabilities of the array, such as observations of polarized emission and gated pulsar observations, will start to become available to the general astronomical community.
The VLBA is outfitted for observations in nine frequency bands as shown in the table below. The receivers at 1.4 GHz and above contain cooled HFET amplifiers from the Central Development Laboratory in Charlottesville. The low-frequency receiver is a room temperature GaAsFET. The cooled receiver for each band is in a separate dewar mounted directly on the feed to minimize noise contributions from waveguides, etc. All receivers cover both right and left circular polarization. There is a dichroic/ellipsoid system that allows simultaneous observations at 4 and 13 cm, primarily for geodesy and astrometry. In the next five years, we plan to augment these standard frequencies by adding new systems to operate at 6.5 GHz (for methanol and OH spectral lines) and 86 GHz.

VLBI requires a very accurate frequency standard and a wide bandwidth recording system at each site. The VLBA sites use a hydrogen maser manufactured by Sigma Tau Corporation for the frequency standard. The recording system is based on a Metrum (formerly Honeywell) longitudinal instrumentation tape recorder that has been heavily modified by the Haystack Observatory. The recorder is similar to the one used in the Mark III and future Mark IV VLBI systems. There are two drives at each VLBA station to allow about 24 hours of recording at 128 Mbits/second between required visits to the station for tape changes. The tapes are 16 microns thick, with about 3.4 miles of tape on a 14-inch reel.

Table III-1
**VLBA Receiving Systems**

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

Notes:
1. MHz/GHz frequency; centimeter wavelength; conventional radio (or VLA) letter codes.
2. Overall aperture efficiency, and total system noise temperature, at zenith. Values are representative of those measured on several VLBA antennas.
3. Single-frequency performance (without dichroic) shown.

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

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

SUN IPX and IBM RS/6000-560 and RS/6000-580 classes. This computing capacity will suffice only for the next year or so, and after that we will need to augment it both in computing power and disk storage capacity.

**Future Development**

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

A vital continuing project is to make the array "phase stable." With a connected element array such as the VLA, the phase of the array elements are found by observations of a phase-calibration sources of known structure. This allows images to be made without using the self-calibration techniques upon which VLBI normally depends. Weak sources, which require coherent integrations over the whole time of an experiment and over all baselines, can thus be observed. Imaging of complex sources is simplified as well. Accurate relative positions can be measured which allows for proper motion and parallax studies and for alignment of images made at different frequencies or different times. If phase calibration using nearby calibrators can be used on the VLBA, it will have a tremendous impact on the science that can be done. The success of phase calibration for the VLBA will depend critically upon the accuracy of the geometric model for the array, the earth and the celestial sources. A simple geometric model can be used to extend the phase-coherence time from tens of minutes up to several hours. During 1994, we expect to achieve full phase coherence by using a more complete and accurate geometric model based upon extensive geodetic and astrometric observations. In later years, we will install water-vapor radiometers for measurement of the atmospheric phase introduced by the water-vapor along the line of sight. At lower frequencies, measurement of the ionospheric phase will be accomplished using dual frequency Global Positioning Satellite (GPS) systems.

One of the major advantages of the VLBA over the older VLBI networks is its ability to work at high frequencies. The antennas were designed for good performance at 43 GHz, and receivers for that frequency have been installed and are working well. The antenna structures were designed to work to 86 GHz, and the surfaces were figured as well as possible, within the technologies used, to allow some performance at this frequency. Early measurements, with a substandard subreflector, gave an efficiency near 20 percent, which is very usable. Some problems with the high-frequency performance of the antennas have been uncovered. We are currently pursuing an extensive series of holographic measurements of the antenna surfaces. In addition, the pointing performance of the antennas must be improved. Once these problems have been addressed, we will be able to start on the exciting project of building and installing a complete set of 86 GHz receivers, thereby doubling the maximum angular resolution of the instrument, making the VLBA the instrument of choice for high-resolution observations at the longer millimeter wavelengths. In 1994, we will construct and place into operation two 86 GHz receivers. This will enable further testing of the antenna performance and some evaluation of the phase stability.

The VLBA will be a formidable millimeter wavelength telescope, capable of high quality imaging with 0.1 milli-arcsecond resolution at 86 GHz. At even higher frequencies, the VLBA recording facilities can be utilized by connecting nearby millimeter wavelength single dishes. For example, the NRAO 12 Meter is already connected permanently to the VLBA antenna at Kitt Peak (about 300 m away) as is the OVRO millimeter array to the VLBA antenna at Owens Valley. A similar connection of the VLBA recorder to one of the millimeter antennas on Mauna Kea is also planned.

A number of other technical developments will take place in 1994 and 1995. For sensitivity-limited observations, the instantaneous recording rate of the array can be doubled for a short period of time by recording on both tape drives simultaneously. This requires substantial work in a number of areas, principally the correlator. The FX architecture allows frequency-dependent gating of the correlation for a pulsar. This principally requires software development in the correlator.

**Scheduling and Observing**

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

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

January 1995), but the principal recording formats will be VLBA and MkIII. The current MKIII system is being upgraded to a new, wider band format, Mark IV, based upon using two headstacks in place of the current single headstack. We plan to implement this upgrade in 1996 or 1997. Other tape systems will be in use at the end of the decade: the K4 and S2 formats. We plan to support these via special-purpose machines to translate from one tape format to another.

# IV. GREEN BANK

## Green Bank Telescope

The Green Bank Telescope (GBT) has a fully steerable clear aperture collecting area of 100 meters diameter, to operate from 300 MHz to 43 GHz, eventually to ~100 GHz. Construction began in 1991 with completion of the foundation in June, 1992. In early 1994 the alidade, the lower structure that rotates in azimuth, was completed.

Late in 1993, the final design of the elevation tipping structure was received from the contractor and approved by NRAO. The development of the design model had taken three years to complete. The last structural computer model, Model 95-2, resulted from over 100 iterations of the design and included inputs from an optimization analysis conducted by NRAO in association with JPL's Ground Antennas and Facilities Engineering Group. The tipping structure was one of the most challenging aspects of the GBT project because of the unique clear aperture geometry of the telescope's reflector, the size of the total structure, including the offset feed arm, and the high degree of surface and pointing accuracy required. The tipping structure consists of 11,208 individual members, 2,004 surface panels, and 6,106 joints and weighs 9,400,000 pounds, including 2,440,000 pounds of counterweights.

To assure the efficacy of the completed telescope, NRAO has conducted a wide range of analyses and sub-programs. They include: wind tunnel tests, concrete and grout studies, exacting shop and field welding controls, and joint design and fatigue study. Additionally, exacting weight control of critical members and a complete quality assurance program covering the contractor, subcontractors and all field operations has been instituted. All of these are instrumental in assuring that the antenna will perform in all aspects as specified, calculated, and predicted.

Construction of the elevation shaft and wheel, the reflector box structure, portions of the counterweight, and the feed arm will be completed in 1994. The back-up structure trial erection will also be carried on in the fall of 1994. The back-up structure is scheduled to be assembled on the telescope during the spring and summer of 1995, with the reflector panel installation completed during the fall of 1995. The target date for completion of construction remains late 1995.

Operation of the GBT has been divided into the following phases:

Phase I - Low Frequency Operation (15 GHz)
Phase II - Open Loop Operation (43 GHz)
Phase III - Close Loop Operation (> 43 GHz)

Phase I is the basic antenna as delivered by the contractor and accepted by NRAO after acceptance testing which proves that the specification has been met. The contractor will install the 2,200 active surface actuators in a zero position and install the associated control wiring back to the actuator control room. The subreflector adjustment mechanism will be in place and will be used by the contractor to prove compliance with specifications. Delivery of the basic antenna is scheduled for December, 1995.

Phase II will be complete when the active surface system is operational and can compensate for gravity deflections of the reflector surface as commanded by a computer program based on data provided by the contractor and verified by NRAO. NRAO has developed an autocollimator system and quadrant detector system, which will be used to enhance the pointing capability of the GBT. It is planned that the laser ranger surface measurement system will be available during this phase. Delivery of the open loop active surface system and pointing enhancements are tentatively scheduled for December, 1996.

Phase III will extend into 1997 and involves operation of the telescope at millimeter wavelengths. This will be accomplished using NRAO provided enhancements involving the laser ranger surface measurement system and the precision pointing system.

**GBT Electronics**

Receivers for the GBT at frequencies of 1.15 GHz and higher will be mounted at the Gregorian focus, whereas the low-frequency receivers will be combined into two receiver packages at the prime focus. There are fourteen Gregorian receivers covering the frequency range 1.15 to 52 GHz. Priorities for the construction of these receivers have been set by the GBT Scientific Working Group. Some are under construction, others are being designed. A complete list of the GBT Gregorian receivers, and their priority and status, is given in Table IV-1. Both of the prime focus, low-frequency, receiver packages are under construction. Box 1 will be complete in early 1994; Box 2 will be built in the latter half of the year. Table IV-2 gives the specifications of the prime focus receivers. Figure 2 shows the completed receivers, left to right, for the bands 12.0-15.4, 8.0-10.0, and 22.0-26.5 GHz.

A prototype Gregorian feed rotator mechanism and the turret cable wrap assembly have been fabricated and tested. The receiver room local oscillator rack, the IF rack and various IF modules have been assembled. The existing spectral processor spectrometer has been upgraded with additional memory and made compatible with the GBT monitor and control technology. A continuum backend and new spectrometer are being designed.

During 1995, the electronics group will complete the hardware design and construction currently underway, and will do extensive system tests to minimize start-up problems when the antenna begins operation. The initial set of feeds and receivers will be completed. The racks which will be installed in the receiver room have been fabricated and will be tested. Cabling plans and other preparations for outfitting the antenna will be completed. Outfitting of the antenna, including installation of cryogenic compressors, helium lines, and electronic cabling will be done as the structural construction allows. Outfitting of the feed arm receiver room is expected to begin on the ground in late 1994 and early 1995.

