US/GR BK/

Long Range Plan
2002 - 2006

NRAO

National Radio Astronomy Observatory

A facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

NRAO

NATIONAL RADIO ASTRONOMY OBSERVATORY

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Long Range Plan 2002-2006

I.1 Summary Perspective

Beginning in 2001, users of the National Radio Astronomy Observatory (NRAO) realized the scientific benefit of the full suite of second generation NRAO telescopes, instrumentation, and algorithmic tools. All of the telescopes that were built at the NRAO in the 1960s, as a way to establish a national program in radio astronomy in the United States, have been replaced by three unique pre-eminent research facilities: the Very Large Array (VLA), the Very Long Baseline Array (VLBA), and the Green Bank Telescope (GBT). Together these telescopes provide astronomers with access to the entire radio spectrum from 100 MHz to 100 GHz, and they do so with the sensitivity necessary to investigate extremely faint, distant objects at an imaging resolution the astronomer can select, from arcminutes to milli-arcseconds.

Scientists have enthusiastically exploited the opportunities the NRAO telescopes provide: the number of scientists and students using the VLA grew by 17 percent in 2000 as compared to 1999, and the number using the VLBA grew by more than 8 percent over the same one-year period. The GBT welcomed its first science users in 2001. The growth in the NRAO user base, has led to the need to make the NRAO facilities as fast and versatile as possible, so that many users with demanding scientific requirements may be served. Meeting this need is the first of the key elements of this Long Range Plan. Specifically, the NRAO users:

- Employ observations made at the NRAO with complementary observations made using other facilities (ground-based telescopes or NASA spacecraft) in order to gain a comprehensive picture of the physical nature of the astronomical object under study;
- Require a suite of integrated hardware and software capabilities to make effective use of the NRAO telescopes to achieve their science objectives;
- And desire to make use of archival data wherever possible in order to speed their research progress.

User requirements such as these call for a thorough development of the observing facilities, the telescopes together with the system for data management and archive. Such an integration of the instrumentation and data management is the second key element of this Long Range Plan.

Scientific discovery is the motivator for all astronomers. Discovery comes from looking more carefully than has been possible, looking in greater detail, or looking where it has not been possible to see previously. New observing capabilities enable discovery. For this reason, the U.S. science community continually encourages the development of new or improved observing facilities, and it does so by regularly prioritizing its needs. Over the last two decades, the National Research Council Board of Physics and Astronomy has recommended at the top of its priority list for new ground-based astronomical facilities construction of the NRAO Millimeter Array, a project that has now evolved into the international Atacama Large Millimeter Array (ALMA). ALMA will give astronomers the capability for precision imaging in the decade of frequencies that lies higher than that accessible to the VLA, VLBA, or GBT, namely, over the range 100 GHz to 1000 GHz. With ALMA, astronomers will see where it has not been possible to see clearly before. In addition, astronomers seek to see with greater clarity and in greater detail than is possible now at lower frequencies. This capability is readily achievable by a comprehensive replacement of the instrumentation on the VLA and the addition of new antenna elements, a project that is known as the Expanded VLA (EVLA). Initiation of the construction of ALMA and the EVLA is the third key element of this Long Range Plan.

Finally, recognizing that the facilities of the NRAO in fact belong to the people of the United States, a vigorous program to communicate to the public the achievements and excitement of radio astronomy is the fourth key element of the Long Range Plan. Over the period of this plan, the Education and Public Outreach (EPO) program of the Observatory will be developed and strengthened so that it can effectively serve the public, students, and pre-professionals.

The NRAO Long Range Plan 2002-2006 rests on the four cornerstone elements noted above:

- Effective operation of the NRAO telescopes to serve the growing user base of radio astronomy;
- Full development of the NRAO observing facilities and their integration with a comprehensive end to end data management system;
- Begin construction of ALMA and the EVLA;
- And develop and strengthen the NRAO Education and Public Outreach program.

We plan to acheive the following state for the NRAO at the end of 2006: several years of experience with a smoothly running, efficient telescope operation organized by activity in an Observatory work breakdown structure; an established instrumentation development program that includes a process for university group involvement; integrated end to end data management systems in place; ALMA starting interim operation and EVLA testing the new correlator; and a vibrant and effective program of education and public outreach.

I.2 The Scientific Challenges

The recent National Research Council (NRC) review of astronomy for the decade 2001-2010, *Astronomy and Astrophysics in the New Millennium,* and the 1997 NRC report on *A Strategy for Space Astronomy and Astrophysics* highlight the following key problems for research emphasis:

- The study of the early Universe when the first galaxies formed their first generation of stars.
- The formation of black holes: Did they nucleate the first galaxies? How do they evolve?
- The evolution of galaxies in time. How do the successive generations of stars form? How does their gas content evolve? What are the dynamical effects due to their environment?
- How do planetary systems form and evolve? In particular, how do giant and terrestrial planets form and evolve?
- How does the astronomical environment affect the Earth?

Observations to address these phenomena require high sensitivity and resolution as well as the ability to pierce the dense screens of dust and gas that often hide the phenomena from view. Fortunately, such capability will be uniquely provided by the next generation of radio telescopes. Radio waves emerge from the dust-enshrouded regions in which stars form, and only radio observations provide images with the milli-arcsecond angular resolution needed to probe the vicinity of black holes.

Geometry and Matter Content of the Universe

New observations of the Cosmic Microwave Background (CMB) from ground-based radio telescopes as well as from the NASA Microwave Anisotropy Probe (MAP) will place critical constraints on the geometry and matter content of the Universe. However, due to the remarkable sensitivity of these new facilities, measurements of the CMB anisotropy are increasingly limited by confusion from weak discrete radio sources. The effect of the confusing sources will be removed by observations made at the NRAO. In the next five years all the major groups involved with CMB research will use the VLA and GBT for this purpose.

Radio distance determinations are completely independent of the indirect hierarchical arguments used to interpret optical observations, and they are relatively free of uncertainties due to evolutionary effects. VLBA observations of statistical parallax and of Keplerian motion in extragalactic masers, VLA observations of gravitational lens variations, and GBT observations (when combined with X-ray measurements of the intra-cluster medium) of Sunyaev-Zeldovich absorption will all reach out beyond the local flow to give direct measurements of the Hubble Constant, and the size and age of the Universe itself. Indeed, VLBA observations of the motion of H_2O masers in the galaxy NGC 4258 provided such a precise determination of the distance to this galaxy that it is now used as the fundamental calibration for the Cepheid distance scale. VLA and VLBA observations of the time delay between gravitationally lensed images also give direct measures of distances out to very high redshifts. Within the Galaxy, scientists will use the VLBA to directly determine distances from trigonometric parallax measurements of pulsars and other galactic objects, dramatically reducing the errors in the calculated properties of these objects.

VLBA observations of expansion rates compared with spectroscopic Doppler velocities will permit distances to extragalactic supernovae to be determined with great accuracy.

The Formation of Galaxies, Stars, and Planets

The formation of stars and galaxies and the evolution of the gas content of the Universe remain among the most important questions in modern astronomy. A large bolometer camera on the GBT operating at 3 mm wavelength will detect distant infrared-luminous galaxies possibly at the earliest epoch of galaxy formation. Deep VLA images will be complemented by the extensive deep imaging programs planned in other wavelength bands by the NASA HST, Chandra, and SIRTF space-based observatories as well as by a number of ground-based optical observatories. The VLA will provide accurate absolute positions for unambiguous identifications with optical, IR, and X-ray counterparts.

ALMA will observe the cores of molecular clouds, the locations where stars are born. With more than 1,000 spectral transitions within its windows, ALMA will revolutionize the study of the astrochemistry of the star-forming regions. Its millimeter and submillimeter continuum sensitivity and resolution will allow ALMA to probe for the first time the sub-parsec scales that are characteristic of the accretion disks that feed the young stars as well as the jets that they produce.

In the submillimeter bands, ALMA will detect the photospheric emission of thousands of normal stars similar to our Sun, and its resolution will allow it to detect the reflex-Doppler motions due to sub-Jupiter type planets.

The current instruments are only able to study extremely massive (and therefore very rare and perhaps unusual) objects in their CO emission at high z, or in a few fortuitous cases, less massive objects that are amplified by gravitational lensing. ALMA will open the study of high z CO emission to normal galaxies, thereby providing fundamental insight into galaxy formation. The GBT will make wide-field surveys for high redshift objects that can then be studied with higher angular resolution by ALMA. The ALMA sensitivity will allow the study of the distribution of thermal continuum and molecular emission in high-redshift galaxies regardless of their location, providing a sample of such galaxies that can be studied with high statistical reliability.

The new spectral capability and expanded frequency coverage of the EVLA will allow it to image galaxies using their redshifted neutral-Hydrogen transition, thus allowing the study of the evolution of the gas content of galaxies as they evolve dynamically through their interactions with their neighbors in groups and clusters of galaxies.

The VLA will be used to measure the evolution of neutral hydrogen as well as molecular gas to obtain extinction-free measurements of synchrotron radiation, free-free radiation, and thermal dust emission in both young stars and high-redshift galaxies. The VLA will also study the evolution of the magnetic fields in clusters of galaxies. Its enhanced sensitivity will probe the intracluster medium in detail through the measurement of the Faraday rotation due to the ionized gas within the cluster. High-resolution, high-sensitivity imaging with the VLA will distinguish nonthermal AGN emission from that associated with star formation. The VLA will image disks and jets in local star forming regions, measure the star formation rate, independent of dust extinction, in high-redshift galaxies, and search for neutral hydrogen emission out to $z \sim 1$ or beyond. VLA and GBT observations will give spectroscopic redshifts independent of precursor optical data and extending such determinations to very early epochs. The goal of this work is to measure evolution of the radio galaxy/quasar population and to measure the cosmological evolution of the star-formation rate. In the next five years, preliminary results will become available: full realization of the effort awaits completion of the EVLA project.

The GBT will be used to explore interstellar chemistry and trace the evolution of chemical elements in the Galaxy. A long-term goal will be to understand the relationship between large organic molecules found in space and the phenomena that lead to the origin of life.

The Nature of Black Holes

VLBA observations of maser motions around the nucleus of NGC 4258 have given compelling evidence for the existence of a super-massive black hole. In this case the mass of the black hole could be determined precisely and a limit on its size smaller than one milli-arcsecond was established. Compact objects such as quasars, AGN, and some stars are often sources of transient high energy X-ray and gamma emission which is accompanied by radio synchrotron emission. The radio observations of jets, filaments, and hot spots found in such galactic and extragalactic sources, as well as at the galactic center, provide unique information about the physical source of the variability phenomena. The radio observations are uniquely important owing to their high angular resolution, lack of confusing sources, and the ability to observe during both the day and night and even under cloudy weather conditions. In particular, the high resolution of the VLBA is necessary to the study of gamma-ray emission observed by the planned NASA GLAST gamma-ray mission because the VLBA, by studying the radio counterparts, can establish the size and dynamics of the emission region.

Of particular interest are gamma-ray bursts (GRBs), whose study has undergone a renaissance since the launch of the Italian-Dutch satellite BeppoSAX and the subsequent discovery of long-lived *afterglows* at X-ray, optical, and radio wavelengths. GRBs are among the most violent explosions in the cosmos, driving relativistic shocks into their surroundings with bulk Lorentz factors up to about 300. The progenitor object(s) of GRBs remain unknown but there is mounting evidence that GRBs may announce the birth of a black hole. Observations with the VLA and the VLBA are used to study the radio afterglow from GRB's as targets-of-opportunity.

I.3 NRAO in the New Millennium

The scientific issues outlined in Section I.2 demand large radio research facilities. Size is important, to achieve either the necessary sensitivity and angular resolution. This is the basic rationale for the National Radio Astronomy Observatory, summarized in the NRAO mission statement.

> *The mission of the National Radio Astronomy Observatory is to design, build, and operate large radio telescope facilities for use by the scientific community; to develop the electronics, software, and other technology systems that enable new astronomical science; to support the reduction, analysis, and dissemination of the results of observations made by the telescope users; to support the development of a society that is both scientifically and technically literate through educational programs and public outreach; and to support a program of staff scientific research that enables leadership and quality in all these areas.*

Each of the major NRAO instruments—the VLA, the GBT, the VLBA—is unique in the world, as will be ALMA. Access to the NRAO facilities is based on competitive proposals, and is open to all qualified scientists, independent of institutional or national affiliation. Meter and centimeter wavelength radio astronomy, which focuses on nonthermal phenomena and the 21 cm radiation from neutral hydrogen, is the focus of the VLA and VLBA. Millimeter and submillimeter wavelength astronomy is dominated by the thermal emission from cool gas, dust, and solid bodies and has opened up the rich field of molecular spectroscopy and cosmic chemistry. ALMA, which is to be built and operated by a partnership between North America and Europe and Japan, is designed for the study of thermal emission at millimeter and submillimeter wavelengths and will "unveil the cosmic dawn," the era of galaxy formation in the early evolution of the Universe. The other NRAO facilities, the VLA, the VLBA, and the GBT are designed *primarily* for centimeter wavelengths, making them the favored choice for the study of nonthermal sources. However, these telescopes are also powerful instruments at wavelengths that extend well into the millimeter range. They bring great power to the study of thermal emission as well as the nonthermal radio emission from active galactic nuclei, jets, supernovae, pulsars, and gamma-ray bursters and to the study of the 21 cm spectral line from neutral hydrogen for which these telescopes are the instruments of choice. The NRAO's vision of the future is built upon these facilities, promotion of their enhancement, plans for their successors, and the technology that underlies their capability.

The four NRAO telescopes are not at the same stage of development. ALMA is being designed and prototyped. The Expanded VLA (EVLA), a project to build an array with performance specification ten times that of the VLA using the VLA infrastructure as a starting point, is poised for funding. The GBT is just beginning operation. Although the VLBA has operated for eight years, it is working its way toward the easier use that would broaden its community of users, having demonstrated the spectacular results that very long baseline interferometry can produce. This means that to a certain extent the program plan for each of these facilities is tailored to its specific status. However, these telescope-specific plans are united by a single over-arching vision of how the user community employs these telescopes for their research.

In the early years of radio astronomy the use of a telescope was as individual as the practitioners themselves, and it remains much that way today for filled-aperture radio telescopes. The advent of antenna arrays imposed new discipline – more standardized observing modes, prepared in advance, were the price paid for the power of the arrays, the solution for managing the complexity that accompanied that power. The same is happening to filled-aperture radio telescopes with array detectors. The observers are still left with the fundamental responsibility for the quality of their data, as well as for the transformation from (good) data to image. Without in any way restricting the freedom of experts to do just that, and while preserving and enhancing their ability to interact with their data, we plan to provide users with calibrated data and initial "reference" images as well. This will open up the use of large radio facilities to the large community of non-experts, a community utilizing space missions on exactly this basis and expecting to use ground-based facilities the same way. This approach is vital to the success of an easily accessed and used radio archive, similar to those in space astronomy and that constructed for ground-based optical/infrared astronomy in Europe. This is the rationale for the COordinated grid-Based Radio Archive (COBRA) described in this Plan. It is vital if radio astronomy is to participate in the proposed National Virtual Observatory (NVO), which will provide for data mining of archives at all wavelengths.

The NRAO facilities will be made more accessible and their use more efficient by integrating the software the astronomer uses into a single user-friendly end-to-end package. We envision a web-based system for submission and refereeing of proposals to all NRAO facilities, including ALMA. This system will have software to assist the user in preparing a proposal; inform the user of proposal status; help the user in preparing scripts for the observations, transfer of data, reference images, etc., and will provide the link to the archival system.

The successful operation of complex facilities such as the VLA, VLBA, and GBT requires a regular program to enhance the instrumentation in order to exploit the new opportunities made available by the rapidly developing technology in radio frequency and digital engineering. For many years now, the NRAO has not had an adequate budget to allow our telescopes to be used at their full potential. In the case of the VLA, the situation has become so extreme, that it can only be rectified by a major upgrade and enhancement of the 20-year-old instrumentation which we propose to do through the EVLA Phase I program discussed in Section II.2. Our Long Range Plan also reflects an aggressive program to instrument the GBT as well as a long overdue program to widen the recorded bandwidth of the VLBA. The new instrumentation program will be developed with input from the community and staff and will also involve university groups in the design and construction of new instrumentation. Many of the planned improvements are built around new devices developed by the Central Development Laboratory(CDL). These devices include mixers, amplifiers, digital analyzers, feeds, and microwave components. The CDL will occupy new quarters in an addition to the Edgemont Road building in Charlottesville during the period of this Plan.

The process of establishing this Long Range Plan began with a staff retreat held in September 2000, the development of the work breakdown structure by the NRAO management team; review of a draft Plan by the scientific staff; subsequent review by the Observatory Program Advisory Committee and Associated Universities, Inc. (AUI); and approval by the AUI Board of Trustees.

Long Range Plan -Selected Major Milestones

YEAR	ALMA	EVLA	VLBA	GBT	CDL	DM
2002	Acceptance of prototype antenna.	EVLA-CDRs	Complete 3 mm system.	Complete 3 mm receiver.	Prototypes of all ALMA front-end components.	Start of COBRA, NVO activities.
2003	Start site work.	Monitor & Control system complete.	Completion of antenna holography /readjustment	User-built instrument completed.	Two-station prototype ALMA correlator complete.	New VLA, VLBA, GBT archives online.
2004	First antenna in Chile.	Start receiver installation. Start correlator construction.	1Gbps channelization.	L-band array receiver on-line.	First ALMA front-ends; 32-station ALMA correlator to Chile.	VLA, VLBA, GBT pipelines operational.
2005	Begin interferometer testing in Chile	New correlator moved to VLA.	1 Gbps recording.	Test wide BW, multi-input spectrometer.	Front-end components for remaining ALMA bands.	Knowledge management system operational.
2006	Begin interim operations with (20) antennas.	Image pipeline and post-processing systems complete.	1 Gbps playback.	Complete 3 CAM balometer camera.	64-station ALMA correlator complete.	ALMA pipeline operational.

During the period discussed in this plan, we will begin two major new initiatives: (1) ALMA will enhance the opportunities for radio observations at sub-millimeter and millimeter wavelengths; and (2) the EVLA will enhance opportunities at centimeter to meter wavelengths. These two instruments, both of which were highly ranked by NAS/NRC decade reviews of astronomy, will cover a range of about 10^4 in wavelength. They are vital components of the national space- and ground-based facilities program that includes the major NASA initiatives at optical and infrared wavelengths (SOFIA, SIRTF, and NGST), X-ray (Chandra, Constellation-X), and gamma-ray (GLAST), and the new generation of large ground-based optical telescopes.

II.1. Atacama Large Millimeter Array

The Atacama Large Millimeter Array (ALMA) is a revolutionary instrument in its scientific concept, in its engineering design, and in its organization as an international scientific endeavor. ALMA will provide scientists with precise images of galaxies in formation seen as they were twelve billion years ago; it will reveal the chemical composition of heretofore unknown stars and planets still in their formative process; and it will provide an accurate census of the size and motion of the icy fragments left over from the formation of our own solar system that are now orbiting beyond the orbit of Neptune. These scientific objectives, and many more, are made possible owing to the design concept of ALMA that combines the imaging clarity provided by a 64-antenna interferometric array together with the brightness sensitivity of a filled aperture antenna.

The period of this NRAO Long Range Plan, 2002-2006, will see radio astronomy in the United States transformed by ALMA. In 2002, construction is planned to begin on ALMA, the first international project in radio astronomy supported by the National Science Foundation. Owing to the scale and complexity of modern telescopes, future initiatives in radio astronomy will likely also be international projects. In 2002, ALMA will begin that evolutionary transition. In the final year of this Plan, scientists from around the world will begin using ALMA, starting with only a few antennas, for their research projects.