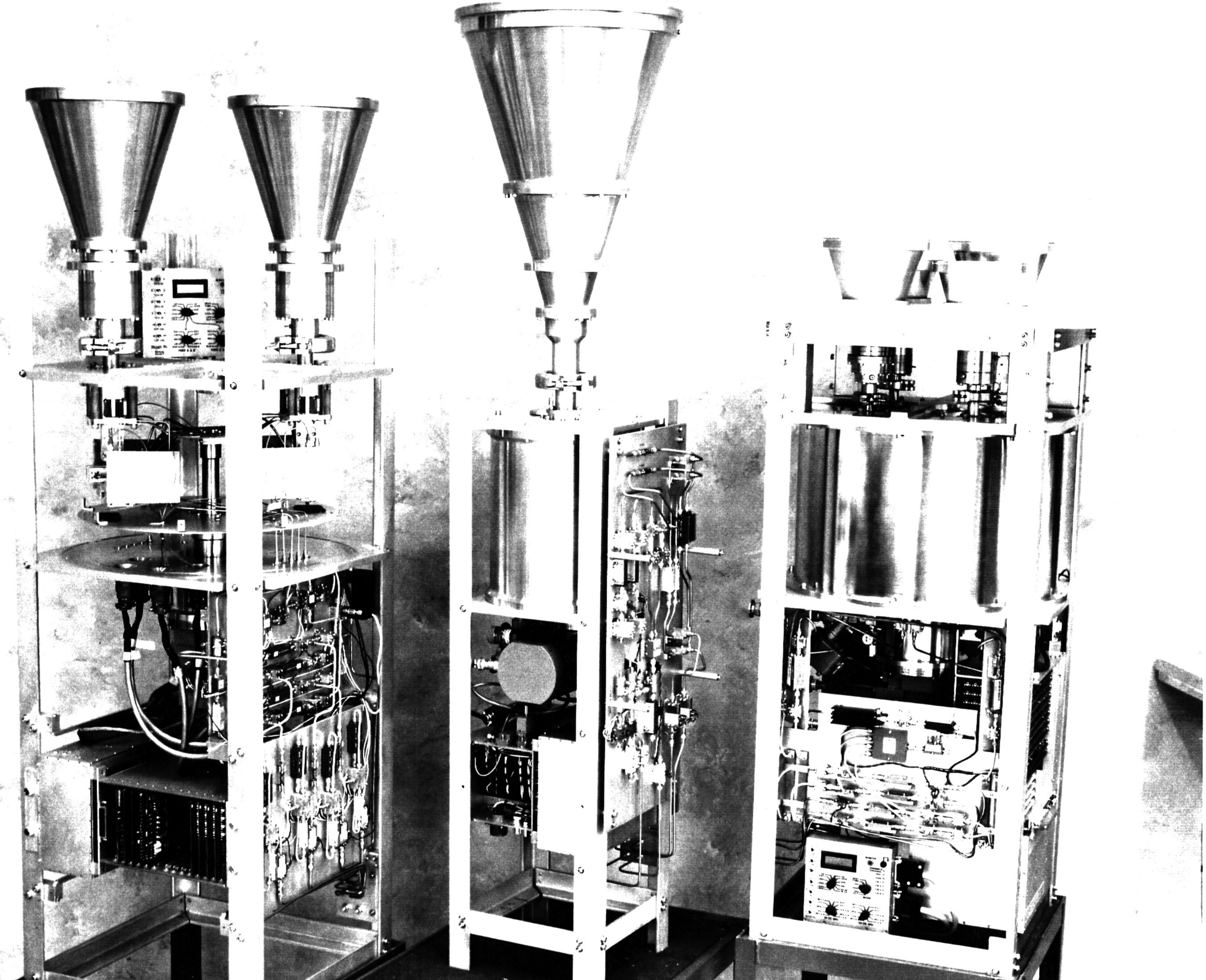


Figure 2. GBT receivers, left to right, for the 12-15, 8-10, and 22-27 GHz bands.

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

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

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

Several test fixtures and a breadboard 2 GHz sampler have been fabricated and are being evaluated. Problems which have been encountered with the chip fabrication are being evaluated by the chip designers and monitored by NRAO engineers. If these problems are resolved, completion of the new spectrometer could be achieved by mid-1996.

**GBT Closed Loop Active Surface and Pointing**

By early 1995 all of the 2400 one-inch retroflectors that will be mounted on the telescope surface panels will have been delivered to Green Bank. The wide-angle retrospheres, which will be mounted at various points on the telescope structure for viewing by several lasers simultaneously, will have been designed, prototypes will have been fabricated, and several dozen will be under production at a commercial vendor. Design of the individual laser units will be finished and most will have already been fabricated in the Green Bank shop. The electronics, frequency standards, control units, and other parts of the laser system will also have been designed and mostly fabricated.

**Table IV-1**
**Gregorian Receivers**

| Receiver | Freq. (GHz) | Dual Feed | Rank | Status* |
|---|---|---|---|---|
| 1 | 1.15-1.73 | No | 1 | Under Construction |
| 2 | 1.73-2.60 | No | 2 | Scheduled for 1994 |
| 3 | 2.60-3.95 | No | 3 | |
| 4 | 3.95-5.85 | No | 2 | Under Construction |
| 5 | 5.85-8.20 | No | 3 | |
| 6 | 8.00-10.0 | No | 2 | Done - Testing |
| 7 | 10.0-12.4 | No | 3 | |
| 8 | 12.0-15.4 | Yes | 1 | Done - Testing |
| 9 | 15.4-18.0 | No | 4 | |
| 10 | 18.0-22.0 | Yes | 2 | Done |
| 11 | 22.0-26.5 | Yes | 1 | Done |
| 12 | 26.5-33.0 | Yes | 3 | |
| 13 | 33.0-40.0 | Yes | 3 | |
| 14 | 40.0-52.0 | Multiple | 1 | Under Design |

* Blank = No current effort.

Table IV-2
**Prime Focus Receivers**

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

It has been decided to make the lasers an absolute measurement instrument rather than the relative instrument previously envisioned. This calls for a much higher precision mechanical design, and for metrology calibration requirements that exceed the state-of-the-art. The acoustic thermometry experiment that correlates laser phase shifts with the speed of sound over a common path is one result of the desire for absolute calibration. It is likely that the laser system will need input from many systems, including the weather station and the acoustic thermometry devices, to maintain absolute calibration on the telescope. The basement of the old 300 Foot Telescope control building has been renovated and a laser calibration lab has been set up there. The facilities and calibration procedures will be in place by early 1995. This lab will be a permanent facility that will also be used to set zero point offsets, check linearity, and otherwise maintain laser calibration during operations of the GBT.

By the end of 1994 the computer system should be fully operational. The lasers now operate over Ethernet and point to 3-D real world coordinates. Control of the system will be with a Sun-based computer to better interface to the various groups involved in the GBT monitor and control systems. In 1995 the software activity will focus on integrating the lasers with other groups — active surface, pointing, and monitor and control.

In 1995 much of the activity will shift from the lab to the telescope. Tasks to be done include mounting of retroflectors, building monuments and underground utilities, use of the surface setting tool and, perhaps, even use of the lasers in the initial surface setting. The field test of the laser system on the 140 Foot Telescope, that was begun in 1994 to gain experience in using the lasers for pointing under realistic weather conditions, will likely continue through 1995.

After the GBT goes into operation the laser system will need to be integrated into the rest of the GBT pointing system. It will be used to understand the behavior of the telescope — its vibration modes, detailed response to sunlight and shade, deformations of the surface shape, and so forth. The laser data will also be combined with finite-element modelling of the telescope in order to understand the as-built structure.

Because successful pointing of the GBT at high frequencies requires the laser system, we anticipate that the first several years of GBT operation will be ones of intense effort in developing and refining our understanding of the data generated by the lasers. There will also be an ongoing need to remove lasers from the GBT for refurbishment and calibration. The operational style of the lasers will need to be determined. In many respects the laser system is the most advanced part of the entire GBT project. It will certainly need continuing technical effort beyond the construction phase to ensure that its full capabilities can be used in operations.

**140 Foot Telescope**

The 140 Foot Telescope will continue to operate as a visitor facility until its work can be taken over by the GBT. It is being maintained at an adequate level and improvements are being made where they increase reliability of systems or are otherwise necessary. Although there are no plans to operate the telescope as a user facility after the GBT comes into operation, its integrity will be maintained as long as it is used. In addition to serving as a visitor facility, the telescope is being used to test GBT concepts, hardware, and techniques. It is the test bed for the GBT monitor and control antenna positioning system, and will be used to field-test the laser-ranging pointing system of the GBT. Several GBT receivers will be installed on the 140 Foot to gain operational experience with them under observing conditions.

There have been low-level but steady improvements to the 140 Foot system. A new IPX workstation and greatly expanded disk capacity insures that there is adequate on-line space for all spectral line observations and adequate computing power to reduce the data. In addition, an IPC workstation was installed for use by the telescope operator and for general use in telescope operations and maintenance. The laser printers have been upgraded and extra workstations bought for use of visitors at the lab building. Data at the telescope are now archived on 8 mm tapes, eliminating the 9-track tapes and also bypassing the Modcomp computer for this task. The spectral processor was upgraded by the addition of more memory and a faster control computer. This resulted in additional capabilities for pulsar observations. The UNIPOPS data reduction system is now mature, stable, reliable and in constant use at the telescope. It has been upgraded so that it can receive and analyze data from the spectral processor. It has new facilities for constructing and manipulating spectral line data cubes. It is now easy to export data to other data reduction packages.

Both channels of the 7.5-12 GHz and 12-18 GHz Cassegrain receiving systems have now been replaced with HFET amplifiers. These have increased stability and lowered average noise over the band. Complete coverage of the 7-26 GHz range is now possible with two independent local oscillators. A backup air conditioning system has been installed.

In the coming year, the remaining K-band maser in one receiver channel will be replaced by an HFET amplifier for use in the 18-26 GHz range. The other, a second channel, was installed in 1993. This would give continuous coverage of all frequencies from 7.5 to 35 GHz with HFET amplifiers. In addition, the 800 MHz receiver that is being constructed for the GBT will be used on the 140 Foot, giving a significant increase in sensitivity at this much-used frequency. The 140 Foot will be connected to the site-wide fiber optics network. This will distribute precise time and frequency standards over the entire site, and will allow transmission of control and IF signals from various telescopes to common points where equipment might be shared.

**United States Naval Observatory Operations**

In the first part of 1995 the NRAO will continue to operate an 85-foot telescope in Green Bank for the United States Naval Observatory (USNO). The antenna is part of a network which uses VLBI techniques for earth orientation measurements. This network is a joint project of the USNO, NOAA, and NASA. The data are used to determine the rotation rate and pole orientation of the earth. The accurate time and orientation information form the fundamental data needed for various radio and satellite-based navigation systems around the world, and for analysis of observations from synthesis radio telescopes like the VLA and VLBA. In addition, research in terrestrial science is based on these observations through the correlation of variations in earth rotation with large-scale weather patterns and ocean currents.

When the 85 Foot Telescope is not being used for VLBI, it monitors the arrival time and flux density of a select group of pulsars. This activity is coordinated by astronomers at Princeton, Oberlin, and NRAO. Pulsar observations are done between 20 and 50 hours each week at 610 and 327 MHz using feeds placed in offset positions on the telescope.

A new 20 meter antenna is under construction at Green Bank for use by the USNO with the earth to rotation network. Completion is expected by early 1995. It will have faster slew rates and greater sky coverage than the 85 Foot Telescope now in use which it will replace. It will be equipped with new S and X-band receivers which are now under construction at Green Bank.

For the first three months of operation on the new antenna, VLBI experiments will run both on it and on the 85 Foot. This phase is expected to happen in early 1995. After the 20-meter has been fully tested and the three-month tandem operation period is complete, the USNO will end its support for the 85 Foot Telescope. All USNO VLBI operations will move to the 20-meter.

Along with the new antenna, the USNO will install one or possibly two new hydrogen maser frequency standards in Green Bank. Although primarily used for a time and frequency reference for the VLBI system, the output from these masers will be available for general use around the site.

We will install a geodetic-quality GPS receiver in Green Bank, funded by USNO, that will be in place by early 1995. This will be part of a world-wide array of GPS receivers coordinated by NASA to monitor earth rotation and pole orientation. These data complement the earth orientation VLBI measurements.

The USNO, in cooperation with Naval Research Laboratory (NRL), has in the past supported a program of monitoring flux densities of galactic and extragalactic variable sources using two other 85-foot antennas as a single baseline interferometer. Galactic clouds are detected by their scattering effects on background sources. Intrinsic variables are also studied. This is the only observatory that does daily observations of Cygnus X-3 and SS433.

A new variable source monitoring instrument is being planned by NRL. Called the FAST array, it is a synthesis array of 20 antennas of 3-meter diameter and maximum baseline length of 0.7 km. It would map the whole sky at X-band every two days and at S-band every day with an rms sensitivity of about 10 mJy/beam. Although unfunded at present, the project could start within the next five years.

## V. 12 METER TELESCOPE

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

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

The 12 Meter has been a leader in the detection and study of high redshift line emission from galaxies, and significant effort will continue in this area. Studies of CO and CI are used to investigate the process of galaxy formation itself. So far, infrared-bright, molecular-rich objects have been seen at redshifts as large as $z = 2.9$. The objects thus far detected in CO will be examined for emission from other molecules and from atomic carbon, and searches will be made to find other forming galaxies.

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

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

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

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

The NRAO 12 Meter is the only millimeter-wavelength telescope in the U.S. operated full-time as a national facility. More than 150 visitors make use of the telescope annually.

It offers users flexibility and the opportunity to respond quickly to new scientific developments. Low-noise receiving systems at a wide range of frequencies, currently covering all atmospheric windows from 68 GHz to 300 GHz, are maintained. Operational reliability throughout is emphasized. Flexible spectral line and continuum backends allow the observer to match the instrument to the scientific goals. The development of multi-beam receivers has inaugurated a new era of high speed source mapping on angular scales complementary to those of the millimeter-wave interferometers. The new telescope control system offers great flexibility and provides a proven remote observing capability. It has also increased the efficiency and convenience of the 12 Meter Telescope. The experience gained will benefit future millimeter-array operation.

**Present Instrumentation**

As many as four receivers are mounted simultaneously at offset Cassegrain foci on the 12 Meter Telescope. Receiver selection is by means of a rotating central mirror and can be accomplished in minutes. The receivers are configured remotely from the control room with

Table V-1
12 Meter Receiver List

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

Notes:
1. Receiver noise is around 200 K SSB for most of the band, increasing somewhat at the high-frequency limit.
2. The 8-feed Schottky system is being upgraded to an SIS system. First testing on the telescope is expected in early 1994. Given noise performance is based on a prototype tunerless SIS mixer.

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

a computer-aided tuning system. A closed-cycle 4.2 K system capable of holding eight SIS receivers sharing the same dewar has been developed. A complete set of state-of-the-art, dual-channel SIS receivers is operational over the entire range 60-300 GHz. The arrangement of several receivers sharing the same dewar is extremely effective in terms of cost, manpower, and in operational demands. This new generation of receivers, available on the telescope now, represents the culmination of a four-year joint development plan between Tucson and the Charlottesville Central Development Laboratory (CDL).

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

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

The eight-feed Schottky system is being upgraded to use SIS mixers, thereby giving state-of-the-art sensitivity in all feeds. The upgraded system will be tested on the telescope in the spring of 1994, although not all eight mixers will be operational then. The time scale for full release to observers is set by the availability of high-performance SIS junctions. We hope the first observers will use the complete system later in 1994. An extension to a 32-feed SIS system is planned during the period of the Long Range Plan. The key to this development is the backend electronics. We have experimented with a prototype acousto-optic spectrometer (AOS), which might eventually have become an 8-spectrometer system to extend the usefulness of the 8-feed system and be expanded to serve a 32-feed system. However, new developments in high-bandwidth digital correlator systems have caused us to abandon this project in favor of new digital technology. A new correlator spectrometer is presently being designed for use with the GBT. This spectrometer will use custom-designed correlator chips. The first batch of these chips is currently under test in Charlottesville. The printed circuit boards designed for the GBT spectrometer, using these chips, will also be suitable for the 12 Meter Telescope 32-feed spectrometer, with little or no modification. Of course, a 32-feed system puts severe demands on the computer hardware and software. The telescope real-time control system has been completely replaced with a modern design which offers great flexibility for future developments. Already, remote observing, controlling the 12 Meter Telescope over a wide-area network, has been demonstrated, and is expected to become a more common mode of operation in the next few years. During 1993 we concentrated on improving the observing efficiency of the telescope and developing and implementing new observing techniques. The data acquisition rate will have increased by between one and two orders of magnitude. Construction of a suitable postprocessing environment based around a network of modern workstations is in progress.

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

**Antenna Improvements**

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

**Pointing.** With the improved surface accuracy, operation of the 12 Meter Telescope at the highest frequencies (~300 GHz) is becoming more productive. This puts a more critical demand on the pointing characteristics of the telescope. In order to improve the pointing, several upgrades have been implemented in the past year. First, the azimuth inductosyn angle resolver mount and cable wrap assembly were rebuilt to eliminate some mechanical hysteresis problems. Second, an improved real-time monitoring system for movements of the prime focus, utilizing a laser and x-y translation detector, has been installed. Third, a 2-axis tiltmeter on the azimuth bearing was installed. Finally, we intend to explore a higher level of automation, with the possibility of offset guiding on optical stars to give accurate tracking of weak sources.

**Polarimeter**

A polarimeter is under construction for the 12 Meter Telescope, which will be used to study linearly and circularly polarized emission in both the broad-band continuum and the spectral line mode. This device should become available early in 1994. The design uses an adjustable grid and plane reflector combination, and can be adjusted to cover both the 1 mm and 3 mm bands. The design is reasonably compact, and will become a prototype design able to give similar capability to the MMA.

**Telescope Control, Data Acquisition, and Data Analysis Improvements**

New enhancements continue to be incorporated into the telescope control system. The analog servo system that positions the telescope will be upgraded to a fully digital system. This should reduce the settling time required after telescope movement and could result in a ten percent or more improvement in the duty cycle of most observing modes (note that ten percent improvement in observing efficiency is equivalent to approximately 30 days of observing time in a typical season at the 12 Meter). The user interface has been enhanced to allow the observer more direct control over the telescope. The option of "batch sequencing" of the telescope will be introduced during 1994. The new on-the-fly observing mode, which was so successful during the holography session, will now become a routine mode for continuum observing. This technique will be made available for spectral-line observing in 1994. Such observing techniques as this will require more advanced data-handling facilities than presently available.

**Long Range Plan**

In addition to continued improvements in the 12 Meter, the Tucson staff will play a growing role in the development of the Millimeter Array. As the MMA project develops, there will be the necessity for real hardware design, prototyping, and testing, including multi-band, millimeter, and submillimeter-wave receivers, digital spectrometers, and continuum backends. Many of the projects already underway in support of the 12 Meter Telescope will become prototypes for, or otherwise contribute to, the eventual MMA project.

Specific improvements to be made to the 12 Meter Telescope instrumentation in the period of the Long Range Plan include the following.

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

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

# VI. THE MILLIMETER ARRAY

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

The MMA is a high-resolution imaging array comprised of forty 8-meter transportable antennas located at a high altitude site. An artist concept of the MMA is shown as Figure 3. The Millimeter Array combines the sensitivity provided by the collecting area of a telescope 50 meters in diameter with angular resolution < 0$''$.1, superior to that of the design goals of the Hubble Space Telescope, and it operates at frequencies 35-350 GHz at which thermal processes illuminate the sky. This unprecedented combination of sensitivity and angular resolution at short wavelengths will make available for astronomical investigation a wealth of unique opportunities and new science, including the ability to:

- Image the redshifted dust continuum emission and gas spectral line emission from evolving galaxies at epochs of formation as early as $z = 10$;
- Reveal the kinematics of optically obscured galactic nuclei and QSOs on spatial scales smaller than 100 pc;
- Reveal the isotopic and chemical gradients within circumstellar shells that reflect the chronology of stellar nuclear processing.

## Recent Progress

Within the last eighteen months the NSF Advisory Committee for Astronomical Sciences (ACAST) gave its enthusiastic endorsement to the MMA and suggested that the Foundation proceed with a three-year research and development phase for the project. We were asked to provide the NSF with a plan for the MMA design and development; we presented the plan to them in September 1992. The plan describes all aspects of the technical and environmental/site work that needs to be accomplished to put us in a position to begin construction for the array. We have attempted to make the MMA Design and Development Plan comprehensive: the plan incorporates not only the work that must be done to develop the hardware needed by the array but it also highlights the need for us to develop techniques for hardware fabrication and testing that will enable us to produce multiple copies of the various components that have nearly identical performance characteristics. The MMA Design and Development Plan anticipates initial funding in FY 1995.