ALMA is a joint endeavor of several nations and many scientific institutes worldwide. The cost and burden of building and operating ALMA will be shared among the participants. This cooperation brings to the Project a broad base of experienced people and resources. Properly used, this breadth of experience has the potential to achieve outstanding performance and to reduce risk in many areas. For ALMA, the challenge is to manage the combined resources in a way that empowers the participants and effectively coordinates their efforts. The mechanism used to achieve this goal is to organize the ALMA efforts in the U.S. and in Europe around "Executive

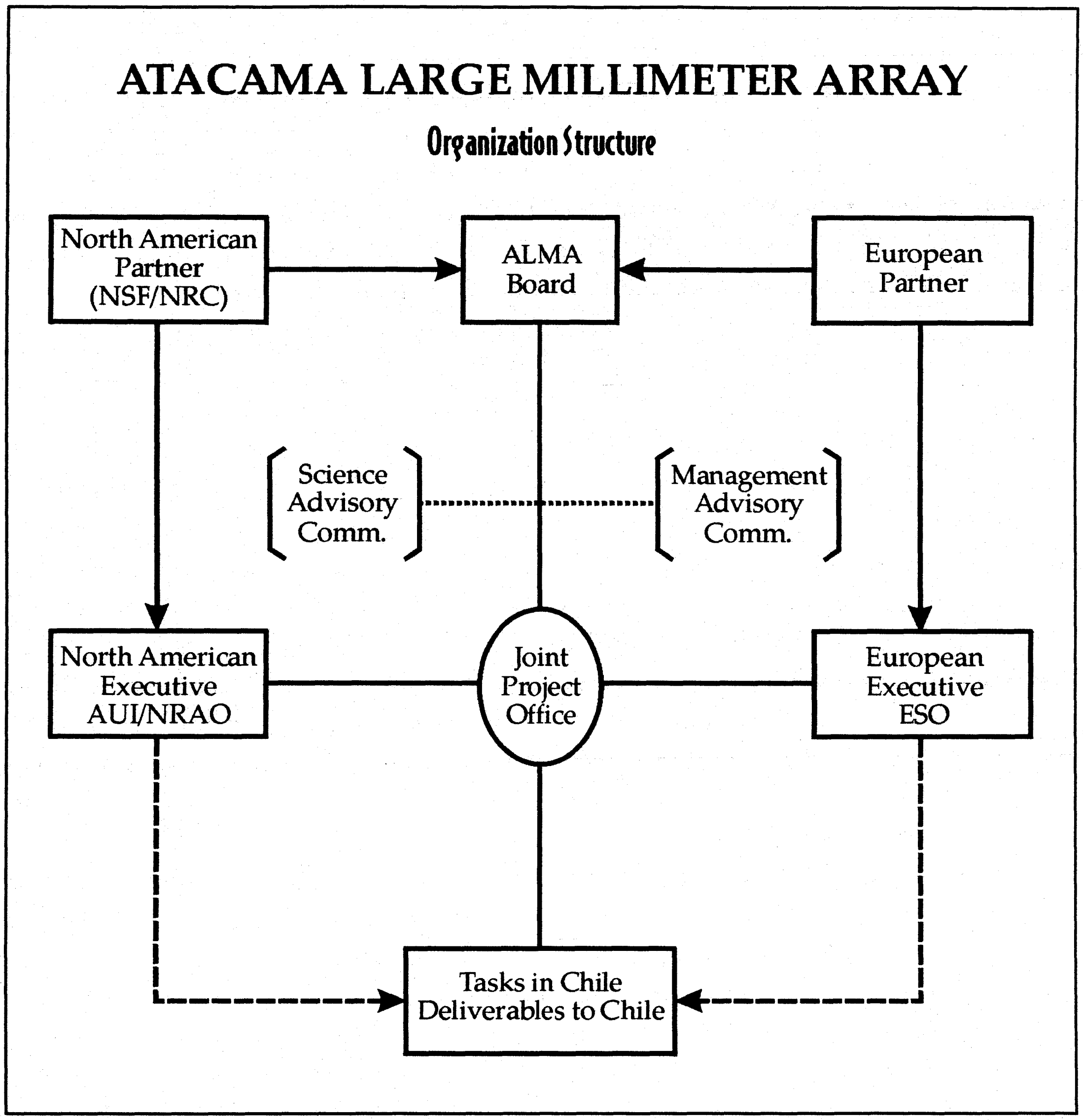


Figure II.1 Organization structure for the bilateral ALMA Project.

Agencies," legal organizations that act on behalf of the participants. In North America, that Executive is AUI/NRAO which represents ALMA on behalf of the NSF and the NRC of Canada; in Europe, the Executive is the European Southern Observatory (ESO) that acts on behalf of its member states and other European institutes participating in ALMA. A more convenient shorthand description of ALMA is that it is a "joint venture of AUI/NRAO and ESO."

It should be noted that the bi-lateral partnership between North America and Europe that existed at the time this Long Range Plan was written is in the process of expanding to include Japan as a third, full and equal partner. The process to bring Japan into ALMA is planned for completion by the endof 2001, in time for the signing of the official agreement to build ALMA by all partners. The description of the current bilateral partnership presented here would then be modified to include Japan.

Primary governance of the project is to be provided by the ALMA Board made up of an equal number of representatives from the European and North American partners, and a representative from Chile. The organization structure for the bilateral ALMA project is shown on the Figure II.1.

Principles of the ALMA Partnership

There are four guiding principles for the ALMA partnership that inform the relation of the partners to each other and that serve to affect the assignment of responsibilities for Project tasks to the two Executives. These guiding principles are recorded in Article 2 of the ALMA Agreement:

- *Parity*: North America and ESO will each make equal contributions to ALMA. To the maximum extent possible, work shall be equally and equitably shared between North America and ESO.
- *Equity*: It is intended that the Parties' participating organizations and institutes shall obtain intellectual and economic benefit from ALMA in all its phases in proportion to the value of their contributions and consistent with the timely and cost-effective execution of assigned tasks.
- *Merit*: Key ALMA personnel shall be selected through international search, solely on the basis of merit and qualification, and their performance shall be subject to annual review.
- *Utilization of Existing Institutions*: New institutions for ALMA shall be established only if absolutely necessary. Personnel shall be provided through secondment arrangements.

The effect of these guiding principles is to assure that the two partners share equally, through their named representative institutions, in the effort, benefit, and risk of ALMA.

Project Scope and Division of Effort

The technical scope of the ALMA Project is summarized in Table II.1.

Table II.1 Major Technical Specifications of ALMA

Number of Antennas	64 Cassegrain antennas of 12 m diameter
Number of Correlated Baselines	2016
Number of Configurations	Five, of maximum baselines 150, 500, 1500, 4500, and 14,000 meters
Number of Antenna Stations	250, antennas are transportable among them
Site	Llano de Chajnantor, Northern Chile at 5000 m (16,500 feet) elevation
Receivers	Four Frequency bands: Band 3: 89-119 GHz Band 6: 211-275 GHz Band 7: 275-370 GHz Band 9: 602-720 GHz
Signal Transport	Digital over optical fibers, 64 Gbits/s sent from each antenna
Correlator	Reconfigurable digital correlator analyzing 16 GHz bandwidth in eight IF channels, each of which has 1024 spectral channels
Software	Control and data handling, data pipeline, image production, remote control operation, data archive
Operation	Service observing with operations center near San Pedro de Atacama, Region II, Chile

The ALMA front-end subsystem—the cryostat and the refrigerator—is designed to support ten receiver bands. Only the four bands specifically noted in Table II.1 are part of the baseline ALMA Project. It is anticipated that the remaining six receiver bands will be added in the operational phase of the project. These six additional frequency bands are the following: Band 1 (31.3-45 GHz); Band 2 (67-90 GHz); Band 4 (125-163 GHz); Band 5 (163-211 GHz); Band 8 (385-500 GHz); and Band 10 (787-950 GHz).

A thorough Work Breakdown Structure (WBS) was used to establish the effort and expense required to complete the construction tasks needed to build the baseline ALMA technical project outlined in the table above. The *costed elements* of this WBS include personnel costs, a benefit rate, an overhead rate to account for General and Administrative expense, the cost of materials and supplies, the projected cost of any contracts that may be involved, and a computed contingency. The sum of these costs, task-by-task, has been agreed by both ALMA partners to represent the *value* of each particular WBS task. It was these *values* that were used to determine the division of effort between the North American and European ALMA partners.

The division of the ALMA Project by assigned "value" between North America and Europe is given in Table II.2 below by level-1 WBS task.

Table II.2 ALMA Project Division of Effort
(Thousands of U.S. dollars)

Task Description	North American Task	European Task	Subtotal
Management/Administration	$12,172	$11,699	$23,871
Site Development	32,135	52,901	85,037
Antenna Subsystem	103,596	107,408	211,003
Front-end Subsystem	26,548	61,907	88,456
Local Oscillator Subsystem	33,303	--	33,303
Back-end Subsystem	21,847	12,549	34,397
Correlator	16,866	--	16,866
Computing Subsystem	16,157	16,157	32,314
System Engineering/Integration	10,131	10,131	20,263
Science	3,480	3,480	6,960
Totals	**$276,235**	**$276,235**	**$552,469**

From Table II.2, the level of involvement of the North American and European partners in each of the major WBS categories can be seen. Not each level-1 WBS task is divided 50/50 between the two partners. Instead, the interests and experience of the two partners were used to effect the division. However, both the effort and the risk (as gauged by contingency) were balanced equitably, as required by the ALMA Guiding Principles noted above. The detailed task division is given in the ALMA Project WBS.

ALMA Joint Workplan

A schematic view of the joint North American-European Workplan for the ALMA Project is given in Figure II.2 below. This illustrates the major activities, milestones and deliverables in the period from the present, 2001, to completion of ALMA in 2010. It highlights the critical path deliveries. This presentation comes from the WBS and the task dependencies that are built into the WBS.

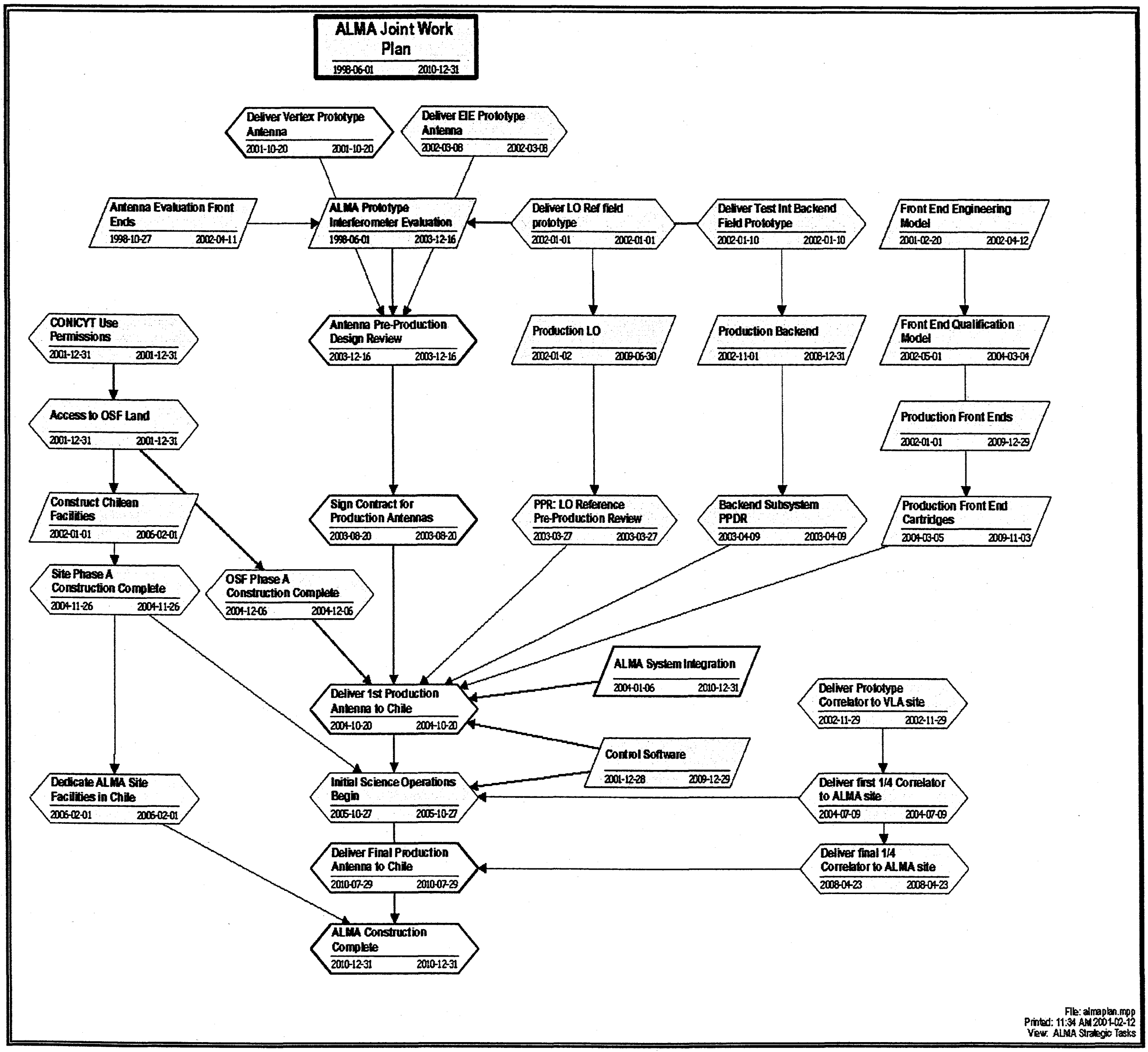


Figure II.2 A schematic view of the joint North American-European Workplan for the ALMA Project

Major ALMA Milestones and Deliverables 2002-2006: In the period of this Long Range Plan, 2002-2006, a significant fraction of the production hardware needed for the array will be delivered to Chile. The designs for much of the hardware were completed in the Design and Development phase of the project, 1998-2001, making it possible for the production instrumentation to be built expeditiously as the construction funding begins. Below is a summary, by year, of the major milestones and deliveries planned for the present Long Range Plan.

2002 Complete Legal Permissions for ALMA in Chile
Obtain Site Access Permissions
Obtain OSF and Link Access Permissions
Initiate ALMA Management with Joint Project Office
Complete Array Site Architect and Engineering Studies
Engineering Acceptance of Prototype Antenna
Deliver Engineering Model Front-end
Deliver Complete Prototype LO Subsystem (4 bands)
Deliver Complete Prototype Back-end Subsystem
Deliver Prototype Correlator
Begin Production Correlator fabrication
Deliver Test Interferometer Software System
Deliver Prototype Correlator Software System

2003 Site Access Roads Layout and Design Complete
Initiate Phase 1 Site and OSF Civil Works
Contract for Production Antennas
Deliver Antenna Transporter #1
Deliver Qualification Model Front-end
Initiate Production LO Fabrication
Initiate Production Back-end Fabrication

2004 Site Civil Works, Phase 1, Complete
Production SIS Test Facilities Complete
First Production Antenna Arrives on Chile Site
Deliver Antenna Transporter #2 and 3 to Chile
Deliver Central LO Subsystem to Site
Deliver Central Back-end Subsystem to Site
Deliver First ¼ Correlator to Site
Deliver Initial Interferometer Software System to Site

2005 Deliver Antennas #2-8 to Chile
Deliver Production Front-ends #2-8 to Chile
Deliver Production Antenna-Based Back-ends #2-8 to Chile
Deliver Second ¼ Correlator to Site
Begin Interferometric Observations (Engineering Tests)

2006 Deliver Antennas #9-20 to Chile
Deliver Production Front-ends #9-20 to Chile
Deliver Production Antenna-Based Back-ends #9-20 to Chile
Deliver Third ¼ Correlator to Site
Begin Interim Operations: Astronomical Observations

Budget and Personnel: The ALMA funding schedule, derived from the WBS tasking for ALMA tasks assigned to AUI/NRAO, is included in the Observatory budget tables in Section VI of this Long Range Plan. Similarly, the staff requirements for ALMA at the NRAO for the period 2002-2006, also drawn from the task requirements tabulated in the ALMA WBS, are included in Section VI of this Plan.

II.2 Very Large Array - Expanded Very Large Array

Very Large Array (VLA)

The Very Large Array is the most powerful connected-element array in astronomy. It consists of twenty-eight 25 m diameter radio telescopes. Twenty-seven antennas are in the array, while one additional antenna, on a rotating basis, undergoes routine long-term maintenance. The VLA has been in full operation since 1980 and has been used by thousands of astronomers during its lifetime of more than 20 years.

For a mature instrument such as the VLA, routine maintenance and replacement of components is critical. The electronics design is now 25 years old so that component obsolescence has required substitutions and redesign on a regular basis. Replacement of all VLA electronics in Phase 1 of the EVLA project will restore the array electronics to the state-of-the-art. Antenna painting and track improvement will continue to be a long term requirement. Several antenna pointing improvements and safety initiatives also will be undertaken.

Nineteen antennas have been repainted since their original construction and we plan to finish painting all 28 antennas by the end of 2002. This will complete the first round of antenna repainting, after which painting will become a lower level maintenance item. A plan to purchase fifteen thousand railway ties and eighteen thousand tons of ballast in 2001 will keep our "five thousand ties per year" plan on schedule until the year 2003.

Efforts are underway to optimize the VLA antennas for high frequency performance. Approximately three bad azimuth bearings that contribute significantly to pointing errors will be replaced in the next several years. Encoder hardware and electronics are being upgraded to achieve an accuracy of 6 arcsecond blind pointing and 2 arcsecond reference pointing. The surfaces of all antennas are being adjusted based on holographic measurements to achieve at least 30 percent efficiency at 43 GHz. A new antenna encoder electronic package was designed and a program for retrofitting the VLA antennas will be completed by the end of 2002. A new encoder mounting bracket and new alignment procedures designed to minimize encoder error are being implemented during the major antenna overhaul cycle; installation of the mounting brackets will be completed by 2002. With the advent of the EVLA, a new antenna control electronics package is planned where consideration will be given to the replacement of the drive cabinet and motors. The planned major expansion of the VLA to include modern electronics with greater capability (the EVLA) is discussed in detail below.

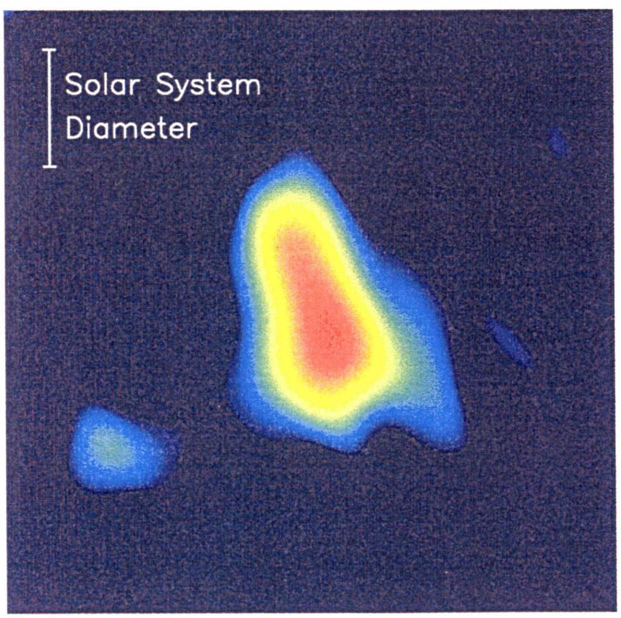


Figure II.3 An image of the 7 mm continuum emission surrounding the massive young star G192.16-3.82. The star is 6,000 light-years distant in the constellation Orion. The image was made using the VLA radio telescope connected by a fiber optic link to the VLBA Pie Town antenna located 52 km away from the center of the VLA. The size of the young star and its surroundings is compared to our own Solar System.

Apex guardrails, dish-hatch grab bar, and the antenna fall-arrest system, which provide safe access to the VLA and VLBA dish and antenna apex, are new safety initiatives due to be completed by the end of 2003. Replacement of the VLA Building fire alarm systems, transporter hydraulic pumps, upgrade of the VLA site radio communications, phasing out of R-22 refrigerant HVAC systems, and the acquisition of badly needed heavy equipment are scheduled to be complete by the end of 2005.

Several new VLA capabilities that are initial steps toward the EVLA have been implemented over the past few years. An important new feature is the fiber optic connection to the Pie Town VLBA antenna, which first became operational during the A-configuration (largest) VLA observing session from October 2000 through January 2001. This capability, which doubles the effective resolution of the VLA, was very successful. More than 15 observing projects were conducted using the Pie Town link over the first three-month period. In the 2002-2006 time frame, the Pie Town link will again be available to proposers during each A configuration session, and we anticipate that up to 25 percent of VLA observations will make use of the link. Key science targets include such objects as supergiant stars, GRB afterglows, starburst galaxies, and Galactic star-formation regions (see Figure II-3 above). The use of this real-time fiber optic link for astronomical observing also will continue to serve as a test bed for both ALMA and the EVLA.

A major goal for the EVLA is continuous frequency coverage from 1 GHz to 50 GHz in frequency (or 30 cm to 6 mm in wavelength). As a step toward that goal, new low noise 1.3 cm (18-26.5 GHz) receivers are now available on 16 antennas and six more new receivers are scheduled to be installed by early 2002. Similarly, 25 VLA antennas are equipped with 40-50 GHz receivers, and all antennas will be equipped by the end of 2003.

VLA Operations Milestones

2002 New 22-GHz receivers on 22 antennas.
Repainting complete on 28 antennas.
Improved operation of Pie Town link.
Encoder retrofit complete.
2003 43 GHz holography and panel resetting complete on 25 antennas.
43 GHz complete on 28 antennas.
New safety initiatives complete.
15,000 new railroad ties installed.
2004 Three azimuth bearings replaced.

The Very Large Array has passed 20 years of continuous operation. Conceived in the 1960s, built in the 1970s, and commissioned in 1980, the VLA initially provided astronomers with a radio telescope one to two orders of magnitude more sensitive and flexible than any other radio telescope. The VLA has since been used by more than 2200 astronomers for more than 10,000 observational programs covering the entire range of astronomy. The impact of the telescope on science has been enormous, with fundamental discoveries having been made in research areas from solar flares to forming galaxies at the edge of our Universe.

Since its dedication in 1980, the capabilities of the VLA have changed only slightly—although receivers have been improved, and new bands added, the other fundamental characteristics of the array—antennas, bandwidths, data transmission, and (most critically) the correlator, are the same as they were twenty years ago. The VLA is now limited by the technologies of the 1970s. In the intervening thirty years, breathtaking changes in technology have taken place which, if implemented on the VLA, will improve the VLA's astronomical capability by over an order of magnitude. Realization of this potential is the primary goal of the EVLA Project.

Discussions with the community on how to improve the VLA's performance have been held by the NRAO since the mid-1980s, and a plan for an upgrade and extension was recommended by the 1991 NRC Astronomy and Astrophysics Survey Committee (the Bahcall Report). By 1995, the scientific need to improve the instrument had become sufficiently critical that a formal NRAO structure was formed to define a comprehensive project, and to prepare and submit a proposal to the National Science Foundation.

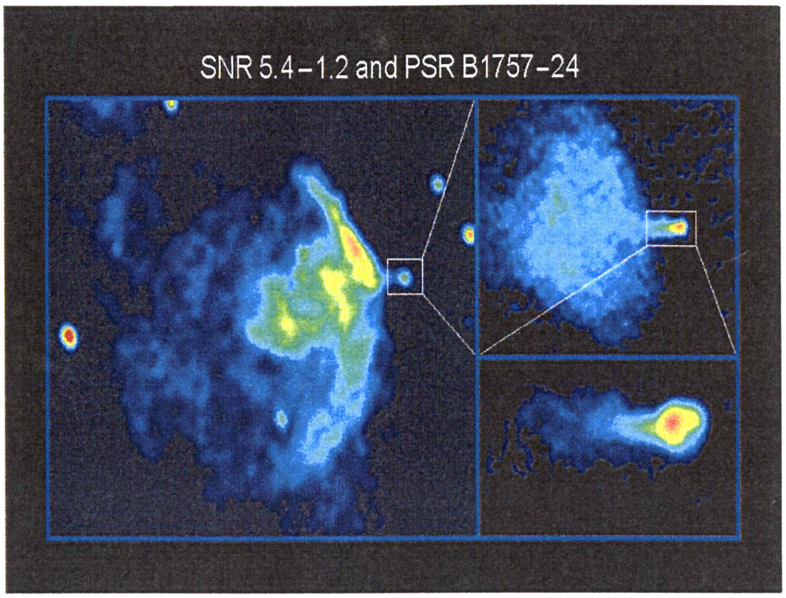


Figure II.4 VLA images of "The Duck." The left panel is a 327 MHz image of the supernova remnant G5.4-1.2, showing the clear asymmetry in brightness between its two sides; the pulsar B1757-24 is located on the western edge of G5.4-1.2. The upper-right panel is a 5 GHz higher resolution image of a smaller region surrounding PSR B1757-24, while the lower-right panel shows an 8.4 GHz image of the cometary-shaped nebula in which the pulsar is embedded. VLA measurements of the motion of the pulsar nebula over a period of six years have established that the pulsar is moving much slower than expected. If the pulsar was born near the center of the supernova remnant, then this implies that the characteristic age of the pulsar, as determined from its spindown, is underestimated by a factor of two or three. The assumption that the characteristic age is a good approximation of a pulsar's true age is a fundamental one, underlying all of pulsar demography.

Because the scope of this project well exceeds that suggested by the name *VLA Upgrade*—largely because the advances of technology now enable transmission and processing of all information available at the antennas—this project is known as the *VLA Expansion Project*, and the "new telescope" will be known as the Expanded Very Large Array (EVLA). The overall goal of the VLA Expansion Project is an improvement of at least an order of magnitude in all the VLA's key observational characteristics—sensitivity, frequency accessibility, correlator capability, frequency resolution, total bandwidth, and spatial resolution. A thorough review of the science potential realized by such an improvement in instrumental capability confirms that this improvement is long overdue, and needs to begin as soon as possible.

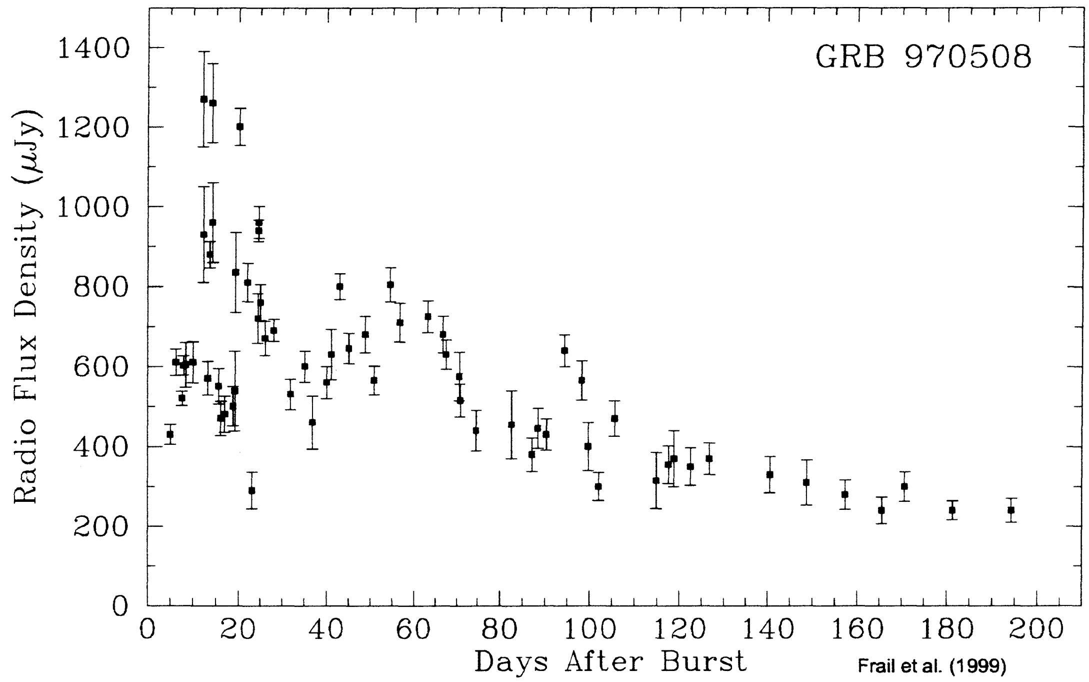


Figure II.5 VLA observations of the flux-density changes in GRB 970508, covering a period of nearly six months following the gamma-ray burst. The time variations at early times are caused by interstellar scintillation, and provide a measure of the intrinsic size of the emitting region. At late times, the flux decrease can be interpreted in terms of models of the geometry and evolution of the relativistic fireball. Typically, no more than 1-2 such objects per year can be followed with the current VLA. The EVLA will be capable of monitoring 100 or more gamma-ray bursters per year at this level of detail.

The scientific goals of the EVLA cover a broad range of topics, and were covered in great detail in the EVLA Phase I proposal (described below). As a centimeter- and millimeter-wave observatory, the EVLA will be capable of unique scientific contributions in at least four major categories: (1) The Magnetic Universe; (2) The Obscured Universe; (3) The Transient Universe; and (4) The Evolving Universe. For example, Faraday-rotation measurements of background galaxies will yield the spatial distribution of magnetic fields in clusters of galaxies, providing unique insights into cluster formation and evolution. Cosmic phenomena obscured at other wavelengths, such as accretion onto black holes, will be imaged directly by the EVLA. Hundreds of gamma ray bursters can be followed each year (see Figure II.5), long after they have disappeared at other wavelengths, providing direct measures of sizes and expansion rates, as well as hard constraints on source geometry. A detailed presentation of the EVLA project was given to the recent NRC Astronomy Survey Committee, and in May 2000, the McKee/Taylor report - *Astronomy and Astrophysics in the New Millennium* - recommended the EVLA as the second highest priority major project for ground-based astronomy.

An early decision by the NRAO was to split the project into two phases: Phase I will address all improvements except angular resolution, and Phase II will primarily be concerned with increasing the resolution of the array by an order of magnitude.

In May 2000, a proposal to fund Phase I of the project was submitted to the NSF. The total budget proposed for this phase of the project was $76.2M in Y2000 dollars, of which $49.9M in new funding from the NSF was requested over a 9-year timescale. The remaining funds will be provided by two declared partners (Mexico and Canada), and by redirection of current operational support to the EVLA project. In particular, it is expected that the Canadian contribution will take the form of a powerful and flexible new WIDAR (Wideband Interferometric Digital Architecture) correlator for the EVLA. In December 2000, an NSF-appointed panel visited the Socorro Array Operations Center (AOC) to review the EVLA proposal. Their report to the NSF was made the following month. The NRAO has submitted additional information about the proposal. This response contains detailed information on the management plan and administrative structure of the project. The NRAO is ready to begin the project; it awaits final approval and funding.

EVLA Phase I

The proposal submitted to the NSF in May of 2000 describes a 9-year plan to implement Phase I of the VLA Expansion Project. This extended timescale was suggested by the NSF on the basis of concerns about the maximum annual funding rate which could be sustained. From the point of view of both the Observatory and the users, this timescale should be shortened, and an alternate 7-year plan, which would save $2.3M, is much preferable. The major difference between the 9-year and 7-year plans is that the former defers most receiver construction until the end of the project, which is undesirable in that the correlator and data transmission portions of the project will be completed two years earlier. Accordingly, in Table VI-2 "Budget Summary" we have shown the 7-year plan.

By 2006, (presuming a start in the second half of 2001), the LO/IF Fiber system will be nearly complete, the correlator will be at the VLA site, under final testing, the on-line control and monitor system completed, and all major software components completed, or nearly completed.

After completion of Phase I, the EVLA will look much the same as the VLA, but will, in fact, be an entirely different instrument. Major differences will include:

- The ability to tune to *any* frequency between 1 and 50 GHz.
- A sensitivity to continuum emission 3 to 20 times (depending on band) better than present.
- Spectral resolution more than 500 times higher.
- More than two orders of magnitude increase in the number of spectral channels.
- Vastly improved spectral dynamic range, allowing much more precise spectral imaging and robustness against radio frequency interference.
- The ability to selectively tune as many as 128 sub-bands, permitting targeting of separated spectral transitions, as well as avoidance of RFI.
- A new operational interface, permitting much more flexible and powerful use of the telescope by scientists, engineers, and operational staff.
- A unified proposal and observation preparation system, ensuring similar interfaces between the user and the NRAO's major new instruments—the EVLA, the VLBA, the GBT, and ALMA.
- A sophisticated observation scheduling system, to maximize efficient use of the EVLA.
- An imaging pipeline, providing Internet-accessible, near-real-time default images from most observational programs.
- An on-line data archive, capable of retaining all telescope data products, including the default images, calibrated, and raw interferometer data.
- A new, sophisticated post-processing package (AIPS++) giving the astronomer the tools to efficiently process all EVLA observing programs.

The proposal submitted to the National Science Foundation provided a 9-year timeline, although the EVLA Project can be completed within seven years, as discussed above. For the preferred 7-year plan, principal milestones are listed below:

2001 Detailed Project Management Plan
System PDR
Subsystem PDRs
Archive Outsourcing Decision

2002 Correlator PDR
System CDR
Subsystem CDRs
Start LO/IF/FO Installation
Initial Archive deployed

2003 Start Feed Cone Installation
Data Processing Architecture CDR
Observation Proposal Handling fully deployed
Control/Monitor System fully supports enhanced antennas
Correlator CDR

2004 Image Pipeline operates on initial platform from archive
Start Correlator parts purchase
Start Receiver Installation

2005 Control/Monitor System ready for correlator
Control/Monitor System ready for archive

2006 Move correlator to VLA and begin test observing
Image Pipeline operates on new data path
Post Processing meets CDR objectives

2007 Correlator operational
Finish LO/IF/fiber optic Installation
Finish receiver installation
EVLA Fully Operational

EVLA Phase II

As described above, the Expansion Project has been split into two phases. The primary goal of the second phase is to increase the angular resolution of the array by about a factor of 10, while maintaining the imaging fidelity and flexibility which so uniquely characterizes the VLA. This will require the addition to the array of up to ten antennas, situated at distances of up to 250 km from the array center. These antennas which give interferometer spacings intermediate between the VLA and the VLBA are known as the *New Mexico Array* (NMA). Two of these antennas will be existing VLBA antennas; the other eight will be new. All will be connected to the new correlator by fiber optic lines, enabling real-time, full-bandwidth operation. In most situations, these new antennas will operate with the present VLA antennas when the array is in the A-configuration. During other configurations, the NMA antennas will be used together with the VLBA to improve its field of view and sensitivity to intermediate scale structure, or it will operate as an independent subarray whose resolution will be ten times that of the present VLA, with a point-source sensitivity equal to or better than that of the present VLA.

The new antennas will be of tremendous value to VLBA observers by roughly doubling the sensitivity and by adding critically needed shorter spacings. This latter benefit will enable VLBA users to make vastly better images, permitting, for example, multiple-frequency observations at the same resolution—a critical capability, which is currently absent, for spectral index studies of extended objects. The proposed new correlator will have the capability to simultaneously and independently operate with real-time data and with tape-based data from multiple subarrays—thus enabling both VLA-style and VLBA-style observations. Ultimately, this new correlator will be expanded to include all of the VLBA antennas, which will all be connected by fiber for real-time operation, permitting the EVLA and VLBA to be considered as a single instrument which will be operable in many subarrays, in real-time.

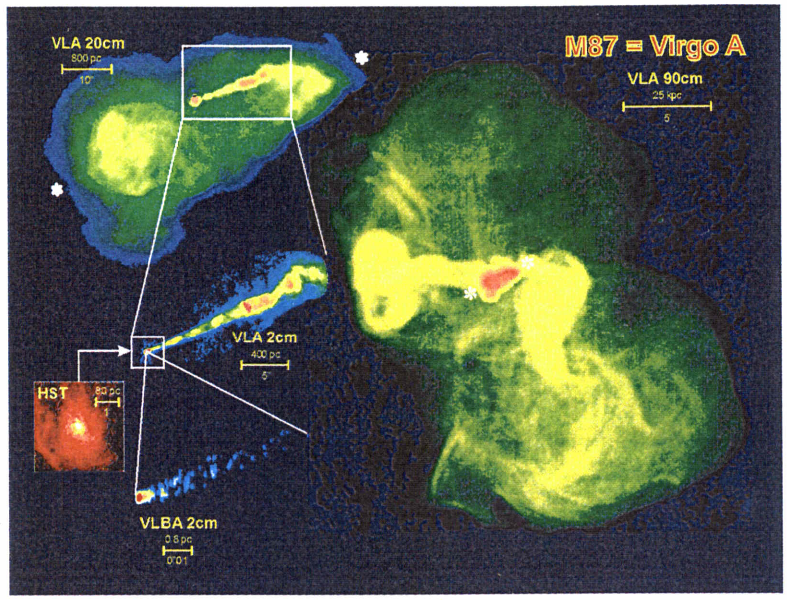


Figure II.6 Many radio galaxies have angular structure on scales ranging from less than 0.001 arcseconds to many arcminutes. To study these structures requires radio telescopes which cover a wide range of resolution. The right hand side of this mosaic was made with the VLA at 90 cm wavelength and shows that the radio halo surrounding the galaxy M87 is a bubble about 300 kpc in extent, with a well-defined outer edge, which sits inside an X-ray emitting atmosphere. The bright plumes emanating from the inner lobes suggests that the halo is still "alive" being supplied with energy from the central engine. The inner radio lobes shown in the upper right cover the region between the white markers and are rather symmetric, although the jet which feeds the lobes is seen only on the northwest side. This image was made with the VLA at 20 cm wavelength. The jet is seen in more detail with the VLA 2 cm image shown in the left central portion. The jet supplies relativistic plasma from the central engine to the outer parts of the source. The VLBA image shown in the lower left has a resolution of 0.001 arc seconds and shows the region at the base of the jet close to the central engine where relativistic plasma is accelerated and focused to form the narrow jet. This VLBA image covers about 1 pixel in the HST image shown in the insert.

Two smaller enhancements not currently part of Phase I are being considered for inclusion in Phase II: (a) A low-frequency capability, covering the band from 300 MHz, or even lower, to 1 GHz, using a wide-band, prime focus feed. This capability would be used to observe red-shifted hydrogen from the early Universe, and for polarization studies from synchrotron-emitting sources. (b) An ultra-compact E-configuration, which would require construction of up to 27 new antenna stations all located in a region 200 to 300 m in size. This new configuration will be used for studies of extended, low-surface brightness emission.

At this time, preparation of a proposal to fund Phase II is just beginning. It is desirable that Phase II construction proceed in parallel with Phase I activities. In particular, if funding begins in 2004 for Phase II, the completion dates for both phases will coincide.

II.3 Green Bank Telescope

The Green Bank Telescope is the most capable, but also the most complex, filled aperture radio telescope ever constructed. It will operate around-the-clock as a visitor facility, covering frequencies from ~100 MHz to ~100 GHz, and will have highly advanced and state-of-the-art instrumentation and operational modes. As a consequence, operational support is demanding.

As GBT systems come on line, as visitors grow in number, and as we develop new capabilities, systems and infrastructure support requirements will also grow. In particular, the Computing Division will expand in size and capability to meet these requirements. Each of the major instrument and software development projects will be coordinated by a project scientist, and the scientific staff will need to concentrate on operational support.

We plan to institute a training program that will allow operators to become more qualified observing assistants than has been the case in the past. When the program is completed, the observing assistants will have basic knowledge of general astronomy, and specialist knowledge of relevant areas of radio astronomy. They will then be better able to provide technical and operational assistance to observers.

In conjunction with VLA/VLBA Operations, we will also develop a maintenance database and work-order system based on the MainSaver software program. The system will allow the operator to record and describe a fault, and to issue a response work order to the appropriate group or person, and track the disposition and ultimate resolution of the fault. The system will keep a running list of unresolved faults and archive all reports for long-term referral. The system can also be used to catalog spare parts inventory.

Construction of the Green Bank Telescope is now essentially complete, but to exploit its full potential it will need to be instrumented with state-of-the art instrumentation, particularly at millimeter wavelengths. The GBT can be among the world's foremost instruments for rapid, wide-field imaging and sensitive millimeter-wave observing. The GBT's size, sensitivity, and large field-of-view will combine to make it the instrument of choice for wide-field, radio imaging at angular resolutions as high as 7 arcsec. It will augment both ALMA and the EVLA by closely matching their point-source sensitivities in the frequency range from 100 MHz to 100 GHz, while increasing wide-field imaging speed and inherent sensitivity to extended, low-brightness sources. The GBT, ALMA, and the EVLA together will provide NRAO observers with a comprehensive, state-of-the-art imaging capability. The GBT is also the largest aperture in existence for the scientifically-rich, 3 mm wavelength band. The planned program will develop the GBT's unique capability in this band for both point-source and wide-field imaging observations.

The scientific potential offered by this program is very exciting. For example, the GBT will be among the most sensitive instruments available for studies of dust emission from galaxies at extreme redshifts. It may be able to make the first determination of the earliest epoch of galaxy formation, a challenging scientific goal of great interest. GBT users will make wide-field redshift surveys to yield a three-dimensional view of the early Universe. They will make some of the most sensitive observations to date of the Sunyaev-Zeldovich Effect and will image the wide-field structure of star formation regions in molecular species and neutral hydrogen to penetrate deep into the dusty cores of proto-stellar nebulae. The GBT will also image the emission from dust and molecular lines in solar system comets and nearby proto-solar disks.

The initial suite of GBT instrumentation, built as part of the construction project, is complete. These instruments include dual-polarization, single or dual-beam receivers covering most frequencies from 300 MHz to 26 GHz, and a 4-beam, dual-polarization receiver for the 40-50 GHz band. The initial instruments also include the GBT Spectrometer, the most advanced and capable autocorrelation spectrometer ever built. The initial suite of instruments was chosen to satisfy the needs of basic single-dish operation, with excellent point source sensitivity for all the primary frequency bands together with wide-bandwidth, high resolution spectroscopy.