**Site Evaluation.** Three sites are under active investigation for the MMA, two in the continental southwest and the third on Mauna Kea on the island of Hawaii. A transportable 225 GHz site-testing radiometer has been operated for a year or more on all three sites,

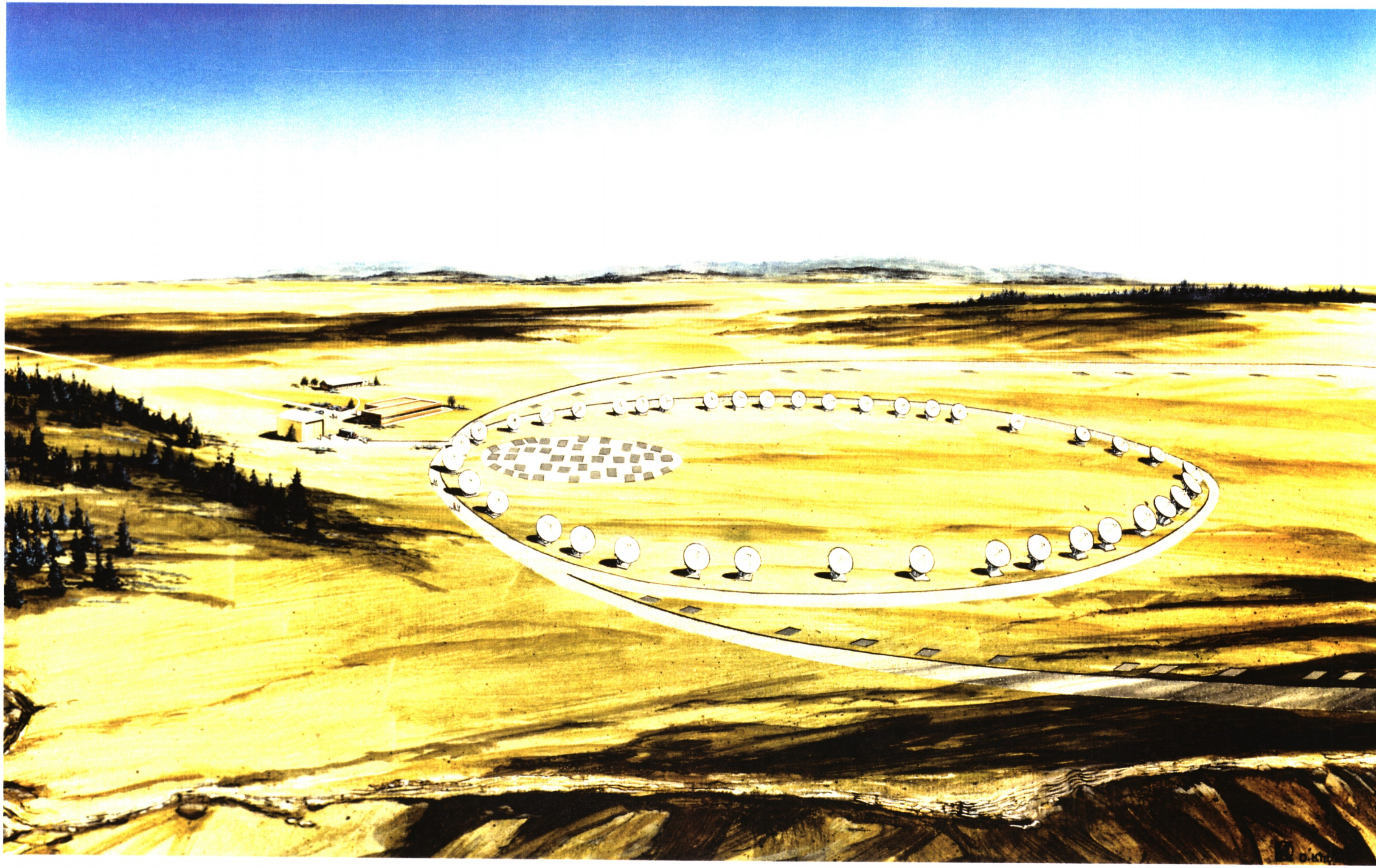


Figure 3. Artists concept of the MMA.

providing us with a measure of the millimeter-wave transparency and stability. All the sites seem capable of satisfying the scientific requirements for the MMA.

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

The scientific performance of the MMA will depend in very large measure on the site chosen for the array. This dependence is so critical for the MMA, and less so for the VLA, for example, because the dominant contribution to receiver noise is the contribution from water in the atmosphere. The sensitivity of the MMA depends on the transparency of the atmosphere. Similarly, the ability of the MMA to produce images with good dynamic range and high fidelity depends on the phase stability of the atmosphere. The atmospheric transparency is wholly beyond our ability to control, but the stability is a property for which we can find some compensation if we can measure and correct for phase fluctuations. Any such compensation will place demands on the antenna design, and for this reason it is important that the antenna design be completed prior to the time that the site selection is made.

Design of the MMA antenna is quite advanced. Figure 4 shows the current concept. It is a slant-axis, offset reflector that has the characteristic of being very compact and rigid so that it resists wind torques and wind deformations. The novel combination of an offset reflector and slant-axis mount reduces gravitational distortions of the surface to less than one-tenth of what they would be in a conventional alt-azimuth design. Finally, composite material is used for the backing structure to minimize thermal effects. The MMA antenna design meets the performance goals set for the array and does so with a simple, lightweight design.

**Receiver Design.** The current generation of SIS mixer receivers now on the 12 Meter Telescope meet the performance specifications for the MMA receivers. They do so however with mechanical tuners. Progress on simple tunerless mixers for the MMA is coming along well at the NRAO (CDL); prototype 200-300 GHz tunerless mixers are now on the 12 Meter Telescope in the 8-beam receiver.

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

**Cryogenics.** The MMA SIS receivers, being niobium superconductors, have to be cooled to 4K or below in order to function. The technique widely used to achieve 4K on a closed-cycle refrigerator is to add a Joule-Thompson (J-T) expansion stage to a standard Gifford-McMahon refrigerator. The Gifford-McMahon cools to 10-12K and the J-T stage goes down

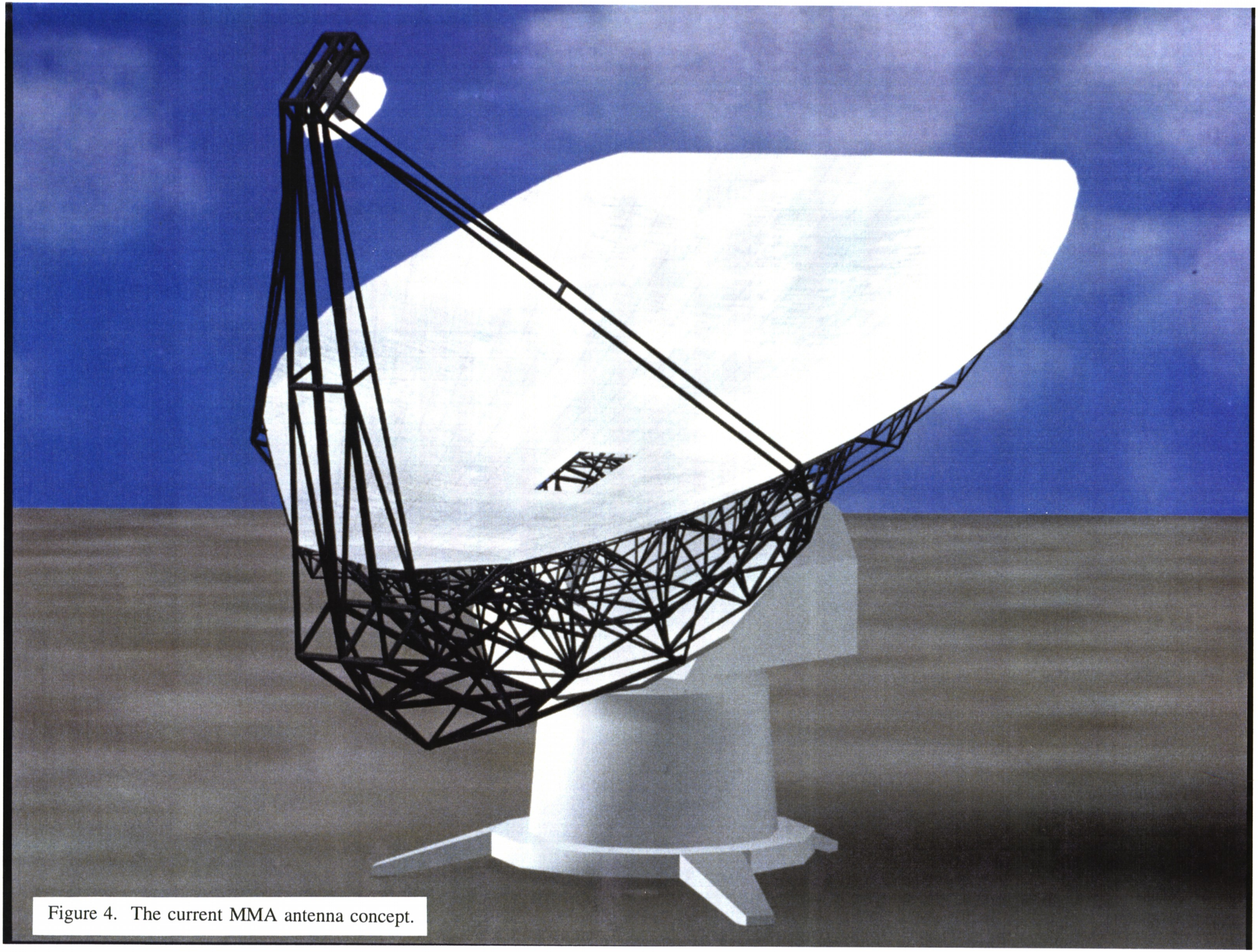


Figure 4. The current MMA antenna concept.

to 4K. Early versions of such a combination refrigerator at the NRAO and elsewhere have been mechanically complicated and unreliable.

The MMA needs a reliable 4K refrigerator. Given this need we have been experimenting for several years with possible prototype designs. Our current prototype is shown in Figure 5. It uses a new commercial Balzers Gifford-McMahon refrigerator with a 4K J-T stage of our design. The Balzers refrigerator is seen in Figure 5 as the cylinder at the bottom of the photo; the 4K stage is at the top. The two cylinders at the top are "hydrogen switches," again of our design that turn on the J-T stage only when the temperature reaches 10K or less, at which point it can function efficiently. The refrigerator shown here has been in use on the 12 Meter Telescope for six months with no failures and no downtime whatsoever, owing largely to its design simplicity. Its future performance will be monitored.

A small company in Tucson, AZ, has copied our design of the MMA 4K refrigerator and is now marketing it commercially. In addition, several firms have come to the NRAO interested in the design of the hydrogen switches.