The next generation of GBT instruments will focus on imaging capability, development of the GBT's 3 mm observing potential, complementarity to ALMA and the EVLA, and flexibility and ease of use for all astronomers. Imaging instrumentation technology is advancing very rapidly, and the next generation of instruments will substantially advance—and in some cases, revolutionize—the scientific output of filled-aperture radio telescopes. The GBT has the potential for truly unique scientific capability in the 3 mm wavelength band, and a great deal of the planned program will focus on developing this capability. All instrument and facility development programs will seek to maximize this complementarity and to deliver a unified capability. Finally, considerable emphasis will be placed on ease of use and scientific flexibility of the GBT. This effort will be done in concert with the Data Management group, and will include initiatives for remote observing, dynamic scheduling, end-to-end program execution, and data archive and retrieval. These programs are described in more detail in the following sections.

3 mm Program

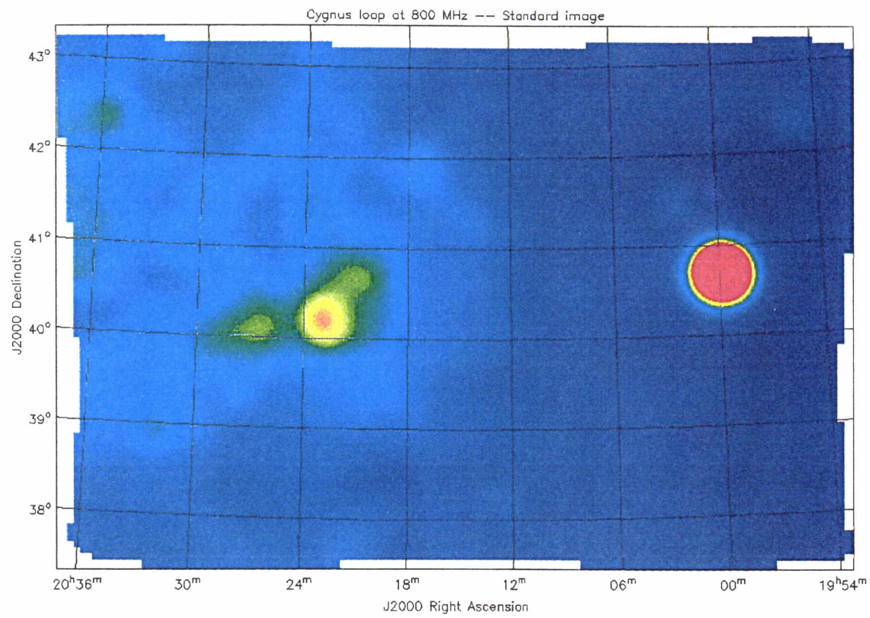


Figure II.7 Image of the Cygnus X - Cygnus A region mapped by the GBT at 790 MHz. The data were processed and the image constructed entirely in AIPS++. The image has not been cleaned and, therefore, represents faithfully the GBT prime focus beam.

A major opportunity for the GBT lies in the 3 mm band. The GBT will have unprecedented sensitivity to 3 mm emission, including dust continuum and high redshift gas. The GBT's potential in the 3 mm band is unique and represents a major advance in astronomical capability. The GBT's potential sensitivity to local dust continuum emission will be about the same as with existing submillimeter-wave telescopes, and will exceed the sensitivity of these telescopes to high-redshift dust and optically-thick, local dust. The GBT also has great potential for complementarity with ALMA in the 3 mm band. The GBT will have point-source sensitivity similar to ALMA at 3 mm and will be able to make wide-field low resolution images more quickly. Wide-field, high sensitivity GBT images coupled with targeted, high-resolution and high-sensitivity ALMA images will provide a very potent capability.

The GBT was designed to work in the 3 mm band, and preliminary technical results indicate that it should meet this goal. The average RMS of individual surface panels was measured at 68 μm. Initial phase-closure experiments with the laser metrology system are yielding encouraging results, and monitoring of atmospheric emission indicates that high 3 mm transparency exists for as much as 30 percent of the year in Green Bank. Long-term planning and a step-by-step program to develop the high frequency capability of the GBT is underway. The elements of the 3 mm development program are as follows:

Metrology, Pointing, and Surface Development. Refinement and continued development of the metrology system hardware and software, including integration with the Monitor and Control system, will be required for 3 mm operation. In addition, enhancements will be made to the GBT servo system to improve its tracking accuracy.

Initial 3 mm Receiver. A working group convened last year and recommended that the first 3 mm receiver to be built should aim for optimum point-source sensitivity and for excellent continuum as well as spectral line performance. The specific design recommended was a dual-beam, dual-polarization correlation style receiver similar in design to that used for the MAP project. A preliminary design for this receiver is complete and work will commence in 2001.

Atmospheric Site Monitoring. Currently, an 86 GHz tipping radiometer and a 12 GHz phase monitoring system are in operation in Green Bank. These data are being studied to determine the most efficient use of the GBT at high frequency.

Dynamic Scheduling. Dynamic scheduling, also known as flexible or queue-based scheduling, will be essential for efficient use of the telescope at the higher frequencies. Dynamic scheduling seeks to match observing programs with the prevailing environmental conditions for most efficient use of observing time, and for the most expeditious completion of observing projects. The observing schedule is thus completely fluid. There are many tools and systems that must be developed before dynamic scheduling can be implemented, including development of an observation database, automated proposal processing and queue-building, queue management tools, on-line tools for monitoring environmental conditions, scripting, observing setup, and program verification systems.

Focal Plane Array Program

The GBT has unique potential for the combination of rapid, large-scale imaging and very high point-source sensitivity. The GBT's sensitivity derives from its 100 m aperture, and its active surface and metrology systems that will allow efficient operation into the 3 mm wavelength band. Its imaging potential derives from its optics design which yields a wide field of view at the Gregorian focus. Furthermore, as a filled aperture radio telescope, the GBT has two properties that can be exploited for wide-field imaging: sensitivity to extended structure on the largest spatial scales, and the ability to utilize incoherent detectors for continuum work and some types of broad-band spectroscopy.

Maximizing the wide-field imaging capability with the GBT requires the development of focal-plane array (FPA) receivers. There are several types of FPAs that are being considered for the GBT: conventional feedhorn arrays with discrete, coherent amplifiers; beam-forming, full-sampling arrays; bolometer arrays; and incoherent HFET amplifier arrays. Focal plane arrays will become the norm as the GBT's standard receivers in the future.

Beam-Forming, Full-Sampling Arrays: The beam forming array is an innovative concept developed at the NRAO consisting of planar feeds that fully sample the focal plane and discrete amplifiers for each feed (See Section III.1). A four-year development program has been defined that will result in a prototype, 19-beam L-Band array on the GBT with competitive noise temperature. This prototype array will be capable of important scientific programs at L-Band (~1.5 GHz), including pulsar and HI surveys and will be the basis for subsequent arrays that extend to higher frequencies and larger numbers of elements (perhaps to ~100). Following the successful completion of the L-Band prototype array, a beam-forming array at a higher frequency band (probably K-Band) will be undertaken.

3CAM Bolometer Array: One of the most exciting development possibilities for the GBT is a very large format bolometer camera. Technology in this area is perhaps advancing more rapidly than in any other area of radio or millimeter-wave instrumentation. It is now feasible to design a bolometer camera with many thousands of pixels that fully sample the focal plane, and with each pixel having very high sensitivity (e.g., ~1 mJy-sec$^{-1/2}$ on the GBT). One submillimeter-wave observatory already has a program underway to build such a camera. Such technology is a major advance for millimeter-wave astronomy, and approaches the analog of optical CCD cameras.

The bolometer arrays under consideration are built by a group at the National Institute for Standards and Technology (NIST) laboratories in Boulder, Colorado. They consist of transition edge sensor (TES) bolometers integrated onto a wafer, and bonded superconducting quantum interference devices (SQUIDs) that provide multiplexed readouts of the array elements. We have had discussions with the NIST team about participation in their research and development program. In addition, we have established links to a group in the United Kingdom who are at work on a second-generation camera (SCUBA-2) for the James Clerk Maxwell Telescope. This camera will have a total of 30,000 pixels, and serious design work has been underway for over a year.

Based on the NIST devices, a concept has been proposed for a large-format, 3 mm bolometer array for the GBT, called 3CAM. This array would have 6400 pixels total, arranged in four separated quadrants of 1600 pixels each. The quadrant structure is required by array and filter size, and by stray light constraints. Within each quadrant, the arrays will fully sample the field (0.5 λ spacing).

Five areas have been identified in which the GBT, equipped with a large-format 3 mm bolometer array, would be uniquely powerful. These include the origin and evolution of galaxies, cosmology and cosmic background anisotropies, the physics of star formation, stars and stellar evolution, and the origin and evolution of planetary systems.

The plan for 3CAM development is as follows. During 2001, a workshop will be held in Green Bank to define the scientific case for a 3 mm bolometer array for the GBT, and a scientific program document will be produced. Over the next two years, the NRAO will begin a feasibility and preliminary design study for the camera, and will participate in the R&D program at NIST at a modest level to develop a prototype of a 3 mm bolometer element, and also to contribute to the overall R&D program for TES/SQUID integrated arrays. In parallel, general 3 mm development of the GBT will be proceeding (see below). In early 2003, a conceptual design and feasibility review meeting will be held, at which we will make the decision of whether and how to proceed with construction of the camera.

3 mm Spectroscopic Focal Plane Array: A 3 mm spectroscopic imaging complement of the continuum bolometer camera will be initiated within this program period. Such an instrument would be extremely valuable for rapid spectroscopic imaging of extended Galactic star formation regions and extragalactic wide-field redshift surveys, among many other projects. A possible model for this instrument is the UMass/ SEQUOIA array, which has 32 beams covering the 85-115 GHz band.

Spectrometer Upgrades: In connection with the focal plane array projects, an expansion of the GBT Spectrometer IF down-converter section will be required. The Spectrometer digital section is capable of processing eight inputs of 800 MHz bandwidth each, or 32 inputs of 50 MHz each. However, only 16 IF down-converters have been built so far. Some expansion and bandpass overlays on the optical fiber IF distribution system from the telescope to the Jansky Lab will also be required.

We will also investigate the development of a very wide bandwidth spectrometer for use with a 3 mm spectroscopic focal plane array. UMass has proposed building a coarse spectrometer with 30-35 GHz of bandwidth for use with a single beam 3 mm receiver that might be brought to the GBT as a visitor instrument. This instrument will allow the unique determination of the redshift of a galaxy. This concept could be extended to build a multi-input wide-band spectrometer for use with a focal plane array receiver that could be used for deep, redshift surveys of early galaxies.

GBT Visitor Supported Instrumentation

We are encouraging the participation of outside groups, particularly university groups, in the development of new instrumentation for the GBT. Visiting instruments and joint projects are mutually beneficial for several reasons. From the short-term perspective, there are more numerous opportunities for innovative instruments than the NRAO can take on with its own staff and resources. Such instruments can add to the aggregate capability and scientific potential of the GBT. In the longer term, such projects enhance the development capabilities at universities and serve to train students as a new generation of instrument builders. Several different university groups have already expressed interest in developing or collaborating on instrumentation for the GBT and we are actively pursuing these initiatives.

Other GBT Instruments and Projects

A number of other important instruments are being built as part of the comprehensive GBT development program. These include:

Ka-Band (26-40 GHz) Receiver. This receiver would address important scientific projects such as redshifted J=1-0 CO (z = 1.9 to 3.4), as well as Cosmic Background and Sunyaev-Zeldovich continuum measurements. This receiver may be built as a collaboration between the NRAO and university groups.

Receiver Upgrades and Additions. It may be possible to upgrade some of the GBT receivers already built with the new, lower noise and higher bandwidth InP amplifiers recently developed at the Central Development Laboratory. This is currently being studied for K and Ku bands. A wide-band receiver covering roughly 3-10 GHz might be possible with these amplifiers, although the development of wideband OMTs and polarizers will also be required. These possibilities will be examined. In addition, there are several gaps in the frequency coverage of the initial suite of GBT receivers, including 2.6-3.95 GHz, 5.85-8.20 GHz, 10-12.4 GHz, and 15.4-18.00 GHz. The scientific case for filling these gaps and the priority relative to other projects will be considered.

Remote Observing. A remote observing package, with capabilities similar to that pioneered at the 12 Meter telescope, will be developed for the GBT. In appropriate circumstances, this capability will allow observers to conduct or participate in observing runs from their home institutions with the efficiency and flexibility similar to that found at the telescope. The features will include:

- On-line status displays
- Video links and electronic whiteboards (again, depending upon available bandwidth)
- Remote data reduction screens
- System configuration and setup screens
- Real-time data displays
- Interference monitoring
- Weather logs and maps
- Digital chart records and other system monitoring and diagnostic information
- Digital observer logs and message logging

Data Pipelining. Large quantities of data produced by focal plane array receivers and by advanced single beam observing modes such as on-the-fly mapping should be processed by automated data pipelines. High data rates over extended observing runs can produce such a large volume of data that traditional storage and post-processing methods are impractical. At its maximum rate, the GBT Spectrometer will produce about 2.5 orders of magnitude greater data rate than the current VLA correlator. Pipelines should be capable of producing results that, for many purposes, are suitable for astronomical interpretation and publication. Pipelines typically require considerable computing power and specific algorithm development for the data processing.

Advanced Observing Modes. The GBT will generate prodigious data rates for pulsar observing, on-the-fly imaging, and focal plane array imaging. Observing techniques and data processing systems necessary to conduct these observations must be acquired. A prime example of an advanced technique is on-the-fly (OTF) mapping. The GBT Monitor and Control system has been designed to accommodate OTF observing, although additional development will be required to acquire and process the maximum data rate the GBT Spectrometer is capable of producing. In addition to data acquisition advancements, additional innovation in observing modes may also be valuable for the GBT. For example, owing to its enormous size and particular design characteristics, special observing modes that minimize starts and stops, such as spiral scanning patterns, etc., may be very desirable.

End-to-End Program Execution. When the individual capabilities described above are fully realized, an integrated system will exist in which an observer can prepare proposals and observing setups with easy-to-use tools and check the setup with verification and simulation tools. The observing script can then be entered into an automated queue, executed to best efficiency through dynamic scheduling, with the observer monitoring remotely, if desired. The data will be processed through an automated pipeline, and be archived for subsequent retrieval by the observer. These combined capabilities will comprise an end-to-end program management facility. Considerable development will be required to provide this capability, but it will stand as a long-term goal.

Timeline and Budget for the GBT Long-Range Development Program

Estimates of the capital and staffing required to carry out these and the other projects are presented below. The estimated spending profile for the development projects is given in Table II.3; these figure are incorporated in the NRAO projections for this Long Range Plan (see table VI. 2) The estimated timeline is given in Figure II.8.

Table II.3 GBT Instrumentation Spending Profile

Project	Calendar Years					Total Capital Cost (k$)
	CY2002	CY2003	CY2004	CY2005	CY2006	
Q-Band Tertiary Mirror	10					10
RFI Mitigation	30	25	25	25	25	130
Beam-Forming Array (L Band Prototype)	200	30	20			250
3 mm Rx	60					60
3CAM Bolometer Array	200	800	1000	1000	350	3350
3 mm Focal Plane Array		50	400	100	50	600
Spectrometer / IF Upgrades				250	250	500
Wideband, multi-input spectrometer			250	100	50	400
Rx Upgrades & Additions	100	50	25	25	25	225
K-Band, Beam-Forming Array				150	250	400
External / User-built Projects	200	200				400
Totals:	800	1155	1720	1650	1000	6325

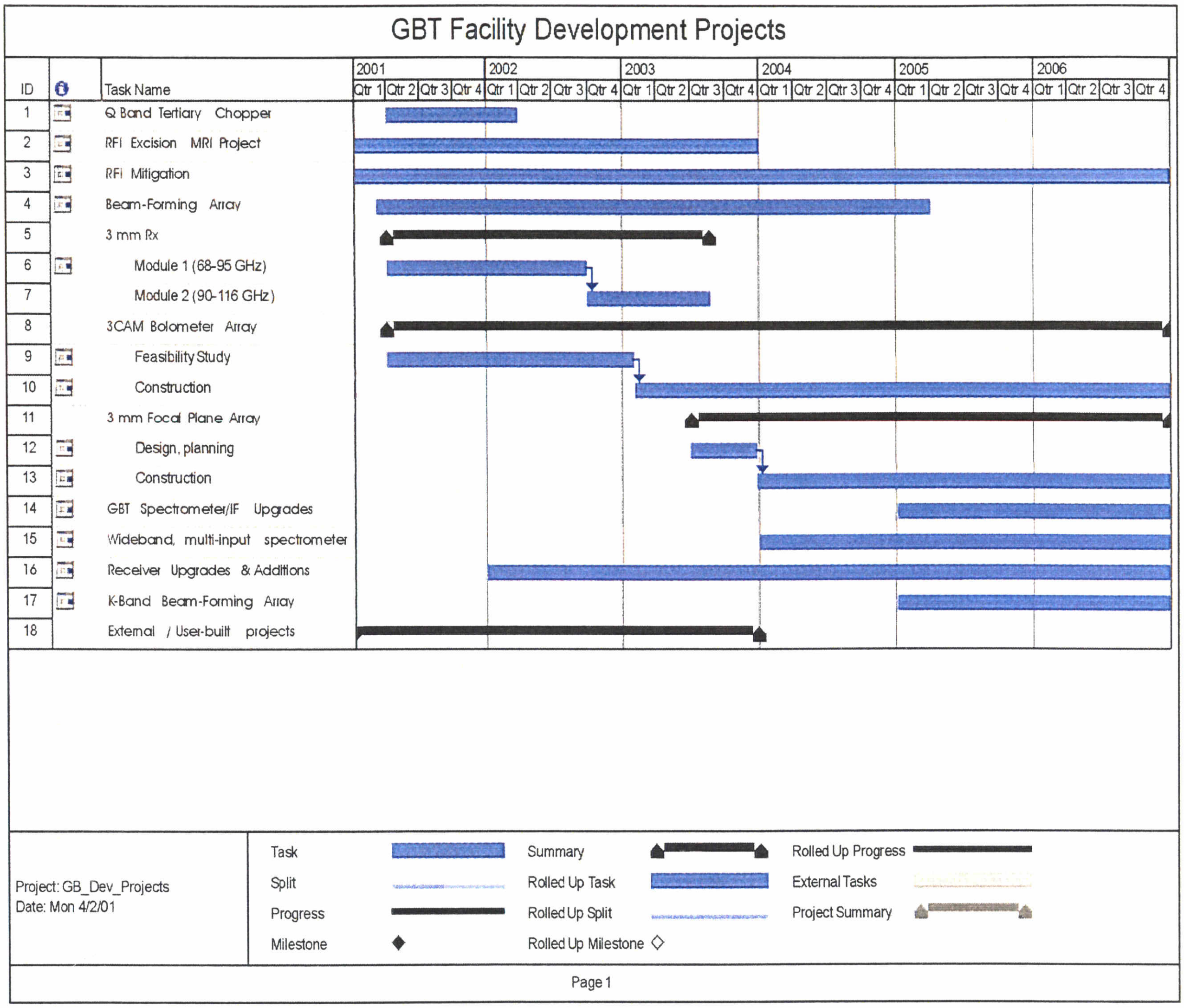


Figure II.8 Estimated timeline of GBT development projects.

II.4 Very Long Baseline Array

The VLBA is an array of 10 radio antennas spread across the U.S. and its territories, from Hawaii to the Virgin Islands. With typical resolutions in the range of 100 *microarcseconds* to several *milliarcseconds*, it is far and away the highest resolution imaging instrument in astronomy. It is the only astronomical instrument capable of such observations as (1) direct imaging of plasma on the sub-parsec (or sub-light-year) scale of the broad-line region in distant active galaxies; (2) measurement of the structures of magnetic fields near supermassive black holes and evolved stars; (3) production of milliarcsecond-scale movies of objects such as evolving stars, supernovae, and extragalactic jets; and (4) direct measurement of the distances of objects as varied as distant Galactic pulsars and extragalactic water-maser galaxies. A specific example of the VLBA's intermediate-frequency performance and flexibility is shown in Figure II.9, an image of the polarized intensity and Faraday rotation of the bright quasar 3C 279 at wavelengths from 2 cm to 4 cm. This image shows that the rotation measure varies on small spatial and temporal scales, as the radio jet probes foreground clouds of plasma near the active galactic nucleus. Indeed, imaging at wavelengths as short as 7 mm shows reversals in the orientation of the magnetic field on parsec scales. Perhaps the seminal result in the VLBA's eight years of operation is the direct, multi-epoch imaging of the sub-parsec warped accretion disk around the Seyfert galaxy NGC 4258, at a distance of 20 million light years. This imaging has provided an extremely accurate measurement of a central black hole of mass 39 million solar masses, as well as providing a direct distance measurement that has been used to set the zero point of the extragalactic distance scale.