**Construction Cost of the MMA**

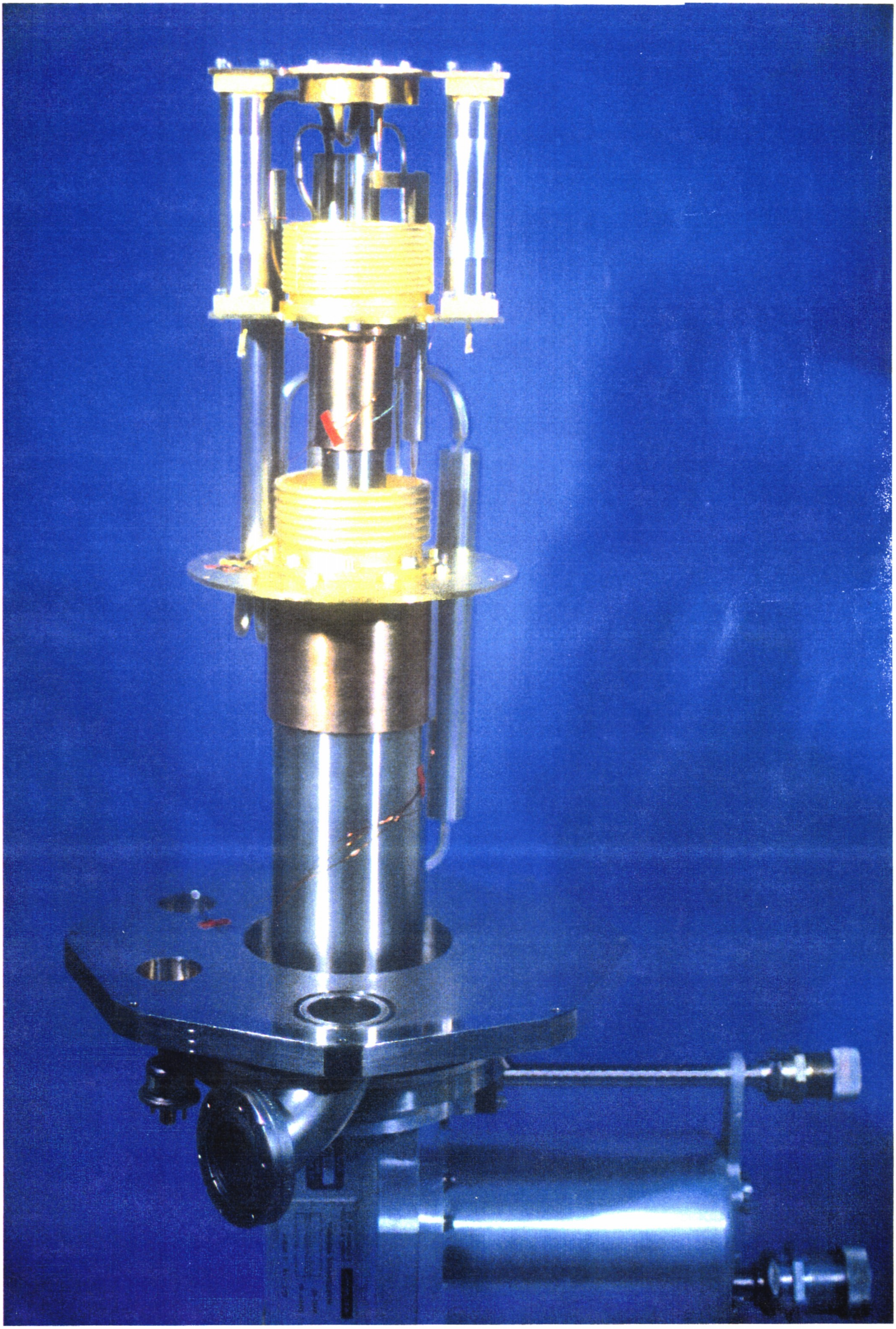
In the MMA proposal submitted to the NSF in 1990, the construction cost of the MMA was estimated to be $120M in 1990 dollars. In dollars of 1994, inflation alone would make the 1990 figure escalate to approximately $140M. Now that the antenna design is mature and we have built the type of SIS receivers we expect to use on the MMA, we can cost the major items of the array with much greater precision than was possible in 1990. We are in the process of reworking the estimate of the total construction cost. Currently we anticipate a cost of $150M in 1994 dollars, that is, our current estimate is roughly unchanged from our 1990 estimate in dollars of the same year. If the array is built over several years, as it must be, and inflation is taken into account, the MMA construction budget is estimated to be as shown in Table IX-3 of Section IX.

**MMA Advisory Committee**

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

The initial meeting of the Advisory Committee was in September 1993. The emphasis of this meeting was on the site evaluation process, antenna design work, and receiver development efforts. Some of the work recommended by the Committee has been done and is included in the discussion above.

Figure 5. The MMA 4K closed-cycle refrigerator.



# VII. COMPUTING

Computing systems at the NRAO are indispensable for NRAO operations and support of NRAO users and visitors. Computing systems are essential for instrument and telescope control, and also for the translation of raw data into scientifically useful images and spectra. Significant computation is required before scientific analysis can even begin. Radio astronomy is unlike many other scientific disciplines in that computer analysis is fundamental to the process rather than merely a useful adjunct to scientific analysis.

The importance of computing and image processing for radio astronomy is demonstrated by the pair of images in Figure 6. The image at the top shows a preliminary VLA image of the radio galaxy 3C 353 corrupted by the incomplete spatial coverage of the array and by atmospheric phase fluctuations, i.e., radio "seeing." The image below shows the same image after several **months** of computer time on one of the fastest computers at NRAO. The processing was required for proper calibration and imaging of the interferometer data. The technique used is exactly analogous to "adaptive optics" in optical astronomy done in a computer rather than with articulating mirrors. Higher resolution images of 3C 353 simply cannot be processed at the NRAO, due only to a lack of computing resources. This sort of imaging represents an example of scientifically important observations that are generally not being carried out simply due to a lack of data reduction facilities. 3C 353 is one of a class of dozens of bright radio galaxies for which this type of imaging is scientifically important and for which adequate computational facilities are not available (images courtesy of M. Swain).

## Strategy

Maintaining observational and scientific capability is the fundamental goal of computing at NRAO. Achieving this goal requires that staff and visitors at NRAO facilities have access to adequate computing resources, both computing hardware and software.

Unfortunately, budgetary pressures over the past few years have resulted in decreased investment in computing at NRAO. The last major investment in computing hardware occurred with the completion of the VLBA; significant computer purchases in 1992 and early 1993 were the result. Budgetary pressures in 1993 forced personnel layoffs which have reduced computing support to difficult levels. At this writing, indications are that the 1994 budget will be tight, forcing cancellation of plans to bring staffing levels in computing up to optimum levels and forcing the deferral of necessary maintenance and upgrades of NRAO computing facilities. A number developments are placing the current balance in computing in jeopardy:

- The VLBA is moving rapidly towards full operational status. Typical data sets are up to several gigabytes in size, resulting in up to hundreds of images. In 1993 there were only a few data sets; by 1995 there will be hundreds per year. NRAO will be forced to limit scientific use of the VLBA by 1995 due to inadequate computing facilities if the budgetary trends of the past few years continue.

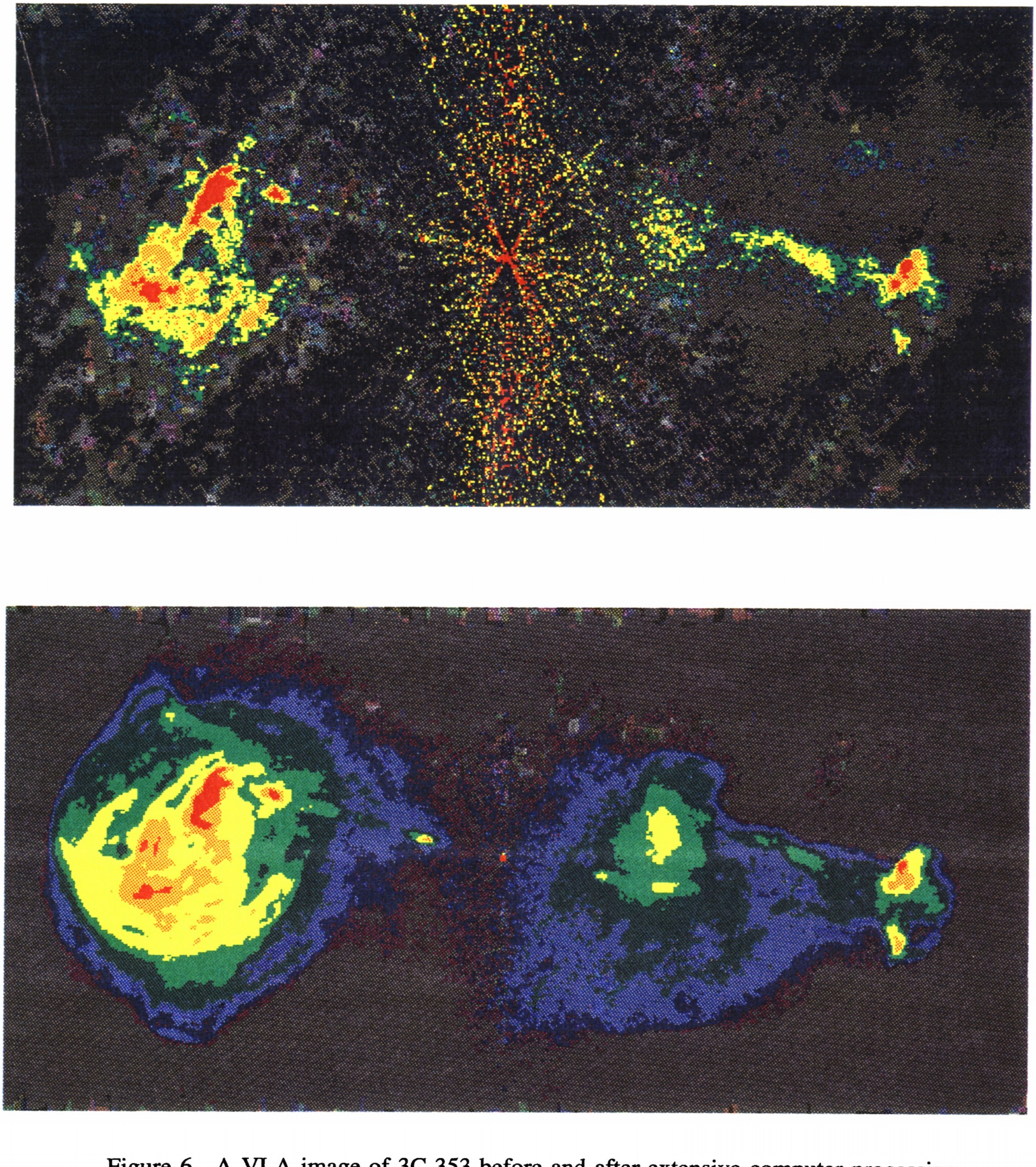


Figure 6. A VLA image of 3C 353 before and after extensive computer processing.