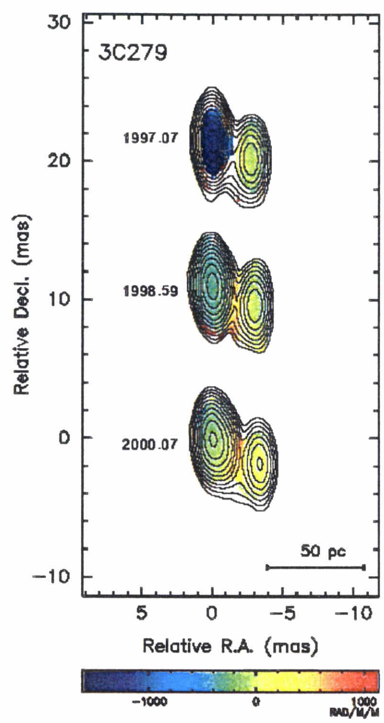


Figure II.9 Rotation measure (RM) mosaic of 3C279 from data at 8 to 15 GHz, for the indicated epochs, with contours of total intensity at 15 GHz overlaid. At epoch 1997.07 a substantial RM of -1300 rad/m^2 was discovered in the core (easternmost component), that subsequently decreased. This is the first documented instance of time variable Faraday rotation in extragalactic radio sources. In epoch 1998.59 a region with RM of about 600 rad/m^2 appeared and remains in evidence at epoch 2000.07. This feature in the RM may be associated with the emergence of a new component sampling a different line-of-sight through the Faraday screen. The estimated magnetic field strength needed to produce the observed RMs is 0.05 mG. The restoring beam has dimensions 1.0 x 2.5 milliarcsec at position angle 0 degrees. The colorbar ranges from -1310 to +1000 rad/m^2.

The critical scientific needs of the VLBA in the time frame covered by the long-range plan are an improved high-frequency capability and a significant increase in sensitivity. We have seen that the VLA, far ahead of its time at construction, now is constrained scientifically by its limited bandwidth and the consequent sensitivity limits. This is a particular disadvantage also for the VLBA; by its very nature as a long-baseline instrument, it can only observe and image sources of very high brightness. Only the brightest of the active galactic nuclei can be seen. Compact clusters of young stars and supernovae in starburst galaxies, generally too small to be imaged by the VLA, are too faint and diffuse for the current VLBA. Only the nearest and brightest of extragalactic supernovae, which potentially can provide direct distance measurements, can be imaged or even detected. In the high-frequency regime, at 7 mm (43 GHz) and 3 mm (86 GHz), the increasing contributions of the atmosphere and system noise, together with reduced coherence times and antenna surface/pointing problems, are even more restrictive. These high frequencies are where the VLBA can achieve its best resolution of 100 microarcseconds, and are precisely the regimes where it is important to image variable phenomena detected at other wavelengths. In the flaring gamma-ray blazars that will be detected by the hundreds by the Gamma-ray Large Area Space Telescope (GLAST), due for launch in 2005, only the VLBA at high frequencies will be able to directly image the regions of gamma-ray emission in order to distinguish among the different models for production of the relativistic jets and energetic gamma rays.

In order to achieve the scientific goals summarized above, the VLBA must not only have enhanced observational capabilities, but it must also be easier to use for the "non-expert." Therefore, an important element of the plan for the VLBA is the development of capabilities that bring it up to a higher standard of user assistance and delivery of data products. This element is necessary for broadening the use of the instrument, and integrating it into the mainstream of modern astrophysics as thoroughly as the VLA and the *Hubble Space Telescope.* Hence, our long-range vision for the VLBA rests squarely on the following three cornerstones:

- Increased sensitivity.
- Enhanced high-frequency capability.
- Ease of use for a broad spectrum of scientists

The VLBA in the Near-Term

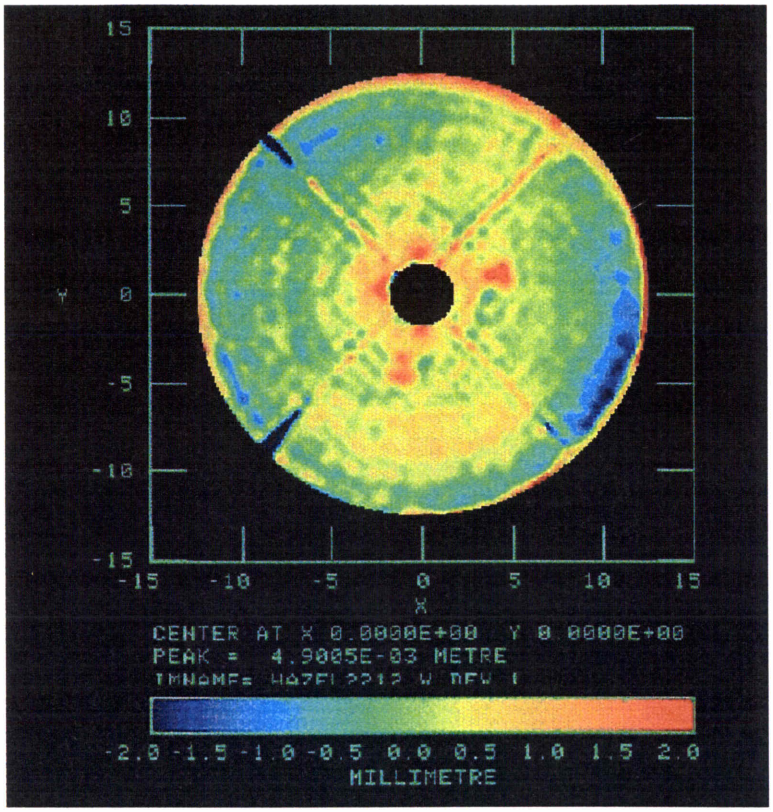
The first cornerstone of the VLBA plan is the sensitivity increases necessary to keep pace with other modern astronomical instrumentation. By 2002, the Green Bank Telescope (GBT) will increase the effective sensitivity of the VLBA by a factor of 2–3, depending on observing wavelength. In some instances, at the lower observing frequencies, the Arecibo Observatory also will be used to enhance the VLBA sensitivity. These large collecting areas will be in addition to the VLA, which now has about 10 percent of its scientific observing time allocated for phased-array VLBI observations. The inclusion of the larger apertures will enable new areas of science to be explored, specifically gamma-ray bursters and radio supernovae, both of which often emit at sub-millijansky levels. The GBT also will provide an important new addition to the ability of the VLBA to image relatively faint spectral lines from maser sources, both from galactic star-formation regions and extragalactic megamaser galaxies. Sensitivity improvements to the

VLBA as a whole are discussed below, in connection with the data-recording and correlation system.

The second cornerstone of the VLBA plan is a greatly enhanced high-frequency capability. Indeed, the most important new observational capability being implemented on the VLBA at present is a 3 mm (86 GHz) observing system. Construction of the first eight receivers is expected to be completed by the end of 2001, with the aid of funds received from the Max Planck Institut für Radioastronomie. We will build the last two receivers in 2002, in order that the full power of the VLBA can be implemented at this wavelength. In 2002 and 2003, we also aim to upgrade some of the first 3 mm receivers to their final state, improving sensitivity and reducing frequency ripple as well as extending the top end of the frequency coverage from 90 GHz to 96 GHz.

During the period from 2002 through 2006, the 3 mm system is likely to become one of the most frequently used capabilities on the VLBA. Previously, such short-wavelength VLBI has been conducted under the auspices of the Coordinated Millimeter VLBI Array, a group of loosely confederated telescopes that observe together for a few days on two or three occasions per year. This is inadequate to monitor and track the rapidly changing features in both galactic SiO masers and extragalactic jet sources. The 3 mm systems on the VLBA will be capable of observations when required scientifically and can be scheduled dynamically to observe when weather conditions are optimal for this frequency band. Final implementation of the 3 mm observing capability, including full polarization imaging, will enable the magnetic field in the circumnuclear region of active galaxies to be deduced with the unprecedented resolution of 100 microarcseconds, corresponding to well under a light year in distant quasars. We expect that the VLBA's 7 mm and 3 mm capabilities will be used frequently in conjunction with observations by both the Chandra X-ray Observatory and GLAST.

In order to make the 3 mm capability most effective, the surface panels on the VLBA antennas need to be adjusted to their optimum relative positions, and some subreflectors may have to be resurfaced. Because of imperfect panel adjustments and imperfect subreflectors, the aperture efficiency of the typical VLBA antenna is now about 15 percent at 3 mm. However, the individual panels are machined accurately enough to enable efficiencies of at least 30 percent; such performance requires an rms surface accuracy of approximately 200–250 micro-meters (0.2–0.25 mm), including both the main reflector surface and the subreflector. We are pursuing local holography measurements at present, and also investigating the possible utility of photogrammetry for measuring both the individual panel-setting and the subreflector shapes. Figure II.10 shows the first preliminary results of a local holography measurement of the Pie Town VLBA antenna, using a 12 GHz beacon from a geostationary satellite. In the 2003–2004 time frame, we expect to improve the high-frequency aperture efficiencies of the VLBA antennas using such techniques, doubling the sensitivity of the VLBA at 3 mm. In conjunction with the improved dish surfaces, further work is planned on the detailed pointing characteristics of the antennas, with a goal of approaching the 3 arcsecond pointing accuracy desired for the best 3 mm operations.



VLBA_PT Surface deviation map 2001Apr04

Figure II.10 Test of the local-holography surface measurement system on the VLBA-Pie Town antenna. Note the panel in the right-hand quadrant (the largest red feature), which was deliberately displaced in order to serve as a benchmark for the measurement system. Similar measurements of all VLBA antennas, and readjustment of main-reflector panels, are planned during the time covered by this plan. The ultimate goal is an rms surface accuracy in the 0.20-0.25 mm range.

One of the issues that has been brought up by observers using the VLBA is that the process of observing and analyzing data is too complex, and requires too much expert knowledge. This area represents the third cornerstone of our plan. Currently, we have produced simplified data-reduction scripts in the AIPS software that make the initial VLBA calibration steps far easier and more straightforward. The initial goal is that default procedures will be available for all data-calibration steps during 2001, making simple experiments such as continuum phase-referencing easy to calibrate without specialized knowledge. As an example, Figure II.11 shows the radio spectra of two weak (6–20 mJy) active galaxies observed for 10 hours each with the VLBA in March 2001. With the aid of the new data-reduction procedures, these two galaxies were completely calibrated, phase-referenced, imaged, and self-calibrated, at four frequencies each, in a total of 10 hours (less than half the total

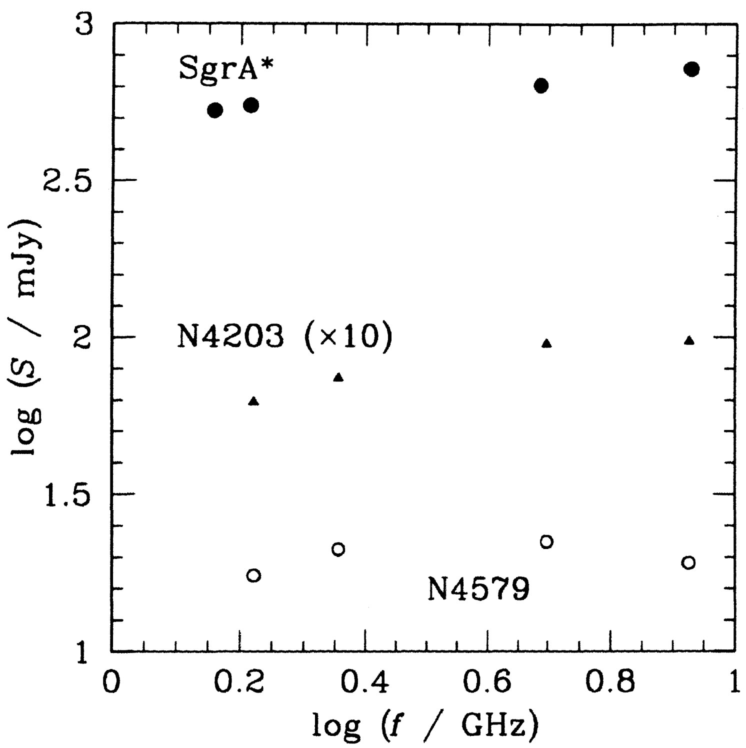


Figure II.11 Four-frequency spectra of two weak active galaxies imaged by the VLBA at four frequencies, compared to the spectrum of SgrA*, at the center of the Milky Way galaxy. The galaxies NGC 4203 and NGC 4579 are unresolved by the VLBA, with radio sources less than 0.05 pc (10,000 AU) in size. The similarity of the spectra indicates a common physical origin, such as in an advection-dominated accretion disk; analysis of the accretion will yield black-hole mass estimates for the two galaxies. The VLBA data, constituting a total of 20 hours of observations, were completely calibrated and imaged in less than 10 hours by making use of the streamlined VLBA data-reduction procedures.

observing time). The galaxy nuclei are unresolved on scales less than 0.05 pc, and show remarkable spectral similarities to the radio source SgrA* at the center of the Milky Way galaxy. With such results, we have reached the stage in which the bulk of the time spent on many VLBI observations can be devoted to scientific analysis rather than to the nuts-and-bolts of data reduction. Using the newly developed procedures, we anticipate offering a data-calibration service to users by 2002 and 2003. In addition, we aim to use this experience to translate the procedures quickly and easily into similar scripts in the AIPS++ package.

Since the first VLBA antennas are now approaching 15 years in age, significant aging problems are beginning to occur. Three specific issues are the elevation bearings, settling and aging of the azimuth tracks and wheels, and deterioration of the hydrogen-maser frequency standards. Enhanced maintenance and inspection programs are under development for the antenna structural elements. A regular program of maser repair is also needed and funding will be requested for this purpose.

VLBA Near-Term Milestones

Year	Capability
2001	Eight antennas equipped at 3 mm
2001	Complete data-reduction procedures in AIPS
2001	Complete holographic measurements of Pie Town antenna
2002	Begin offering data calibration service
2002	Ten antennas equipped at 3 mm
2002	Reach decision on possible subreflector replacement/modification
2003	Complete holographic measurements of all antennas
2003	Upgrade initial 3 mm receivers
2003	Begin translation of data-reduction procedures to AIPS++
2004	3-arcsecond pointing
2004	Aperture efficiency improved to average of 25%-30% at 3 mm

Vision for VLBA in the Long-Term

The *New Mexico Array* antennas of the EVLA project, Phase II, will fill the gap in baseline lengths between the current VLA and the VLBA. The three cornerstones of the VLBA plan, discussed previously, are required to bring about complete complementarity of the VLA and the VLBA and to effectively merge the two instruments. In terms of VLA configurations, which are spaced by about a factor of three in resolution, filling the gap will effectively add four new configurations. The two smaller ones use the VLA and NMA antennas, including the two VLBA antennas at Pie Town and Los Alamos. The two larger ones use the NMA antennas and the other VLBA antennas. When this capability becomes available, the EVLA and VLBA effectively become one instrument with the full range of baselines between 25 meters and 8600 km. The resolution used for an observation will be chosen based on scientific needs rather than available instrumentation.

Why fill in the baseline gaps between the current VLA and the current VLBA? An entire set of spatial scales is being missed by the current instruments. Depending on the observing frequency, this missing scale is in the range from 10 to a few hundred milliarcseconds, just the scale that is probed currently by the *Hubble Space Telescope,* and that will be explored in the future by the *Next Generation Space Telescope*. Put in terms of the sensitivity cornerstone, the current VLBA can only detect sources with brightness temperatures of about 10^7 K and higher. However, many astronomical phenomena, such as young supernova remnants and accretion tori around active galactic nuclei, are thought to have brightness temperatures in the range between 10^5 K and 10^7 K. These are objects that shine brightly at soft X-ray energies. But, they are too small to be imaged by the current VLA, and too extended or faint to be imaged by the current VLBA. Filling in the gaps in baseline coverage, together with the increases in sensitivity discussed below, will also fill in the significant scientific gaps that currently exist. The combined EVLA/VLBA then will be able to work together with high-performance observatories utilizing different parts of the electromagnetic spectrum.

Effective use of the EVLA and VLBA as a merged instrument will require tight coordination of scheduling and complementary hardware capabilities; all VLBA upgrades over the next decade must be aimed at bringing about this high level of compatibility. Such compatibility is necessary to continue progress toward our third cornerstone, ease of use of the combined instrument.

The areas where VLBA scientific capabilities must be upgraded for complementarity with the EVLA are in data transmission system bandwidth, correlator capacity, and frequency coverage. The current sustainable bandwidth of the VLBA is 500 times smaller than what will be available on the EVLA, far too extreme a ratio for effective combination into a single instrument. This bandwidth is limited severely by the VLBA recording system. Upgrading the data transmission/recording/correlation system is therefore the most urgent requirement for the VLBA. (Making use of a multi-gigahertz system also will require new intermediate-frequency and sampling equipment.) Specific options for such an upgrade are discussed further in the next subsection.

Scientifically, why is a higher data-transmission and correlation bandwidth needed? Entire classes of objects are now inaccessible to the VLBA because of its limited sensitivity. For example, consider Super Star Clusters such as those in NGC 5253. These could be imaged in starburst galaxies at distances up to 100 Mpc, but only if baselines of several hundred kilometers have a brightness temperature sensitivity better than 10^4 K. Such sensitivity is achievable only with gigahertz recording/correlation bandwidths, and the effective merger of the EVLA and VLBA For the longest VLBA baselines, structures such as radio jets in weak active galaxies are "resolved out" due to the lack of adequate brightness sensitivity, a problem that can be (partly) alleviated by increasing that sensitivity by an order of magnitude. With the move of the VLBA to observations at 3 mm wavelength, where the atmospheric coherence time is quite short, an increase of a factor of 10–30 in observing bandwidth will enable a factor of 30–100 times more sources to be imaged. This will provide the capability of doing extremely high resolution studies of all blazars as they flare in the gamma-ray regime, rather than just the few tens of such sources that can be imaged at 3 mm with the limited bandwidth now available.

VLBA Data Recording/Transmission/Correlation System

The existing tape-recording system limits the VLBA's bandwidth/sensitivity in two ways. Currently, the VLBA is capable of recording at peak data rates up to 512 Mbps (only 128 MHz bandwidth with 2-bit samples); even such a modest data rate can be used at only a small duty cycle, due to the limitations of the current system's open-reel tapes. Progressing beyond this limit in the near-term requires a new VLBA data recording system with a sustainable data rate of at least 1 Gbps (Gigabit per second) for at least 24 hours (72 hours preferred to get through weekends). Fortunately, new VLBI recording systems in the 1–2 Gbps range are already under development. These use either video cassettes with robotic changers ("S3" system under development at York University in Toronto), or "mostly-off-the-shelf" disk-based technologies (under development at Haystack Observatory in Massachusetts). The designers of both these new recording systems have committed to compliance with the recently adopted VLBI Standard Interface (VSI) specification, which should substantially simplify the connections from telescope through recording system and into the correlator. They have similar cost estimates of about $4M for the ten VLBA stations, the VLA, and the GBT, plus the correlator's 24 playback units. Either system would push the capabilities of the current VLBA correlator to (for 0.5–1 Gbps) or beyond (for 1–2 Gbps) its technical and operational limits.

Approaching the EVLA bandwidth of 16 GHz will require a completely new correlator, and perhaps a change in philosophy for the method of data transmission. The most attractive and cost-effective way to achieve the correlation capacity is to augment the EVLA correlator appropriately. This would also be a large step toward making the EVLA and VLBA a single instrument. The WIDAR correlator design, which can deal with the long VLBI baselines, allows just that. The preferred long-term option would be to build a 48-station correlator that could handle the full EVLA bandwidth from all antennas (EVLA+VLBA). But the current WIDAR correlator design also allows for the options of correlating two stations with 4 GHz bandwidth, or four stations with 1 GHz bandwidth, for each 16 GHz station input. Thus, augmentation of the baseline 32-station correlator for EVLA Phase I to a 40 station correlator easily could handle a 1 GHz VLBA bandwidth for 20 or more stations, simultaneously with 27-station VLA correlation at 16 GHz. The increased VLBA bandwidth represents an increase in sensitivity of nearly a factor of six, all achievable, at an estimated additional cost of $3M for adding eight stations to the WIDAR correlator.