- The GBT will become operational near the end of 1995 or during early 1996. Efforts are underway to insure that software will be in place to handle GBT data reduction. Funding levels in 1994 are forcing a choice between fully supporting existing single-dish instruments in Green Bank and Tucson or preparing adequately for the GBT.
- Advanced experiments with the VLA are producing 1-2 orders of magnitude more data than typical experiments during the 1980's. These sorts of experiments strain the processing facilities at NRAO sites or at NRAO users' home institutions. The NRAO user community is, in effect, self-limiting its use of NRAO facilities and not tackling scientifically important problems because of limited computing resources in the community.
- Array receivers and rapid imaging techniques, combined with high resolution spectroscopy, are revolutionizing single-dish radio astronomy, with data rates 2-3 orders of magnitude greater than in the past. Hardware to handle these data are not in place at NRAO; necessary software developments have also been delayed.
- Scientific visualization techniques are going to become essential for dealing with the large data volumes from new instruments and receivers. Personnel limitations have prevented any significant work in this area. Two important problems in visualization are already known: the visualization of three dimensional spectral images, and the visualization of large raw data sets for calibration and editing purposes.
- By the end of the decade, the Millimeter Array should be nearing operation. Investments in computing (hardware, software, and algorithms) will be necessary if the MMA is to achieve maximum science return. Real-time imaging with the MMA is a scientific necessity which requires improvements in hardware and development of new software and algorithms.
- Plans to upgrade the VLA will result in a dramatic increase in the VLA's scientific capabilities and place heavy demands on computing to handle the increased data rates. Significant software development will be required to take full advantage of the VLA upgrade, especially in the area of wide bandwidth imaging and large field imaging.

Scientific computing is driven by the demands of new instruments and new techniques. The developments above are all placing huge demands on the data reduction facilities at the NRAO and the personnel required for software development. The current status quo in computing will prove very deleterious to the prospects for maximum science return from present and future NRAO instruments.

The basic strategy at NRAO for computing over the next few years is summarized below.

**Computing Hardware**. NRAO will strive to maintain adequate computer hardware in the face of increasing data rates and increasingly sophisticated processing algorithms. During 1993, minimal hardware purchases and upgrades were possible. The result was that only slight improvements in capability were achieved, in the face of rapidly rising demands. With the expected funding in 1994, serious problems are going to develop due to limitations in computing hardware. For example, the Array Operations Center in Socorro does not have computing facilities in place to handle the expected load from the VLBA. Once the VLBA is fully operational, a significant backlog of VLBA experiments will develop. The solution is to plan for catching up in 1995 and 1996, followed by long-term maintenance of NRAO computing hardware. In Tucson, planned upgrades of computing hardware are being deferred from 1994 into 1995. Beyond that, the developments of high resolution spectrometers and multi-beam observing techniques will result in both dramatic increase in scientific output and in increased demands for computing facilities by users of the NRAO 12 Meter Telescope.

The maximum return from NRAO's investment in advanced instruments and facilities will be achieved if adequate investment in computing hardware is maintained. During the early to mid 1980's, approximately half of all data reduction for NRAO instruments was done on computing facilities at the NRAO. The current situation is that NRAO can provide only about 5-10 percent of the data reduction capability for observations with NRAO instruments. The NRAO user community is already, in effect, limiting scientific observations because of insufficient resources for the data reduction. For example, there are relatively few projects of the scale of the 3C 353 observations because there is no way to reduce a large number of such experiments. The VLA could conceivably produce hundreds of similar data sets every year; most observers do not have the facilities to reduce such data at their home institutions; NRAO cannot supply such facilities at the present time.

The budgetary strategy outlined in the tables below addresses the problems in computing hardware at the NRAO by proposing a long-term solution of continual upgrade and improvements in current computing hardware at NRAO. Scientific computers have a useful life of only three to five years due the rapid increases placed on computing and the rapid improvements in computing capability available from industry. NRAO plans to move from a feast and famine approach to a more efficient strategy of continual upgrades and improvements. This strategy will allow NRAO to support its current crop of instruments (VLA, VLBA, 12 Meter, 140 Foot) and also be prepared for the new instruments coming: the GBT, the MMA, and the VLA upgrade.

**Software Development.** The main emphasis in software development at NRAO has been in two areas: supporting the main NRAO instruments in an operational sense (VLA, VLBA, 12 Meter, 140 Foot, and soon the GBT), and developing and supporting software systems for reduction of radio astronomical data produced with NRAO instruments. Limited budgets through 1994 have forced difficult choices and imposed limitations on NRAO's ability to deal with the instruments NRAO operates.

An important focus of the off-line reduction efforts at NRAO has aimed at bringing the AIPS++ software into operation, and building on that to provide advanced capabilities needed in all areas of radio astronomy: connected element interferometers, very long baseline interferometry, single-dish spectroscopy, and single-dish mapping. The Observatory is also struggling to keep its current flagship software products, AIPS and UNIPOPS, operational until AIPS++ is fully available in the next 2-3 years. Significant effort must go towards developing the algorithms required by the VLBA and orbiting VLBI software development.

Current personnel resources for software development are inadequate. The long-term plan reflects necessary increases in personnel if NRAO is to meet its obligations to the community. There are urgent needs for additional people for AIPS support (one individual likely to be appointed in 1994), AIPS++ development (one position is probably going to be deferred due to budgetary restrictions), and single-dish/UNIPOPS support (funds are unlikely to be available in 1994). Software development in support of the VLA is stable for the near term, although the planned VLA upgrade will impact this area. The VLBA is critically short several software positions. As a result, bringing the VLBA up to full operational status has been delayed. In the long term, as the AIPS++ software is brought to full operational status, the people currently working in AIPS support will be able to transfer to AIPS++ support. The modest increases in personnel for off-line reduction proposed in the plan will probably be available for efforts related to software development for instrumental development during the 1997-1999 time frame.

NRAO will also be investing in several new areas of software development. In particular, advanced scientific visualization should be coupled to the data reduction systems needed by NRAO users, or else astronomers will not be able to deal with the large data rates from newer instruments and observing strategies. Algorithmic research on imaging techniques has greatly slowed at NRAO due to personnel limitations. The proposed plan addresses these concerns by proposed increases in personnel assigned to certain key areas: scientific visualization and imaging algorithms.

Finally, user support has suffered due to personnel limitations. Extremely long response time for resolution of software problems is an unfortunate consequence of the current staffing levels. The Long Range Plan addresses this partially in 1995. Full resolution of this problem will be achieved as AIPS++ comes fully on-line during the late 1995 to 1996 time frame.

In summary, current staffing levels are inadequate to support and develop software for current and planned NRAO instruments. Efforts in several areas (scientific visualization, advanced image deconvolution techniques, single-dish analysis, AIPS support and development, and parallel processing methods for radio astronomy, to name a few) have been curtailed or halted due to limits on the available personnel. NRAO has been forced into the uncomfortable position of putting most of its long-range software development in the AIPS++ basket in order to provide for the development of future capabilities.

**Single-Dish Computing**

The largest effort in single-dish computing is focused on designing and implementing the control system for the GBT. That effort will begin the transition from implementation and integration to operational status during the 1995-96 time frame. GBT computing is the highest priority in the single-dish area. Unfortunately, budgetary restrictions during 1993 and 1994 have forced an inadequate level of support for the support and development of single-dish analysis software. The main analysis package for observational data from the NRAO 140 Foot and 12 Meter Telescopes is the UNIPOPS package. UNIPOPS is relatively stable, but is inadequate in the face of rapidly developing observing techniques such as on-the-fly (OTF) mapping or multi-beam observations. Although AIPS++ will deal with these types of new observing techniques within the next 1-2 years, this has left a gap in the support of current techniques. OTF mapping is an extremely promising technique, but must currently be restricted due to the unavailability of software and hardware to reduce OTF data rapidly and reliably. The procurement and personnel plans below address these problems by proposing a new position for computing and appropriate hardware upgrading. In the interim, NRAO must restrict the use of these new techniques.

The long-term strategy for single-dish data analysis is clear: single-dish data analysis will be an integral part of the AIPS++ package. The benefit of this strategy is that a synergy between the techniques needed for single-dish and interferometric analysis will develop. For example, both techniques can produce large 3-dimensional spectral image cubes. There will be a large similarity in the analysis and visualization methods needed for such images.

**VLA Computing**

The most urgent need faced by the VLA is for upgrade and replacement of its on-line control system. The current system is over eight years old, and is starting to show its age in terms of reliability and maintenance costs. Initial planning and design for the upgrade was scheduled to begin during 1994, but may now need to be delayed into 1995 due to the tight 1994 budget. This is a risky strategy, but the current constraints leave NRAO little choice. The budget plan reflects planning and design work in 1995, followed by implementation in 1996. The upgrade will be the minimum to keep the VLA operational, but will also provide the foundation needed for the eventual VLA upgrade.

**VLBA Computing**

Estimates of the computing requirements for reducing VLBA data were based on a relatively modest model of VLBA observing: detailed images of sources produced from long integrations. It now appears that surveys and rapid imaging experiments will be a significant portion of VLBA observing, resulting in up to hundreds of images from a single experiment. VLBA data sets are typically much larger than VLA data sets because of the multiple frequency bands and short correlator dump times which must be used. The full impact of VLBA data reduction requirements has not yet been felt; the current crop of high-end workstations available at the AOC will not be adequate for VLBA data reduction for the long term. A medium to large VLBA data set will probably require dedicated access to a ~80-100 MIPS machine for several weeks by a single user. There are currently only four such machines available at the AOC and two in Charlottesville. These machines are adequate to handle only a small part of the data load produced by the correlator. By the end of 1994, it is likely that NRAO will be forced to limit observations using the VLBA to the simpler experiments originally planned rather than the more scientifically productive surveys and global experiments that are scientifically valuable as a simple consequence of inadequate computing resources.