Somewhat independently of the bandwidth considerations, the joint operation of the VLBA and NMA would be made considerably simpler if VLBA data transmission could be done over optical fibers with correlation in real time. This area will be studied thoroughly in designing the NMA, and it is expected that much of this development can be carried over to the VLBA. Although the cost of fiber transmission is falling, it is expected to be many years before we will be able to afford the desired large bandwidths for the entire VLBA. The VSI specification was designed to accommodate real-time transmission as well as recording, so the interfaces to either of the new recording systems discussed above would allow a relatively transparent change to fiber transmission as early as possible.

Cost Estimates for New VLBA Recording/Correlation Systems

This section gives cost estimates for new VLBA recording, playback, and correlation systems, as discussed above. These estimates are preliminary, and depend on ongoing hardware developments outside NRAO. Cost estimates are restricted to a 2 Gbps (0.5–1 GHz) system, since higher bandwidths are likely to be feasible only after the time period covered by the present plan. No cost estimates are given for connecting the entire VLBA via fiber optic links, due to the uncertainty in time scale for this connection and the extremely rapid change in the field of commercial high-bandwidth data transmission. In addition, no costs are included for widening the accessible frequency bands at the VLBA in order to achieve compatibility with the EVLA. Possible dates for realization of the different advances are based on estimates of technology readiness, and would depend on availability of funding.

2 Gbps System	Costs	Planning Dates
VLBA Channelization – 4 Channels, 128 MHz (0.5 Gbps) each	$2.0M	2004
VLBA Recording – 2 Gbps cassette- or disk-based recording system	$1.4M	2005
VLBA Playback – 2 Gbps cassette- or disk-based system	$2.7M	2006
Enhancement of WIDAR from 32 to 40 stations	$3.0M	2006

III.1 Science Support Programs

User Support Programs

The Observatory has always recognized the need to support its user community in the reduction, analysis, and publication of the data obtained on NRAO telescopes. Programs that provide software systems for processing data, travel support for observing and data reduction runs, and support of page charges have been in existence for many years. We have expanded these programs, starting in 2001, by paying for full travel and page charge costs associated with using NRAO telescopes, and instituting new programs during the period of this Plan that will address the present requirements of users.

All space astronomy missions provide funding for the analysis of data and its eventual publication. This NASA policy, continued for many years now, has changed the landscape of astronomical research. There has been a huge expansion of the field in general. NSF funding for university grantees has failed to keep pace with this expansion, making it difficult to obtain funds for ground-based research. As NSF is virtually the sole source of support for radio astronomy, the university users of radio telescopes have especially suffered. This is particularly true for those not at universities with radio facilities of their own. *It is essential that NSF provide funds for data analysis that accompanies observing time on ground-based facilities.* The Astronomy and Astrophysics Survey Committee has recommended this for new (NSF) ground-based facilities. We will propose such a plan for GBT users, and, in due course, for users of the EVLA, VLBA, and ALMA.

The university groups are the sole source of new instrumentalists in radio astronomy. To the extent that these groups continue to operate facilities of their own, the supply of instrumentalists will continue. We plan to support the activity of these groups with a program of instrument development and construction for NRAO telescopes. As was mentioned above, this program will begin with the GBT. The intent is not to merely use these groups as subcontractors. Rather, when the scientific programs of these groups require new instrumentation on NRAO telescopes that they are capable of providing, we will share in the funding of such instrumentation. The program will be a *managed* program, that is, with memoranda of understanding that clearly define scope, standards, cost, and schedule, and have review mechanisms to track progress.

Observatory Scientific Staff

The rationale for the Observatory's scientific staff policy is based the conviction that excellent service to the user community is best provided by first-rate research-active scientists. The requirement that the NRAO scientific staff not only provide service, through their functional duties, but also be active in research, leads to a requirement on the Observatory to provide the resources required for that research. These resources consist of the typical research support (computing, library, communications, copying, travel, etc.) and, most important, the time to do research. The computing resources available to the scientific staff will improve during the period of this Plan as part of the planned improvements in all of NRAO computing, although we intend to maintain our policy of placing a higher priority on the computing resources for visiting users. Increases in other research support items, such as travel, will be made as appropriate from year to year. Providing better means to protect uninterrupted research time to the scientific staff is a goal of this Plan. A variety of means will be necessary: days, weeks, or months set aside for research; internal sabbaticals; exchanges with other institutions; encouraging use of the present Leave for Professional Advancement program; etc. The provision of the time required could lead to hard decisions on the scope of activities we can conduct or the pace at which we conduct these activities, as we do not propose any significant increase in the size of the scientific staff.

A Director's Discretionary Fund will be established to support the increased requirements in this area.

III.2 Central Development Laboratory

Instrumentation and electronics development performed at the Central Development Laboratory (CDL) is directed toward receiver development for NRAO telescopes. Support for the GBT, VLA, VLBA, and ALMA will include:

Table III.1

Research and Development Area	Applicability			
	GBT	VLA	VLBA	ALMA
HFET amplifiers	x	x	x	x
SIS mixers				x
Electromagnetic structures	x	x	x	x
Local Oscillator components	x			x
Digital correlators	x	x		x
Feed arrays	x			

HFET Amplifiers

HFET amplifier work has resulted in successful development of all-InP HFET amplifiers useful from 3 to 116 GHz, and balanced amplifiers using GaAs devices below 2.0 GHz. The highest frequency amplifier developed so far covers the band 68-116 GHz with a noise temperature of 60 K.

At frequencies below 2.0 GHz, balanced amplifiers which have a noise temperature of 2-3 K have been developed and are used in the low-frequency GBT receivers. In collaboration with JPL, we will evaluate the performance of MMIC amplifiers for the 75-115 GHz band; it is possible that for large-scale production in the future, use of these integrated chips rather than discrete devices may offer cost advantages which offset some performance deficits. We expect over the next few years to phase out the use of GaAs devices except perhaps at the very lowest frequencies, extending the use of InP devices as low as 1 GHz. The performance of HFET amplifiers in wideband radiometric systems is affected by the random gain fluctuations usually called "1/*f* noise." We have acquired an advanced capability for characterizing the phenomenon and will continue actively to investigate it.

The NRAO will continue to supply amplifiers, mixers, and electromagnetic devices that are not available commercially to the scientific community on a cost-reimbursable basis. This vital function of the CDL has resulted in advances in receiver capability on radio telescopes throughout the world and we intend to continue this important service in addition to our primary task of making components for NRAO use.

SIS Mixers

Superconductor-Insulator-Superconductor (SIS) mixers fabricated of niobium are designed at the CDL. Good performance of sideband-separating and balanced mixers for the ALMA 211-275 GHz band has been demonstrated. We will complete the development of an integrated SIS mixer chip which combines all these features. Other means of providing the features of sideband separation and balanced operation will be pursued vigorously, using passive structures. These include waveguide hybrids and power splitters machined into split blocks, allowing use of multiple single-ended mixer chips to achieve the desired configurations. Another SIS development goal is to achieve an IF bandwidth of 8 GHz per polarization, with a target band of 4-12 GHz, using either a wideband isolator or a preamplifier integrated with the SIS mixer. We have successfully developed a discrete transistor amplifier implementation, adapting the 3-13 GHz InP HFET amplifier which has been developed at the CDL. This is the widest bandwidth SIS mixer receiver yet reported. We will progress beyond the prototype stage by mating this preamplifier to the sideband-separating, balanced SIS mixers. We will pursue issues relating to reproducibility and quality control for all these alternative designs. We have greatly improved SIS mixer testing by automating this complex process, reducing testing time from 16 hours to 5 hours per mixer; this effort will continue in order to make it possible to test the very large number of mixers required for the ALMA receivers. In order to provide receivers for other ALMA bands, we will develop additional SIS mixer designs, including 85-115 GHz and 602-720 GHz.

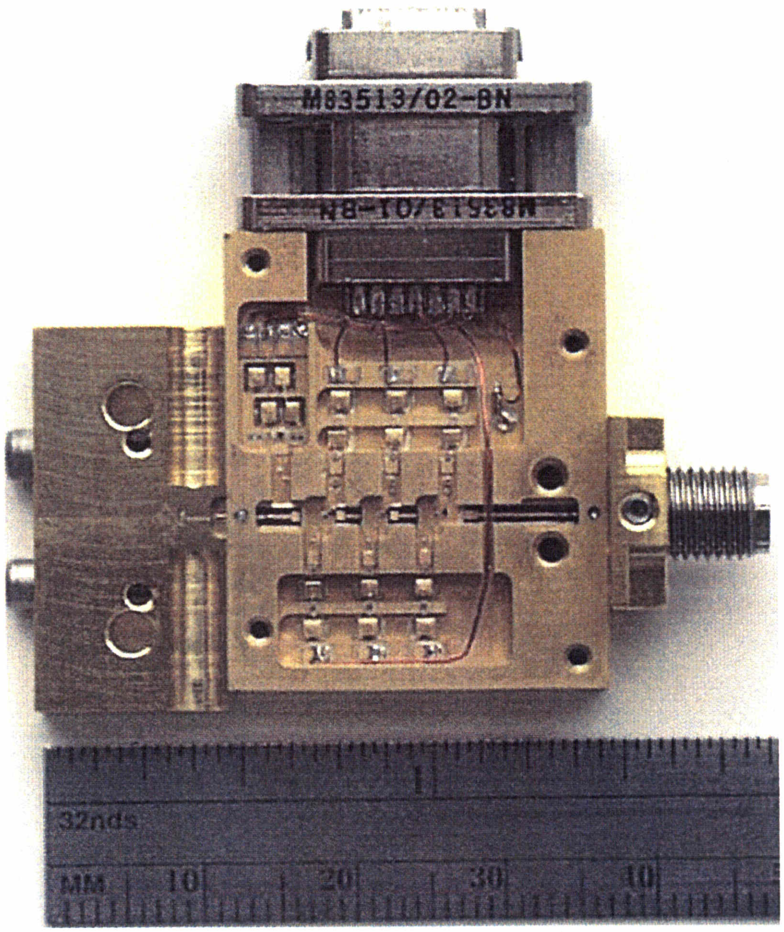


Figure III.1 SIS Mixer-Preamp for 211-275 GHz. The SIS mixer section with waveguide inputs for RF and LO is on the left. The mixer output is directly coupled to a 3-stage 4-12 GHz IF amplifier which uses InP transistors. The combination gives an IF bandwidth of 8 GHz, more than twice that ever achieved before.

In the future, the NRAO may work on the development of Niobium Titanium Nitride (NbTiN) mixers for frequencies above about 700 GHz. These devices are still quite experimental, but they hold the promise of giving somewhat lower receiver temperatures than standard Nb mixers above this frequency. There are currently problems with reproducibility which might be profitably addressed by experienced NRAO SIS mixer designers.

In the future, the NRAO also may work on the development of Hot Electron Bolometer mixers for receivers at frequencies above roughly 1000 GHz. These devices are still quite experimental, but they hold the promise of giving much lower receiver temperatures than SIS mixers. For heterodyne receivers on either Earth- or space-based telescopes, they have the potential to become the device of choice.

Electromagnetic Structures

Reflectors, lenses, feeds, polarizers, vacuum windows, and other electromagnetic devices are essential for receivers. A new 18-26 GHz full waveguide band polarizer has been designed and built in quantity for the new VLA K-band receivers. Along with a new InP HFET amplifier, this has resulted in a noise temperature at the zenith of about 50 K for the new receivers, a factor of 3 improvement over the old system. New electromagnetic modeling software is being used to design new polarizers for the 26-40 GHz and 12-18 GHz bands. For ALMA and EVLA development, we will continue to develop feeds, waveguide hybrids and power splitters, quasi-optical components, vacuum windows, etc. We will continue to research new window materials and construction techniques to achieve minimum RF loss combined with wide bandwidth and acceptable gas leakage. Vacuum windows using a PTFE-Teflon-crystalline quartz-Teflon-PTFE sandwich have been developed and produced in quantity for the VLBA 80-95 GHz receivers; these show great promise for extending the interval of time before refrigerators must be shut down due to leakage.

Local Oscillator Components

For ALMA, we have demonstrated that using an electronically-tuned YIG oscillator below 40 GHz, power amplifiers, and frequency multiplier chains, we can generate the necessary LO signals with the required signal purity and no moving parts. Frequency multipliers have been used successfully to generate suitable LO signals for pumping an SIS mixer up to a frequency of 230 GHz. The phase and amplitude noise characteristics of such an LO chain have been demonstrated to meet the stringent performance requirements for array operation up to 950 GHz. We will continue to develop wideband, tunerless frequency multipliers using planar diodes both in discrete arrays and in integrated circuits. This work will result in the development of LO drivers and frequency multipliers for all the ALMA bands. The reference signal for the LO drivers is to be supplied over a fiber optic connection by beating together two phase-locked infrared lasers operating in CW mode at slightly different frequencies; this work is carried out at the Tucson facility.

Digital Correlators

The baseline ALMA correlator development will continue at the CDL. The specification of 16 GHz bandwidth, dual polarization, and 1024 spectral points for 64 antennas requires a computation rate of 1.7×10^{16} multiply-and-add operations per second. The new correlator uses a digital Finite Impulse Response (FIR) filter for bandwidth selection. This will improve the stability of the correlator output by eliminating the need for multiple analog filters, mixers, and oscillators in the baseband converter. A new correlator chip with 4096 lag correlator elements is being designed and will be produced in prototype quantities in 2001. Testing of prototypes of all correlator boards will also occur during 2001. A prototype correlator will be produced for use at the VLA test site in 2003. The first quadrant of the correlator, capable of handling up to 32 antennas, will be delivered to the Atacama site in late 2004. During this development, support for existing correlators at all NRAO sites will continue to be provided.

Feed Arrays

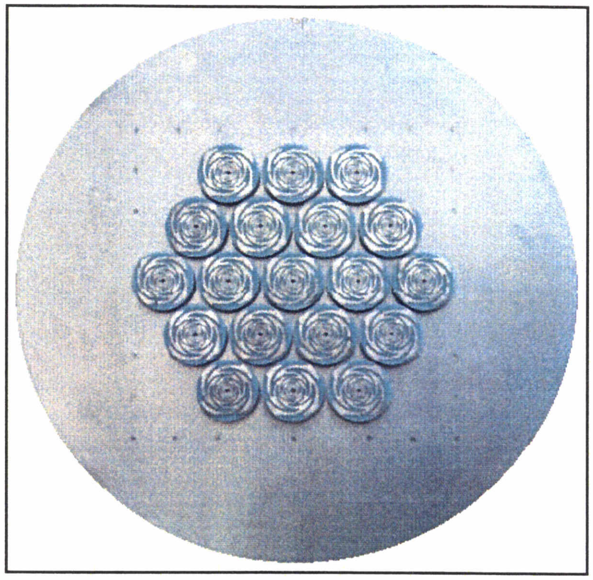


Figure III.2 A 19-element Focal Plane Sampling Array. This feed array, operating at 1.2-1.6 GHz, fully samples the focal plane of a telescope in the area it covers. This permits synthesizing multiple well-formed beams at any position within that area by cross-correlating and weighted combining of several received channels with the appropriate amplitudes and phases.

The next generation of instruments will undoubtedly involve array technology. The scientific throughput from both large filled-aperture antennas such as the GBT and aperture synthesis telescopes such as the VLA would be greatly enhanced by increasing the telescope's field-of-view using a phased array of sensitive detectors across the focal plane together with the signal processing power required to achieve real-time imagining and spectroscopy. Such an array can also be used to correct aberrations in the telescope optics and for adaptive interference mitigation. Effective research and development of such complete imaging-spectrometer array systems for use throughout the radio spectrum is a major interdisciplinary endeavor, requiring expertise in such diverse areas as semiconductor physics, MEMS, cryogenics, low noise electronics, microwave engineering, antennas, photonics, digital signal processing, and system engineering to name a few. We are pursuing a novel interdisciplinary initiative that will address the cutting-edge research necessary for this emerging new generation of instrumentation while simultaneously bridging the technology gap between future users and creators of these instruments.

At present, filled-aperture radio astronomy systems with multiple beams on the sky use multiple conventional channels, each with its independent feed and receiver. We have developed an array feed system where the actual beams on the sky are formed by a cross-correlation signal processing network. As part of the correlation process, first order optical aberrations (coma and astigmatism) can be corrected and constant sources of RFI can be nulled. This will allow a large number of beams to be placed at the prime focus with the field electronically flattened to provide a cost-effective but extremely powerful method of focal plane imaging. A prototype L-band array feed receiver which packs planar feeds close together (see Figure III.2 above) and achieves multiple beam synthesis by weighted combination of multiple feed outputs has been developed and tested on the 140 Foot antenna; it showed that multiple beams with good beam shape and efficiency can be synthesized from appropriately phased linear combinations of the basic feed elements. This work will be continued with the objective of eventually building an L-band array receiver whose noise performance equals that of individual receivers in each of many synthesized beams. Working groups have been established to study both the scientific and technical issues for beam-forming arrays.

The initial development program requires about $250k in capital outlays and a total of about 14 staff years of effort over the length of the project. The technical challenges lie in the area of achieving competitive noise temperatures in each receiving element, the closely related area of cryogenic cooling of individual amplifiers and feeds, and in the substantial signal processing capacity required by the cross-correlation network. As these technical challenges are solved, it will become possible to extend the number of beams and scale the design to higher frequency. The signal processing for an advanced, large format array will require a large correlator, which perhaps can be built as a spin-off of the planned EVLA correlator.

III.3 Data Management

The EVLA, VLBA, GBT, and ALMA will give scientists access to an unprecedented suite of tools to investigate a wide range of astrophysical problems. To aid astronomers in the use of these telescopes, the NRAO has undertaken to provide calibrated and imaged data from most observations with NRAO telescopes. This will free the astronomer to concentrate on the astrophysics rather than the mundane details of data analysis. Furthermore, the results from observations on NRAO telescopes will available (after the usual proprietary period) via web-searchable archives, thus allowing other scientists to benefit from observations made with NRAO telescopes.

In order to fulfill this undertaking, the computing services at the NRAO were reorganized in May 2000 under a new part of the Observatory: Data Management. This is organized similarly to the Business area: the Associate Director for Data Management determines plans, policies, and priorities, and the local Site Directors, Assistant Directors, and other management staff have responsibility for execution, reporting back through the AD for Data Management. Data Management is advised and aided by a Project Scientist (Frazer Owen), and a Scientific Working Group (chaired by Owen). A DM Executive Committee composed of the local heads of computing, and software project leaders meets monthly, and aids the DM core team in management activities.

Data Management has three main areas of focus:

1. The Data Management Initiative (DMI): improving the data services and products offered to users of NRAO telescopes.
2. Technology Development: developing technology support for the DMI and general observatory computing.

3. Central Computing Services: coordinating and supporting computing activities throughout the Observatory.

Data Management Initiative

After extensive discussions both internally and with the various NRAO advisory bodies, we have adopted the following goals and commitments to our users:

- To deliver an improved scientific data product to users, including calibrated data and reference images.
- To provide easy (web-based) access to archives of contemporary and historical images, surveys, catalogs, etc. for all NRAO telescopes.
- To pursue vigorously development and collaboration with the university community and other observatories in areas relevant to observer access and use of radio telescopes.

These DMI goals are common with those of ALMA and of the EVLA, and upon funding of these projects developmental efforts can be shared. The NRAO has an interest in assuming overall responsibility for the production of the ALMA processing system, and is currently negotiating for this activity within the ALMA project phase II definition. The EVLA proposal asks for funding to develop capabilities aligned with key elements in the Data Management Initiative: the pipeline and the archive. DM will contract with the EVLA Project Management to develop these elements for the EVLA.

The larger U.S. radio community has an interest in the same goals as the DM initiative. Consequently, we have organized a team (NRAO, NCSA/U. Ill., & NAIC/Cornell) that has proposed to the NSF/CISE Information Technology Research program with the goal of establishing a virtual facility (COmmon grid-Based Radio Archive: COBRA) dedicated to simplifying the use of radio telescopes, and to making scientifically useful archives widely available to all astronomers. COBRA would provide a focal point for these developments throughout the radio astronomical community, and would also serve as a resource and point of contact for processing and archiving of radio observations. The radio astronomy community and the NRAO both have a strong background in the utilization of state-of-the-art computing technology for advancing science. The AIPS++ consortium (NRAO, ATNF, JBO, BIMA, & NFRA), has devoted considerable effort to developing the technology that can be used in this development. If our IT-R proposal is successful, funding could start in the fall of 2001 and run for five years, forming a key element of the Observatory work in the DMI for the period covered in this report.