**The AIPS++ Project**

The Astronomical Information Processing System (AIPS++) is a software system primarily for astronomical data analysis being developed by an international consortium of institutions mainly supporting radio telescope instrumentation. The members of this consortium are: Australia Telescope National Facility, Australia; Berkeley-Illinois-Maryland Array, USA; Herzberg Institute for Astronomy/Dominion Radio Astrophysical Observatory, Canada; Netherlands Foundation for Research in Astronomy, The Netherlands; Nuffield Radio Astronomy Laboratory, UK; Tata Institute for Fundamental Research/NCRA, India; and the NRAO. The AIPS++ project is planning initial delivery of a beta release at the end of 1994, followed by a full release during second quarter 1995. AIPS++ should achieve full functionality near the end of 1995 or during early 1996. During 1995 and 1996, support personnel currently working in the AIPS project will be transferred over to AIPS++. This plan is an attempt to provide the smoothest possible transition for the NRAO and AIPS user communities to AIPS++, within the usual budgetary and personnel constraints NRAO faces.

Table VII-1
**Software Development Personnel Plan**

| New Positions | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 |
|---|---|---|---|---|---|---|
| VLBA Operations | 2 | | | | | |
| VLA/VLBA Operations | 1 | | | | | |
| AIPS Support | 1 | | | | | |
| AIPS++ Support | | 1 | | | | |
| Single-Dish Support | | 1 | | | | |
| Algorithm Development | | 1 | 1 | | | |
| Visualization | | 1 | | | | |
| User Support | | 1 | | | | |
| GBT Operations | | | 1 | | | |
| MMA Support | | | | TBD | TBD | TBD |
| MMA Operations | | | | TBD | TBD | TBD |

**Computer Research Equipment Plan 1994-1999**

The table below shows the overall computer plan. The large bump during the 1995 to 1997 time frame is caused by the combination of extremely lean budgets during 1993 and 1994 and the start-up of the VLBA during 1994 and the GBT during 1996.

Table VII-2
**Computing Equipment Plan**
(thousands of dollars)

| NRAO Site | 1993 Actual | 1994 Est. | 1995 | 1996 | 1997 | 1998 | 1999 |
|---|---|---|---|---|---|---|---|
| Tucson | 69.9 | 32 | 155 | 195 | 60 | 90 | 50 |
| Green Bank | 13.5 | 35 | 185 | 260 | 215 | 85 | 125 |
| Socorro - AOC | 57.8 | 45 | 395 | 290 | 175 | 150 | 150 |
| Socorro - VLBA | 0 | 35 | 365 | 355 | 135 | 150 | 110 |
| Charlottesville | 43.5 | 10 | 210 | 170 | 140 | 75 | 115 |
| Total Computer Equipment (k$) | 184.7 | 157 | 1310 | 1270 | 725 | 550 | 550 |

# VIII. EDUCATION PROGRAM

With observing sites and scientific offices located in ten states and the territory of the U.S. Virgin Islands, the NRAO has a public visibility that is being exploited to further science awareness and science education. Formal education in the form of supervised research experiences with the NRAO radio telescopes is provided to professional and pre-professional scientists. Programs that emphasize how scientists work and what they hope to accomplish are provided to secondary science teachers and interested amateur astronomy groups. Finally, public educational activities are sponsored at all the NRAO observing sites in the form of guided and self-guided tours, public access to the images of objects in the radio sky, and descriptions of the nature of objects studied by radio astronomers. A few of the highlights of the NRAO educational program are summarized below.

## Professional and Pre-Professional Education

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

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

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

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

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

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

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

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

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

In addition to the REU summer students there are students working at the NRAO from other institutions. During the summer months students not supported by the NRAO REU program come from other institutions at their own expense to work with the NRAO scientific staff and to participate in the NRAO student program. We expect a steady growth in the summer student program through the period of the Long Range Plan.

**Scientific Workshops and Symposia**

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

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

Synthesis imaging workshops are held every three years. More than 115 students (mostly graduate students) attended the most recent workshop, the third in six years. Thirty-one NRAO staff scientists developed the theory and application of aperture synthesis in various lectures that were given over a ten-day period. The proceedings of all the workshops have been published. We expect this series to continue.

The VLBA promises to make VLBI readily accessible to the large number of users accustomed to observing with the VLA. In order to accelerate the process, the NRAO focussed the recent synthesis imaging workshop on the techniques of VLBA imaging. Thirty-one lectures were presented by 24 lecturers. About 100 graduate students and others attended for approximately ten days. We expect to sponsor synthesis imaging workshops in the future that highlight both VLA-related and VLBA-related imaging theory and practice.

**Tucson Scientific and Technical Meetings.** In the last few years, the NRAO in Tucson has hosted a number of international, specialist scientific and technical workshops. These have been well attended by the leading world authorities in the respective fields as well as representatives from high technology industries. In 1992 a workshop was held on "Remote Observing," hosted jointly with the Royal Observatory, Edinburgh. The proceedings of this workshop have been published by World Scientific Publishing. In 1993 a specialist workshop on "Next Generation Digital Correlators" was held. Proceedings of this workshop are available from NRAO in Tucson. Also in 1993, NRAO sponsored jointly with Steward Observatory a symposium, in "Infrared Cirrus and Diffuse Interstellar Clouds." The proceedings of this symposium are to be published in the ASP Conference Series. In May of 1994, NRAO Tucson is hosting an international workshop on "Multi-feed Systems for Radio Telescopes;" proceedings will be published also in the ASP Conference Series. For 1995, a major scientific symposium is planned, commemorating the 25th anniversary of the discovery of the CO molecule with the 12 Meter Telescope, then known as the 36 Foot.

## Public Education

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

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

**Green Bank Educational Program**

**General Public Tours** (about 17-20,000 visitors yearly). The tour season begins on Memorial Day and lasts through the end of October. From Memorial Day through mid-June and from Labor Day through the end of October, tours run on weekends only. During the rest of the season, tours run daily. Three tour guides are hired for the season. They are college students, science, engineering, or science education majors.

A tour consists of an introductory talk given by the guide, a slide show, and a bus tour of the telescopes. In addition, the guides offer demonstrations of lasers and retro-reflectors, cryogenics, and superconductivity. The guides assist school groups in using small radio and optical telescopes.

**Science Teachers Institute** (in partnership with West Virginia University). Two 2-week programs a year for science teachers from around the country. Thirteen institutes have been successfully completed since 1987; 327 teachers have participated. While at the NRAO, participants investigate problems using the 40 Foot Radio Telescope, receive lectures on general astronomy and on current research in radio astronomy, build a scientific instrument to use in the classroom, and participate in education discussions and activities. This program requires much participation from NRAO staff as lecturers during the day and evening, as hosts during in-depth tours of all of the facilities, and as advisors to small and large groups of participants.

Participants have academic year duties as well. They must host four workshops for teachers in their home state and develop and implement project-based units with their students. The number of teachers indirectly benefitting from our institutes is estimated at 15,000. It can be estimated that over 100,000 students have benefitted from our institute program over the past seven years as well, using an average of four classes of 21 students/teacher/year.

The current grant carries through to the spring of 1994. A proposal to renew the program was submitted to the NSF in August 1993.

**National Youth Science Camp (NYSC).** Two graduating seniors are chosen from each state in the U.S. to participate in the NYSC. During their three-week stay in West Virginia, they explore many topics in science. They attend lectures given by practicing scientists, take tours, and also study some topics in depth. These in-depth investigations are called Directed Studies. Small groups of campers, typically 10-12, are allowed to participate in a given Directed Study. NRAO offers two overnight directed studies at the 40 Foot Telescope. The campers are given operating instructions and access to our library before they begin their overnight. They usually decide for themselves what they wish to do. Usually they embark on several observing projects, with smaller groups working on each one. We also give the entire delegation a tour of the Observatory.

Since its beginning in 1962, the National Youth Science Camp has served about 3000 students. NRAO has been involved, sometimes to a much greater extent than outlined above, with all of these students.

**U.S. Department of Education Science and Math Initiatives.** This is part of a program offered by Frostburg State College, Glenville State College, and Fairmont State College. Each sponsored program exposes about 40 disadvantaged high school students to different areas of science. NRAO is one of several science institutions that has participated in these projects (to the largest extent with Glenville State College). We have offered in-depth tours, interviews with scientists, and observing at the 40 Foot. As part of the Glenville State College Project, one of our staff scientist acted as advisor to a small group of students who decided to do astronomy projects during the school year. Some of their projects involved remote use of the 40 Foot Telescope.

**Extended Visits.** Small groups of students use the 40 Foot. These groups come from colleges, Governors' Honors Academies, gifted programs, and classroom teachers who have participated in our institutes or chautauqua programs. These visits occur in summer and throughout the school year. Their stays range from several hours to a week. While at NRAO, students may ask to speak to a scientist or to take an in-depth tour of the 140 Foot or Green Bank Telescope site. Before visiting for an extended observing run, students must submit an observing proposal which models 140 Foot observing proposals in form. A total of 8356 people were served during the period 1990-1994.

**Society of Amateur Radio Astronomers (SARA).** SARA holds its annual conference at Green Bank. Members gather to share information on home-made radio telescopes, receivers, data logging software, etc. They receive technical advice and assistance in calibrating their components from NRAO engineers while on site. SARA is committed to sharing their knowledge with others, particularly teachers and students. Our assistance to them is repaid through the educational efforts of SARA.

**Hands on Science (HOS).** This program, developed by a nonprofit parent/teacher group in Maryland, consists of after-school "recreational" science activities in one, one-hour session each week (eight weeks per class). The program was offered to K-6 grade students. The program is currently being offered at the local elementary school. Many of the class leaders have been NRAO employees: engineers, scientists, and technicians. The program is coordinated by the NRAO education officer in Green Bank. We have offered HOS for three years and expect to continue in the future.

**School Group Tours and Extended Visits.** School group tours can be arranged throughout the school year. The tours are customized as much as can be according to the grade level of the students, student interests, the length of time they wish to spend at the Observatory, and so forth.

**Elderhostel.** This is a one-week program for groups of 25-30 older adults co-hosted by Glenville State College and the NRAO. The program is held in Green Bank. NRAO provides lodging, tours, a talk or two, and instructions on 40 Foot Telescope use. The hostelers use the 40 Foot under the guidance of Glenville State College staff. Glenville State College staff provide the general astronomy instruction.

**Chautauqua.** This is a three-day intensive workshop for professors of small colleges. Traditionally, these professors are not active in research. The chautauqua is a way for them to update themselves in current science and technology. The chautauqua requires the participation of several of our staff. Astronomers and engineers offer lectures on science, the GBT, how receivers work, while others lead the group in in-depth tours of the Observatory. The participants also receive instruction on the use of the 40 Foot. Several initiate 40 Foot Telescope observing projects with their students; some return to Green Bank, others use the telescope remotely. The chautauqua program has been supported for six years; thirty professors participate each year.