The Observatory is also a key partner in the national effort to develop a National Virtual Observatory (NVO), which was highly recommended by the recent report of the NAS/NRC Astronomy and Astrophysics Survey Committee. The NVO will link the archives of ground and space-based observatories, the catalogs of multi-wavelength surveys, and the computational resources necessary to support science based on these resources. The inclusion of radio astronomy observations, both pointed and surveys, is clearly very important for the long-term scientific impact of radio astronomy. The NVO will principally be a repository for scientific results such as images and catalogs, so it is important that the NRAO commit to making an image part of the standard product from an observation. It is expected that some funding from the NVO will be available to connect the NRAO archives to the NVO.

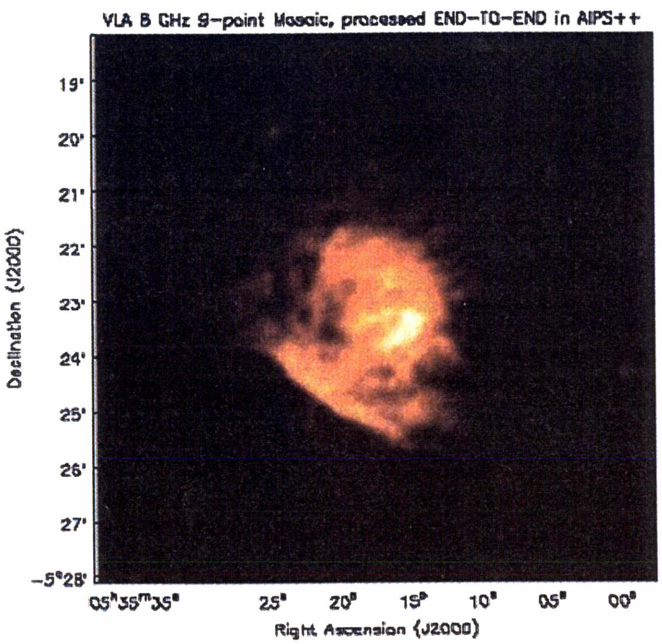


Figure III.3 One of the early uses of the GBT will be to generate large angular scale information to complement observations like this one of the Orion nebula from the VLA. Work is proceeding to make the combination of single-dish and interferometer data inside AIPS++ very straightforward.

It is clear that for the DMI to work, NRAO must provide coordinated, end-to-end management of observing from initial proposal to final scientifically useful data products. The most urgent issues that must be addressed by the DMI lie in the area of data archiving and pipelining. A hallmark of radio astronomy is the large volume of data that must be managed, stored and reduced. There has been a steady increase in the size of data sets produced by NRAO instruments, and in the amount of processing and analysis required. Examples of techniques that are pushing up the size of data volumes at the NRAO include mosaicing, on-the-fly imaging, interferometric spectral line observations, and new spectrometers on single-dish telescopes. Current facilities at sites for managing voluminous data sets are inadequate; with particularly lengthy delays caused by lack of data storage space and limited tape drive capacity. Additionally, the archives of telescope observations are not easily accessible from the Web, and only contain data prior to calibration.

There are three problems to be considered here. In the short term, we must be able to export large volumes of data to our users. In the medium term, we must be able to move the data into web-accessible archives. In the longer term, we must be able to populate the archive with calibrated and imaged data.

Addressing the short-term issue of data export first, limited deployment of higher-speed, higher-capacity tape media such as Digital Linear Tape (DLT) and similar devices such as Exabyte Mammoth was done in 1998, but it has not been possible to supplement this since. New workstations are also being purchased with an increasing amount of disk space, which reduces the need to juggle data sets but introduces a serious problem archiving the data to tape. In 2000, at the urging of the NRAO User Committee, several of the old 5 GB Exabyte and 2 GB DAT tape drives were upgraded on visitor systems at the AOC, so that a minimum of 7 GB is now commonly available. Additional upgrades will be needed for the remaining older drives. While an improvement, this does not go far enough; we need to provide the NRAO's users and visitors with new options for dealing with their data, to increase

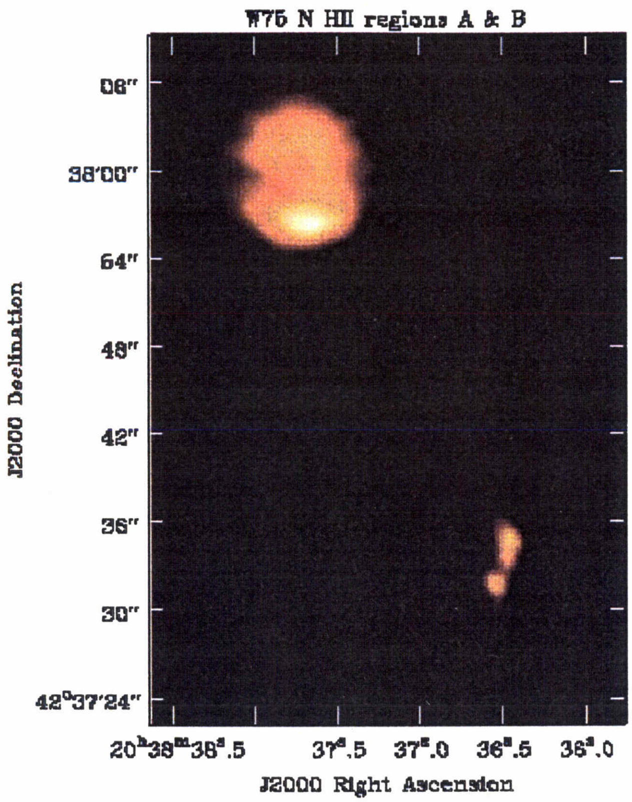


Figure III.4 W75 N in 6 cm continuum emission.

Ionized gas in 6 cm continuum emission in the massive star forming region W75 N. The extended shell source in the north-east (HII A) is an older HII region. The radio emission is associated with an infrared source indicating that the central star is in the final stages of emerging from the cloud. The cluster of compact HII regions in the south-west (HII B) is younger and and contains at least four massive protostars. The young cluster is powering one of the most energetic outflows in the Milky Way Galaxy and has already caused at least 300 solar masses of material to be expelled from the central cloud core.

The data was calibrated from end-to-end in the AIPS++ software package. The image was cleaned with the new multi-scale clean algorithm which is designed to simultaneously clean both large and small structure in the image. Hence, the extended structure of HII A can be imaged accurately while preserving the small scale structure of the HII B cluster.

the efficiency of data processing and reduction. The greater storage capacity and transfer rates of new tape media are not only necessary to reduce the effort and time required to back up large amounts of data, but are critical for those projects which produce very large files.

In the medium term, we must consider the requirements of archiving very large volumes of raw data. The VLBA archive currently contains more than 7 terabytes of data stored on 2 GB DAT tapes. The accumulated data archive of the VLA, spanning 23 years, is about 2.5 terabytes, increasing by roughly 10 percent per year; this rate will go up considerably when the EVLA is implemented. Also, the GBT spectrometer will be capable of generating data at a rate exceeding that of the VLBA. Clearly, the tape media currently being used for these purposes has neither the capacity nor the longevity required for permanent archives. Alternatives will be investigated as part of the Data Management Initiative. As an initial estimate for the material cost of the new archives for the VLA, VLBA, and GBT, we have allocated $100k per telescope as follows: $100k in 2002 for the VLA, $200k in 2003 for VLBA and GBT. Provision of the necessary software will be part of the DMI. If possible, we will subcontract much of the software for archiving to another organization, such as the Space Telescope Science Telescope, with experience and a track record in this area.

In the longer term, the archives will be filled by pipeline-processed data. Development of the necessary software for pipeline processing will occur in AIPS++, supported by funding from the EVLA, ALMA, and COBRA.

Finally, the development of archives and pipelines requires a number of changes throughout the data path for NRAO telescopes. The information presented by the user in the proposal and observing schedule must be preserved in the data flow through the observing system, into the pipeline and archive. The observing schedule must provide enough information for the pipeline to determine how best to calibrate and image the observations automatically, and for the observing system to schedule observations dynamically. Also, the observer may need to interact with the observations in real time. All of these areas will be addressed by the DMI.

The core DMI activities will require both increased staff and the increasing funding for equipment. We plan to hire five more computing staff members in support of the DM program: a chief architect, and four supporting staff members. These staff will work in close collaboration with the AIPS++ group (see below) to apply the functionality of the AIPS++ package to DM projects.

DM Technology Development

The DM Technology Development group is responsible for the development of technology needed to support the DMI and other NRAO computing activities. It is a force for consolidation and cooperation throughout the observatory. Technology Development is responsible for investigating both hardware and software, but much of the current focus is on data analysis software.

The Observatory is in the midst of a transition from our existing data analysis packages, AIPS and Unipops, to the AIPS++ package, which has been under development by a consortium of radio observatories. The first release of the AIPS++ package was made in October 1999, with subsequent releases in June 2000 and November 2000. Use of the package has begun and is expected to grow. AIPS++ will be the prime data reduction and analysis package in use at the Green Bank Telescope, replacing Unipops. AIPS++ has been used extensively throughout the GBT construction for various engineering purposes, and is now being used during the commissioning phase, and for subsequent scientific observations. AIPS++ is now focusing on the finalization of software for the reduction of synthesis observations. During the period of this Long Range plan, AIPS++ will have made the transition from a development project to a production system that can be turned to various uses. Our plans for the COBRA and for DM activities in general are therefore strongly based on AIPS++.

AIPS++ has a number of other ongoing projects that will result in new capabilities in the next years. The parallelization initiative, conducted in collaboration with the National Center for Supercomputer Applications, is proceeding well, and has resulted in various key synthesis imaging applications enabled for parallel computers, including those for wide-field imaging as needed for EVLA. Future work includes additional software for mosaicing observations such as those planned for ALMA. Similarly, a visualization effort, funded by a grant from the NSF/ACR program will result in novel highly interactive reduction facilities in 2001. Current staffing in AIPS++ is inadequate in both system support and user support. As the package becomes more widely used, both these areas will need additional staff, and we therefore plan to hire a system support person in 2001, and another user support scientist in 2002.

During the period that AIPS++ is coming up to full capability, we will continue to support the large user base of the AIPS package. Work in AIPS will concentrate on supporting existing users, and on tracking key changes in the capabilities of NRAO telescopes.

Central Computing Services

Central computing splits into a number of different areas:

- Observatory-wide Computing: responsible for budgets, acquisitions, and contracts throughout the Observatory.
- Security: responsible for computing security policy and enforcement throughout the Observatory.

- Communications: responsible for the Observatory communications infrastructure: principally networks.
- Information Infrastructure: for Web services, groupware (*e.g.* calendars and meeting scheduling), directory services (*e.g.* phone book and LDAP), and other tasks providing support Observatory-wide.

Observatory-wide Computing: Over the past two years, 1999 and 2000, the Observatory budget again drastically limited progress in addressing many of the problems of our aging computing infrastructure. The level of Observatory-wide Computing funding in 2000 for such items as equipment, training, and software, was one third that available in 1997 and 1998. This meant that vitally needed upgrades could only be done for about 8 percent of the workstations used by NRAO's staff and visiting observers. If the current rate of replacement were to continue, the service lifetime of staff desktop computers at the NRAO would be roughly 12 years—clearly longer than it could actually be considered useable given the pace of development in the computer and software industries. Our plan is to restore the current rate of replacement to 25 percent level, ensuring that during the course of this Long Range plan, all workstations are replaced at least once.

Upgrade or replacement is also dictated by the increasing demands on computational capability from both increased demands by NRAO users and increased observational capabilities brought about by technological advances and enhanced processing techniques. These upgrades would allow most workstations at the NRAO to be replaced or upgraded by the end of their useful lives (typically no more than four years for scientific workstations). They would also allow us to upgrade the smaller network server systems at sites such as Tucson and Green Bank.

Roughly $300,000 per year is allocated for computer hardware acquisitions/upgrades, covering desktop computers, visitor facilities, and servers, for the duration of this Long Range plan. This level of investment will accomplish three goals:

- Permit the NRAO to provide staff and visiting observers with systems and storage options that are capable of handling medium to large problems.
- Allow the NRAO to address the problems it faces with an aging computer infrastructure.
- Provide capability for addressing high-end scientific problems that are beyond the capacities of current computing facilities at the NRAO.

Attention must also be paid to the computing facilities needed by the NRAO engineering staff. The NRAO is pursuing several initiatives leading to development of major new observational instruments, or greatly enhanced capabilities for existing instruments. Chief among these efforts are the Green Bank Telescope project, the Atacama Large Millimeter Array, and the EVLA. These projects, like many ongoing engineering tasks for existing instruments, are heavily dependent on the use of advanced engineering workstations and the accompanying software to carry out various aspects of design and fabrication. If engineers at the NRAO continue to carry out their work using obsolete or inadequate workstations and PC's, their productivity will suffer. Improvements in this area were minimal in recent years and will need further investment over the next five years. We also need to ensure that the engineering staff has access to current releases of major software packages, to reduce the difficulty that has been encountered in exchanging information. Little progress in this area has been possible since 1998, much of it piecemeal from construction budgets. Approximately $100,000 is needed to allow the acquisition of both appropriate workstations and required software; in particular maintenance contracts are required Observatory-wide to prevent the recurrence of compatibility problems due to uncoordinated upgrade schedules.

Security: Computer and network security will continue to be a major concern at the Observatory over the next five years. The NRAO computer security practices must balance the need for reasonable access by users to our computing services from outside the Observatory with the need to protect those services from willful damage by unauthorized users. We continue to see increasing attempts to "probe" computers and networks from outside the NRAO (thousands of such packets every day). These probes are often used to detect vulnerabilities in our systems' configuration. There have also been a few break-ins that briefly disrupted some of the services we provide and had the potential for greater damage. We expect that our Security Policy and procedures will need continual attention as the threats from the outside Internet continue to escalate in frequency and severity.

Communications: The networks at the NRAO have limitations, particularly for data bandwidth between machines. A salient feature of radio astronomy is the large and continually growing size of typical data sets. The network links between machines may result in bottlenecks, and can reduce the effectiveness of sharing computing resources at a site. Continual attention to improving the network performance will allow increased efficiency in the use of computers at the NRAO, and allow more flexibility in meeting future computing demands. The improvements required in networking include the following:

- Local area networking at the various NRAO sites must be upgraded to match the continuingly increasing loads. In 2000, there have been upgrades at Green Bank to support the demands of GBT operations, in Socorro to permit switched-Ethernet networking in the Electronics Lab, and in Tucson with new facilities to accommodate expansion due to ALMA development. We expect further upgrades at all sites to be necessary within 2 - 3 more years.
- Intra-site networking via the leased NRAO Intranet must be upgraded. The current contract is being renegotiated.

- Links to external sites and the successors to the Internet must be upgraded. Current network connections allow only limited access for remote observers; the pioneering efforts at the 12 Meter to provide support for remote observers should be leveraged to provide such capabilities for remote observer access for the other NRAO instruments. Some progress in the software needed for GBT remote observing support will be possible in the near future due to the special NSF communications infrastructure grant. In addition, in June of 2000, the New Mexico Institute of Mining and Technology, with which the AOC shares its Internet connection, received a high-speed networking grant from the NSF CISE. During 2001, this grant will provide the AOC with a connection to the high-speed Abilene and vBNS+ networks, to which a number of users of NRAO telescopes and the NCSA are also connected. We also need a high bandwidth Internet connection to Green Bank and are studying the options.

We have allocated $50k per year for networking improvements at all sites, and will add one position to the Observatory Communications group in 2001 to help manage the increasing workload in the vital area.

Information Infrastructure: The tightly networked computing systems at the NRAO are vital to allow the Observatory to provide significant support to its users, especially outside users. For example, the NRAO is able to provide support and documentation through the facilities of the World Wide Web. Users can access on-line documentation, download software, peruse recent NRAO preprints, newsletters, and technical memos, or download available images from the completed NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty-centimeter survey (FIRST). However, the Web presence has grown over time, and some consolidation is now vitally needed if we are to preserve the level of service now offered to users. In 2001, we plan to move to redundant servers at the various sites to provide quick response independent of user location and net "weather." We also plan to improve computer-based management of the NRAO knowledge base. Managing the knowledge base means that the knowledge built up by many years of operation at the NRAO will be preserved and made available to both NRAO staff and NRAO users. Knowledge Management (KM) is a rapidly developing area. We expect a KM plan to be implemented in the middle years of this Long Range plan. To aid in the work of the KM group, we plan to add one more member of staff in 2002. In addition, we have allocated $100,000 for the KM plan in years 2003 - 2005.

III.4 Spectrum Management and Interference Mitigation

Spectrum Management

Interference from manmade radio transmissions is an increasing challenge to radio astronomy observations. The expected continued proliferation of personal communications systems and especially satellite-borne transmissions will increasingly restrict the frequencies and times that astronomers can use for radio observations. The NRAO, along with other radio observatories, works with national and international spectrum management bodies to limit the impact of radio transmissions to radio astronomy. The radio spectrum management activities at the NRAO can conveniently be classified as local, national, or international.

The Local Level: At each of its major sites there is a staff member who is responsible for problems of interference from other spectrum users in the locality. The staff at Socorro also takes responsibility for the distant VLBA sites. Tasks include monitoring interference using equipment at the sites and information from observers and operators, and identification of interfering transmitters. Action for mitigation can be taken in appropriate cases, such as those where the interference results from a spurious emission that can be eliminated without affecting the legitimate operation of a transmitter. Contacts with other local frequency coordinators, such as those at White Sands, and participation in local organizations, such as the Sandia Crest Users Association in Albuquerque, provide valuable information on identification of signals and warnings of new installations being planned. Calculations of path loss allow prediction of power levels at proposed transmitter sites that would cause interference at an observatory. Local staff involved with RFI issues at each site coordinate with each other to derive strength by sharing experience and technology.

The National Radio Quiet Zone is a 13,000 square-mile region in West Virginia and Virginia in which radio transmissions are required to fall below a given signal strength at the GBT. This region is unique in the entire world. Radio frequency interference is a growing threat to radio astronomy, and the NRQZ provides a critical measure of protection for radio science in Green Bank. In coordination with the FCC, Green Bank Operations reviews up to 300 license applications per year for new transmitters in the Radio Quiet Zone. In addition to the administrative function, a great deal of time is spent working with license applicants to reach technical solutions so that their signal strengths fall below the required level. Owing to the increasing threat of RFI, additional resources are planned for this group in the coming years.

The National Level: Within the U.S., the Committee on Radio Frequencies (CORF) of the National Academy of Sciences speaks for scientific radio needs including those of radio astronomy. Typically one or two members of the NRAO staff serve on CORF or play an advisory role and are active in its affairs. One of the major responsibilities of CORF is to respond on behalf of the radio astronomy community to Notices of Inquiry and Notices of Public Rule Making that are issued by the FCC to obtain public comment on proposed changes in the U.S. frequency allocation tables or other regulations. Responses are usually drafted by the attorney retained by CORF with guidance and review by members of the committee. CORF also provides documentation on radio astronomy requirements in preparation for World Radiocommunication Conferences at which international frequency allocations are made, lobbies members of the FCC, and generally represents scientific interests.

The NRAO organizes a teleconference on alternate months to facilitate exchange of information between NRAO site frequency coordinators, their counterparts at other observatories in North America, and the NSF Electromagnetic Spectrum Manager.

The International Level: Frequency allocations in the International Radio Regulations result from the series of World Radiocommunication Conferences of the International Telecommunication Union (ITU). The technical division of the ITU is known as the Radiocommunication Sector (formerly the International Radio Consultative Committee (CCIR)). A series of study groups is organized through the Radiocommunication Sector, of which SG7, Science Services, includes radio astronomy and space sciences. Each study group meets in Geneva at approximately two-year intervals. For each administration participating in the work of the ITU, the study group members also meet more frequently as national groups to prepare input material for the international meetings. Several NRAO staff members continue to be active in ITU SG7.

Studies performed for radio astronomy are aimed at elucidating technical requirements for the understanding of other spectrum users. The threshold levels of interference to radio astronomy and the practicability of frequency sharing with other services are particularly important. The results, when internationally approved, are published in the form of Recommendations of the ITU, and through World Radiocommunication Conferences they become incorporated into the Radio Regulations, where appropriate.

The Interunion Commission on Allocation of Frequencies for Radio Astronomy and Space Science (IUCAF) is an organization of URSI, the IAU and COSPAR, and is principally concerned with protection of frequencies allocated to radio astronomy bands.