**Remote Access to NRAO.** Access to 40 Foot Telescope data is now possible through Internet. Teachers, precollege students, and undergraduate students have requested observing time, sent observing programs, and retrieved 40 Foot data via e-mail. Scientists have also been contacted by students through the Internet, most formal through the Science by e-mail program. Marshall University (Huntington, WV) is spearheading this program for five science classrooms in rural southwestern West Virginia.

**Socorro Educational Program**

The VLA Visitor Center, opened in 1983, hosts at least 15,000 visitors annually. These visitors come year-round from throughout the United States and from around the world. Comments written in the center's sign-up book indicate that for many tourists the VLA is a specific, planned stop on their trip. Many tourists call or write NRAO well in advance of their trip to obtain information about visiting the telescope.

The visitor center features an automated slide show with audio narration, displays on the history of radio astronomy, the operation of the VLA and VLBA, and rotating displays on scientific results from the VLA and VLBA. The visitor center is the starting point for a self-guided walking tour of the central portion of the VLA site. A free brochure provides background information for visitors making the walking tour. Signs at stops on the walking tour explain the components of the VLA visible from each stop. The walking tour provides visitors with close-up views of an antenna, the antenna assembly building, the transporter vehicles, and, from an outdoor balcony on the control building, views of the VLA's electronics and control rooms.

Though the visitor center is not staffed, we provide regularly scheduled guided tours on summer weekends, using NRAO summer students as guides. Throughout the year, by appointment, we provide staff tour guides for school groups and other organizations. The number of such guided tours averages about 35 annually.

Future plans for the VLA Visitor Center focus on two main themes: evolving and improving the displays and providing staffing for the center.

Displays at a facility such as our visitor center must constantly evolve to reflect continuing technical and scientific developments. We are looking beyond that normal evolution, however, to improve the methods used to convey information to the public. One aspect of this improvement is to incorporate more hands-on or interactive displays. During 1994, we plan to install a working microwave radiometer sensitive enough to detect the radio flux from a person's hand placed over its feedhorn. We are exploring other ideas for active exhibits. The visitor center currently includes two videotape playback setups, and we hope to produce new program material for these. In addition, we are investigating ways of using inexpensive personal computers to display recent scientific images and explanatory text, possibly interactively, to visitors.

The long-term evolution of the visitor center displays will necessarily involve interaction with professionals at museums and other observatories. We want to keep abreast of technology available for education as well as of newly developed techniques for successfully imparting the excitement of science to the general public.

While visitor comments indicate that the self-guided tour is a well-liked feature, we know that a knowledgeable guide makes the visitor's experience significantly more informative and rewarding. Many of those who receive a guided tour tell us that they previously did the walking tour, but greatly appreciated the subsequent chance to hear explanations and to ask questions of a guide. Personal interaction with visitors also provides feedback on the effectiveness of the displays and on areas where visitors have questions and possible misunderstandings about astronomy. Our year-round, by-appointment tour program has been reaching schools throughout New Mexico and surrounding states, but is now operating at about the maximum capacity we can handle without staff members dedicated to this purpose. With staffing for the visitor center, we could publicize this service more widely and reach many more schools. In addition, we could initiate daily tours at a specific time or times, advertise this fact, and allow tourists to plan their visits to take advantage of this feature.

For these reasons, we are exploring ways of providing full-time staffing at the VLA Visitor Center. We see two primary methods of doing this. The first would be to obtain funding to staff the center with full-time employees. We are exploring programs at the national and state level that might support this. The second alternative is to recruit and train volunteers for this purpose. Using volunteers would still require staff time for training, supervision, and coordination, and would require resolving questions about liability, transportation, and other logistical aspects. We are exploring the feasibility of using volunteers recruited from either the public at large or from various organizations, such as amateur astronomy groups.

The two staffing models outlined above are not necessarily exclusive. A small full-time staff could be used as a core of expertise and for the required oversight and coordination, and their effect greatly multiplied through the use of volunteers. A phased approach to staffing the visitor center may prove the best way of accomplishing this goal, and NRAO is examining these alternatives.

**Tucson Education Program**

NRAO staff scientists in Tucson continue to work closely at all levels with Steward Observatory, at the University of Arizona. NRAO scientists already help with supervision of graduate students, but in the near future will also become more involved with student education. Lectures on astronomical techniques will be given jointly by NRAO and Steward Observatory staff.

The 12 Meter Telescope is included in the special tours done by Kitt Peak National Observatory in connection with their monthly Public Nights. About fifty people visit the 12 Meter on each of these occasions. Many special tours of the 12 Meter Telescope are arranged upon request throughout the year. The participants range from groups of professional engineers to amateur astronomers and interested members of the public. There is a model of the 12 Meter Telescope and other material displayed prominently at the Kitt Peak Visitors' Center, which is visited by 80,000 each year.

**VLBA Sites**

Several of the VLBA stations are either prominently visible or well-known in their local communities. These stations are visited by a significant number of people each year. Though these stations are minimally staffed, the on-site technicians have provided information and guided tours to numerous groups, including school classes, amateur astronomers, amateur radio groups, and professional engineering organizations. NRAO has prepared an informational brochure on the VLBA, and each station is provided with a stock of these brochures for distribution to visitors. Each station also is provided with a set of slides and book of caption information to assist the site technicians with their presentations to the public. As the VLBA ramps up to full operation, we will expand efforts to keep the site personnel aware of the scientific achievements of the VLBA to assist them in their presentations. At each VLBA station, NRAO has erected an informational sign describing the purpose of the instrument for interested passersby.

Two VLBA stations are located near major optical observatories, at Kitt Peak, Arizona, and Fort Davis, Texas. At these locations, NRAO works with their visitor centers staff to provide information on the radio telescope at their site and on radio astronomy in general. NRAO is working with the NOAO staff to produce a new display on radio astronomy for their Kitt Peak visitor center.

## IX. BUDGET AND STAFFING PROJECTIONS

The projected operations budgets for the Observatory through 1999 are given in Table IX-1. The budgets are for NSF operations only. Construction costs are not included. There is only one significant increase beyond routine inflation: Transfers to the operations budget from the GBT construction budget of personnel required to operate the GBT. This is shown as a separate line.

Table IX-1
**NRAO Operations Budget Projections**
($ in 000's)
(NSF Operations Only - No Construction)

| | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 |
|---|---|---|---|---|---|---|
| Salaries | $16,023 | $16,720 | $17,400 | $18,100 | $18,800 | $19,560 |
| GBT to Ops | 0 | 800 | 1,165 | 1,200 | 1,260 | 1,310 |
| | $16,023 | $17,520 | $18,565 | $19,300 | $20,060 | $20,870 |
| | | | | | | |
| Benefits | 4,967 | 5,520 | 5,850 | 6,080 | 6,400 | 6,680 |
| Other | 8,700 | 9,320 | 9,600 | 9,890 | 10,180 | 10,500 |
| NSF Ops | $29,690 | $32,360 | $34,015 | $35,270 | $36,640 | $38,050 |

NRAO has two new initiatives — the MMA and the VLA Upgrade. Projected total costs are presented in Table X-2 in possible multi-year distributions. These costs are estimated costs and the figures given are in dollars for that year, that is, an attempt has been made to include inflation.

Table IX-2
**NRAO New Initiatives**
(Estimated Costs, $ in 000's)

| | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | Total |
|---|---|---|---|---|---|---|---|---|---|
| Millimeter Array | $1,000 | $4,000 | $20,000 | $35,000 | $35,000 | $35,000 | $35,000 | $10,000 | $175,000 |
| VLA Upgrade | 0 | 2,000 | 6,000 | 6,000 | 6,000 | 6,000 | 5,000 | 2,000 | 33,000 |

Note: The distributions over years shown are to illustrate possible funding scenarios; phase and duration are arbitrary.

Projected staffing levels for all activities at the Observatory, NSF operations, construction projects, and non-NSF research, are given in Table IX-3. The growth in the operations staff is minimal following the return to Green Bank Operations of personnel now on the GBT budget. Seven positions are added in 1995 for the VLBA to complete staffing for that facility at the minimum required.

Table IX-3
**NRAO Personnel Projections - Operations and Construction**
(Full Time-Y/E Ceiling)

| | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 |
|---|---|---|---|---|---|---|
| Base Operations | 405 | 427 | 430 | 433 | 433 | 435 |
| GBT Construction | 23 | 8 | - | - | - | - |
| Millimeter Array | - | 3 | 5 | 15 | 24 | 44 |
| VLA Upgrade | - | - | 6 | 10 | 10 | 12 |
| Non-NSF Research | 11 | 11 | 12 | 12 | 12 | 12 |
| Personnel Total | 439 | 449 | 453 | 470 | 479 | 503 |

Non-NSF funded research is shown in Table IX-4, with actual figures for 1991-3 and projections for 1994-6. Estimates beyond 1996 are too uncertain to be worth listing. Notice that funding is complete for four projects. The common-cost recovery funds projected for 1994 are down significantly from 1993 and are expected to decline further in 1995. Aside from projects that consist largely of pass-through funds (USNO Hawaii and Green Bank antennas), the non-NSF research total is $\lesssim$ 10 percent of NSF operations.

Table IX-4
**NRAO Non-NSF-Funded Research**
($ in 000's)

| | Actual | | | Projected | | |
|---|---|---|---|---|---|---|
| | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 |
| USNO Interferometer Addition* | $429 | $199 | $171 | $258 | $0 | $0 |
| USNO Interferometer Operations | 856 | 804 | 839 | 580 | 625 | 650 |
| USNO Hawaii Telescope* | 317 | 1,885 | 224 | 35 | 0 | 0 |
| USNO - GB Antenna & System | 0 | 0 | 935 | 3,808 | 500 | 540 |
| NASA OVLBI Earth Station | 646 | 993 | 883 | 735 | 500 | 500 |
| NASA OVLBI Science | 197 | 432 | 643 | 1,934 | 1,000 | 1,300 |
| SSTI* | 39 | 0 | 0 | 0 | 0 | 0 |
| VLA - 7 mm Project* | 0 | 0 | 610 | 210 | 0 | 0 |
| Miscellaneous | 70 | 29 | 84 | 50 | 50 | 50 |
| TOTAL | $2,554 | $4,342 | $4,389 | $7,610 | $2,675 | $3,040 |
| CCR | $670 | $802 | $1,356 | $884 | $700 | $725 |

* Project Funding Complete