Interference Mitigation

The NRAO is becoming more aggressive about RFI mitigation at its observing sites. Spectrum management activities are extremely important to protect the spectrum and the quiet and coordination zones allocated for radio astronomy. However, the GBT and the Expanded VLA will have receivers that cover nearly all of the centimeter-wave spectrum. Observers want to use more of the spectrum, but the wide band receivers are more susceptible to RFI. A considerable technical effort is required to control local sources of interference and to reduce the effects of intentionally radiated signals outside of the radio astronomy bands.

Current and future plans of the Observatory call for an increasingly pro-active approach to RFI control. Rather than wait for observer reports of RFI in their data, we are beginning an RFI inventory at Green Bank and Socorro of all frequencies covered by the respective telescopes. Once complete, the inventory will be the basis for monitoring the spectrum and detecting new sources of interference before they are discovered in the astronomical data. This will provide observers will a planning tool, and it will help detect new local sources of RFI so that preventive action can be taken. The sensitivity of the inventory and monitoring receivers and signal processing equipment must be sufficient to detect anything that the telescopes can see. Efforts are underway to deploy a suite of moderate to high gain antennas for RFI detection and to harness existing spectrometers or build new hardware to permit long integrations on the monitoring passbands.

The proliferation of modern digital equipment (computers, large correlators, etc.) makes a radio observatory a concentration of RFI-generating devices. The most critical electronics for the GBT have been installed in shielded rooms, and shielded enclosures have been added to the VLA antennas. Much of the equipment installed on the GBT has undergone tests for RFI in an anechoic chamber, and corrective measures have been or are being taken to suppress emissions to levels below the ITU-R R.A. 769 standards for radio astronomy. However, a great deal more needs to be done to establish quiet sites by the standards of modern receivers. The most cost effective suppression of RFI from digital equipment is done at the printed circuit board design level. This requires an enhanced expertise in low-radiation design techniques and a more careful specification of radiation limits on new designs. The Observatory intends to improve its capabilities in these areas. Some of the most interesting prospects for improving the RFI situation for radio astronomy are techniques for making radio telescopes more immune to signals that are intentionally radiated by many other users of the radio spectrum outside of the protected bands. These techniques include rapid pulse blanking, adaptive and parametric signal cancellation, and array null steering. Beginning with an NSF MRI grant, co-funded by the SETI Institute, and an NSF ATI grant to Brigham Young University with Co-PIs from the Observatory, we are engaging in active research into RFI signal suppression at the receiving end. This has the possibility for opening up portions of the radio spectrum that are otherwise considered lost to radio astronomy.

Eliminating RFI at the receiving end is not an easy task. The techniques of noise and interference cancellation developed by the audio, communication, and military industries are only the first step in finding methods that work with radio astronomy receivers without corrupting the very low noise spectrum of our radiometers. Our initial efforts have begun uncovering the details of this problem. The signal processing requirements can be a significant fraction of those needed for normal spectrometric and aperture synthesis processing so we anticipate new demands on resources for this type of interference suppression.

Both the MRI and BYU grant programs are being very pragmatic with their research. They are focusing on specific cases of RFI that are particularly important to active and anticipated astronomical research projects on the GBT, the VLA, and Arecibo. Each type of interference will require different technical solutions so there is no one method than can be developed to solve many problems. Following a successful methodology pioneered by the ATNF group in Australia, work on each interfering signal begins with capturing bursts of data from a telescope or one of our monitoring antennas. These data are then distributed to participating research groups for software analysis to determine signal characteristics and to try various interference excision algorithms. As successful algorithms emerge they will be transferred to real-time DSP systems to be field tested. Final implementation in field programmable gate arrays (FPGAs), digital signal processing (DSP) chips, or general purpose computing machines will depend on the processing requirements of each algorithm.

All of the RFI mitigation research throughout the international radio astronomy community has been informally merged into a cooperative effort via email exploder, data sharing arrangements, and past and future site visits. Data acquisition facilities now exist or are being developed at Green Bank, the SETI Institute's rapid prototype array (RPA), and BYU. Ohio State faculty and NRAO Charlottesville staff will participate in algorithm development.

Further funding of RFI mitigation research will be required for the foreseeable future. Proposals for continued funding must be based on the successful implementation of techniques that are of direct benefit to observers.

The Observatory currently supports an active education and public outreach program, based on the conviction that the public, which funds the Observatory, should be informed at to its activities; that it is the obligation of every publicly funded research institution to contribute to the development of a scientifically literate society; and that responsible management of the Observatory includes careful attention to all aspects of our interaction with the public. This program is diverse, including teacher training institutes and Chautauqua programs for college teachers at the Green Bank and New Mexico sites, a co-op program for engineering students, research experience programs for undergraduates and teachers, the operation of an educational 40 Foot Telescope in Green Bank, field trip programs for K-12 and university groups, participation in the Masters of Science Teaching program at New Mexico Tech, support of science fair competitions, and a program of talks on astronomy and ALMA by our resident scientist in Chile. To bring more unity and focus to this effort, we are recruiting an EPO scientist who will coordinate the entire program. An EPO Strategy for the Observatory will be constructed in late 2001.

IV.1 Education Programs

Jansky Research Associates

Each year the NRAO awards the Jansky Postdoctoral Fellowship to typically three or four outstanding young researchers who have recently obtained their PhD. The appointment is initially for a duration of two years but is normally renewed for a third year. In addition to salary and related benefits, the appointment includes support for travel and other research costs. These appointments are highly competitive as, unlike many postdoctoral appointments which are associated with grant support, they offer the opportunity for independent research and are not tied to specific projects, programs, or supervisors. Upon leaving the NRAO, most recent Jansky Fellows have obtained an attractive appointment as a faculty member, a second, often highly competitive postdoctoral appointment, or in industry. A few Jansky Research Associates also take up permanent positions on the NRAO scientific staff.

Our postdoctoral program also benefits the NRAO as well as the broader astronomical community. These young researchers experience a rich immersion in all aspects of radio astronomy. They have unrestricted access to our radio facilities and ample opportunities to interact and work directly with some of the world's experts in image processing, instrumentation and astronomical research. The presence of young, energetic researchers with new ideas for using the instruments, is a refreshing benefit to the NRAO staff.

Co-Op Program

In past years, the NRAO has been an enthusiastic partner in undergraduate student co-op arrangements involving several universities. Normally, a co-op student participates in the program one semester per year for two to three years. The program has been highly successful in cultivating an interest in astronomy among engineering students by providing direct participation in the development of state-of-the-art instrumentation. Furthermore, as an educational program, the co-op program leads to the development of the practical skills necessary for the technical professions. Several current employees were first introduced to the NRAO through the co-op program. We plan to continue the co-op partnership with renewed vigor, since the commissioning of the GBT, the EVLA and ALMA, will provide many exciting opportunities for co-op students over the next decade. Specifically, we will expand this program by supporting three to four students. In the future we will seek to expand this program further to include five to six co-op students.

Graduate Student Programs

The resources available at the NRAO offer unique opportunities for graduate student education and research. Students are given an opportunity to enhance their formal education at an academic institution with active involvement in both astronomy and instrumentation research projects. The Observatory offers two programs: NRAO Graduate Internships and NRAO Predoctoral Fellowships. The Graduate Internship, designed for students in their first or second year of graduate study, is geared primarily toward those students who are considering possible career paths in radio astronomy or related disciplines. The Internship will enable promising students in radio astronomy, electrical engineering, and computer science to come to the Observatory for a period of 1-6 months to work under the supervision of a staff member and participate in scientific research, technical projects, instrument development, or computer science.

The Predoctoral Fellowships are designed to support graduate students who have committed themselves to obtaining a Ph.D. in radio astronomy or a related discipline and have satisfied the candidacy requirements of their academic institution. The successful Predoctoral Fellow comes to the Observatory to pursue a program of doctoral research for a period of up to two years. In cooperation with the student's academic institution, the Observatory provides the student with access to all of its facilities, a monthly stipend, and full participation in its benefits program.

New discoveries in the field of radio astronomy have always been associated with advances in the art of instrumentation. The early pioneering work in radio astronomy was done by physicists and engineers who began to apply the technology developed during WWII to the creation of unique radiometry instruments for the research task at hand. However, as the size and complexity of the radio telescopes grew, the instrument development moved from the physics laboratory to national centers such as the NRAO. Over the years, this shift away from university-based instrumentation research has created a technology gap between the astronomers who have become instrument users and the engineers who have the responsibility for developing new instrumentation. This gap will only widen with the ever increasing complexity of modern technology unless some corrective action is taken.

The NRAO is actively leading the development of a comprehensive graduate science and engineering training program that will link the scientists working on new detector technology, the astronomers with interesting ideas for new instruments, and the wealth of engineering talent available at the University of Virginia (UVa) and the NRAO to develop the next generation of radio astronomy instrumentation. Our program provides a unique opportunity for both undergraduate students, graduate students, and faculty from both engineering and science to work together as a team on an instrument, from the concept through deployment and use. Project size may range from undergraduate student projects and graduate dissertations through major equipment development. Discussions between the NRAO staff and Department Chairs and Faculty of the UVa's Astronomy and Physics Departments and the School of Engineering and Applied Science are converging on a concept for greater cooperation between our two institutions for such instrumentation research.

We have encouraged the creation of the Advanced Instrumentation Research Laboratory (AIRL) for radio astronomy, located in the Astronomy Department at the University of Virginia, whose primary purposes are education and a common laboratory area for collaborative research. The Astronomy Department has provided start-up money for a graduate course in Radio Astronomy Instrumentation, beginning in the spring, 2001 and generous space for the AIRL. The course emphasizes hand-on learning as the students make use of the laboratory to design, build, and evaluate a radiometer, which they use, together with a small horn antenna donated by the NRAO, to detect galactic HI. All research projects in the laboratory will be self supporting through grants and other project-specific resources. The laboratory infrastructure will be supported through use fees attached to the project grants. The interaction of AIRL with the NRAO will (1) enhance the NRAO's role in the education of young radio astronomers with emphasis on instrumentation, (2) link students closely with NRAO activities, (3) encourage graduate student participation in creating the next generation of instruments for radio, millimeter-wave, submillimeter wave, and infrared astronomy, (4) foster teamwork between astronomy and engineering students through effective project-specific alliances among research groups at the NRAO and the University of Virginia, and (5) provide direct access to software tools and research equipment not currently available at the NRAO. The NRAO currently supports two Ph.D. graduate students in the AIRL program and plans to continue to support and perhaps expand this program pending yearly evaluation of its success.

Over the last few years three Chilean students profited from an NRAO program designed to bring engineering students to work on their thesis in our labs for a full year. In Chile, engineering, being a professional degree normally take six years of studies and requires completion of a thesis. Students in the NRAO program remain enrolled at their University in Chile while working in the USA under the supervision of our staff.

In this way the NRAO is making a contribution to the development of a solid high-level technological basis in Chile. Because ALMA is arguably the most involved technological project ever to come to Chile exposing Chilean engineers to some of its aspects is likely to raise the local standards in engineering. It will also help generate a modest but knowledgeable group of Chilean engineers and scientists fully aware of ALMA's characteristics and capabilities, and it will open channels of communications with the Chilean universities and institutions.

In order to give this program more exposure and open it to a wider choice of engineering students, NRAO is planning on getting the Chilean Commission for Science and Technology (CONICYT) involved in the selection of future candidates.

Research Experience for Undergraduates Program (REU)

The year 2002 will be the forty-third year of the NRAO Summer Research Program, which has graduated more than 800 students during its tenure. The program continues to generate interest in radio astronomy, to produce radio astronomers and to provide teaching opportunities for the NRAO staff. The list of currently active astronomers produced by the program is long and impressive.

During the program's long history, the mix of students has varied from being comprised of only graduate students, to only undergraduate students, to a mixture of both. The best mix has proven to be that which is currently employed—mostly undergraduate students, but with half that number of graduate students. This provides the undergraduate students with good networking to grad schools, advice from cohorts a few years further along in their program, and alternate mentoring sources when the staff mentor is called away for other duties. Requests by staff for summer students and the number of highly qualified applicants remain higher than can be satisfied by current resources. It is particularly useful for Jansky Fellows to work with summer students, as their subsequent careers often involve teaching; the summer student program is chief among the few opportunities they may have at the NRAO to enhance their teaching resumes.

In the next years, funds will be sought to allow the REU program to grow. The 2001 REU program is perhaps 30 percent below optimum and in 2003 we will submit a new REU proposal to NSF to increase the number of REU students at each of the sites, particularly at Green Bank. Outside of the REU program, we plan to include Chilean students in summer research.

A new EPO staff member will work actively to improve participation by minorities in the REU program. Over the past decade, women have come to account for half of both applications and acceptances. However, minority participation has been below the 10 percent level in average years; it is difficult to increase this without active recruitment. The EPO staff member will also track students leaving the program to provide feedback to enhance its effectiveness. For the first part of the 1990s, the number of summer research undergraduates going on to obtain their Ph.D. in astronomy has been about 35 percent. The REU program is targeted to help students make career choices, not to foster them in pursuing a career path they have already chosen. However, it has proven difficult to follow students, as they may drop out of astronomy only to return to it later, or they may change their names.

Our REU programs in recent years have been supplemented by the presence of teachers, who are participants in the Research Experience for Teachers (RET) Program. We plan to expand the RET program to Socorro in 2002 and, based on experience, plan to expand it in future at both sites.

Green Bank Visitor Center and Education Program

Each year, more than 25,000 people visit the Green Bank Observatory, mostly during the summer months. This includes students and educators, as well as the casual tourist. Many visit because they are in the area for other attractions, but some come a considerable way to see the Green Bank Telescope(GBT). The current facility offers tourists a brief slide show and a bus tour around the site.

Work is now well underway on a new Education and Visitor Center at Green Bank, which will serve as the focal point for the diverse educational activities at the Observatory. The new Visitor Center will allow us to enhance our tourist program significantly and to deepen the educational experience of the visitors. The building is funded by grants from NASA and will contain an auditorium, classrooms and a computer lab, and a 4000 sq. ft exhibit area. A separate grant has been obtained from the NSF Informal Education Division to design and construct exhibits that focus on the research being done in Green Bank, and on radio astronomy in general. Groundbreaking for the new facility is expected in 2001 with completion scheduled in late 2002. Expanded visitor programs will allow tourists to see movies and other visuals that will run

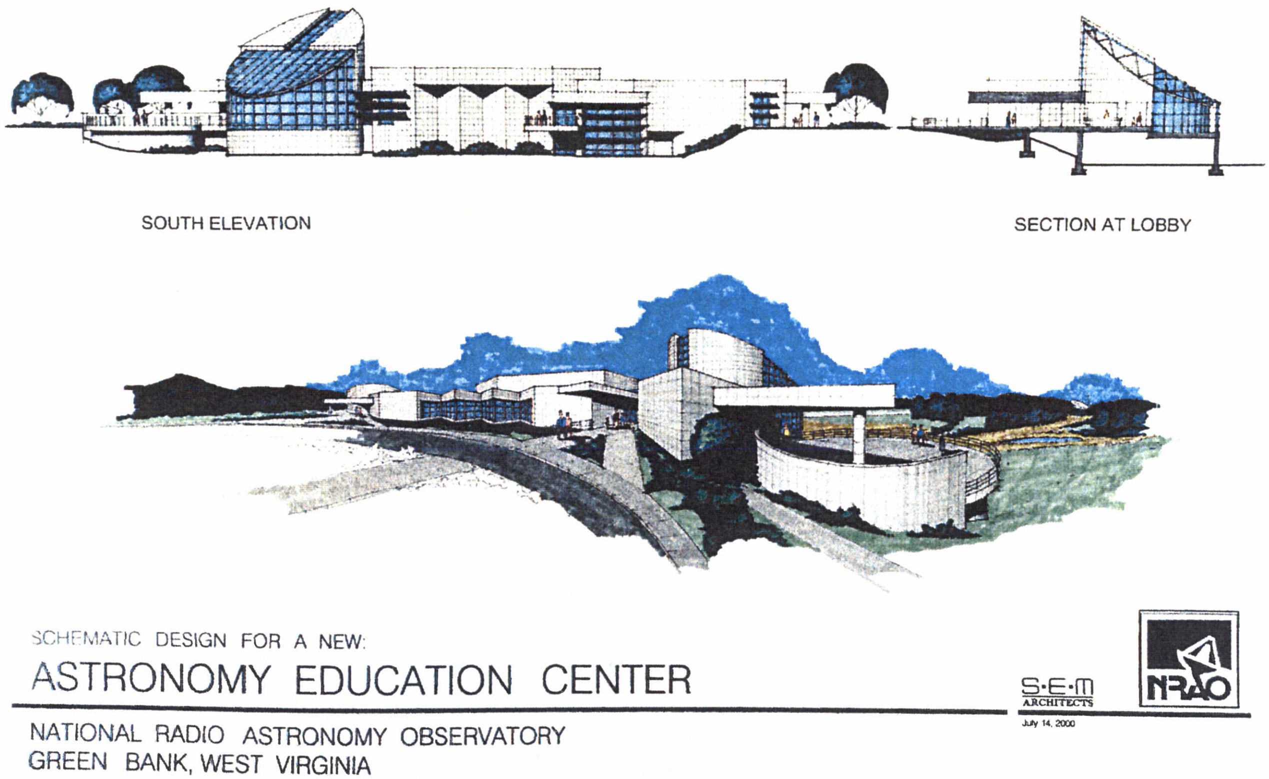


Figure IV.1 Artist's rendition of GB Education and Visitor Center. The project is being funded by NASA and NSF Education.

continuously in the auditorium. These will describe the Observatory and serve as an introduction to the telescopes that will be seen on the bus tour. But more general astronomy and science films will also be given in the auditorium, in addition to science demonstrations—it will be a continuously active space for varying presentations throughout the day. Tourists will also benefit from the large exhibit area. They will be able to interact with hands-on displays which cover topics from the electromagnetic spectrum to recent discoveries in radio astronomy. They will be able to control a scale-model of the GBT and obtain real-time information about the science that the GBT is doing at that very moment. Live data from the telescope will be available for public viewing. The bus tour of the site will be enhanced with a series of stops where visitors can disembark and spend time looking at displays in the shadow of the telescope.

The new facility will not only improve the quality of the experience that we can offer tourists, it will make it logistically possible to handle greatly increased numbers of visitors, and we expect to expand our advertising efforts to increase the number of visitors to the site several fold.

At present, several thousand K-12 school children visit the Observatory every year to participate in day-long programs. Between 2002 and 2006 we will expand the educational offerings so that the Observatory can be the destination of school trips for every school district from the region and the State. It is our goal to have every child in West Virginia participate in an educational program at the Observatory at least once before they graduate from high school. The education center will take advantage of the research done at Green Bank and the presence of the unique radio telescopes, to stimulate student interest in science. Some of the exhibits in the new building are being designed for group interaction under the supervision of an educator, so that students can have a deeper, longer experience than is typical at many museums. The scientific and engineering staff at Green Bank will be active participants in many of the programs, giving students a unique chance to meet people involved in frontier research.

The staff of professional educators at the new center, in cooperation with visiting teachers, will develop programs that will make a field trip to the NRAO an integral part of science courses. Science projects will be designed so that they can begin while visiting the Observatory and continue in the classroom at home. The education center will also produce materials such as Internet-broadcast demonstrations, traveling exhibits, and inquiry-based materials for use by K-12 students. Some of the exhibits currently under construction are being viewed as prototypes for an "NRAO on the road" presentation, which will be lent to museums and science centers around the country. Our advisory committee of museum directors and educators has encouraged us to view the Observatory as a potential source of materials in science education for the entire nation.

A key part of the Green Bank educational efforts, which will be enhanced by the new facility, is in training science educators. Most people who teach science have actually never done research, and this gulf creates considerable confusion and misunderstanding among young people about the nature of science. In the coming years we will continue our program of teacher training which has been supported for a number of years by grants from the NSF, and which has proved so successful in bridging the gulf between the classroom and the lab. With the unique facilities of the Observatory at Green Bank, and the resources available in the new education center, we will broaden our activities to reach more teachers and explore new ways of conveying the fundamental ideas of science to the largest possible audience.

Many other educational activities will occur at Green Bank in the coming years, include specialized Chautauquas for professors at small colleges, special overnight programs for groups such as the Girl Scouts and students from the National Youth Science Camp. It will be the site of Elderhostels and meeting of the Society of Amateur Radio Astronomers. This growth in facilities and programs over the next five years should place the Observatory at Green Bank in the forefront of science education in the nation.

VLA Visitor Center and Education Program

We are developing a plan for a new VLA Visitor and Education Center, in conjunction with the VLA Expansion Project. By the beginning of 2002, a baseline plan for this center will be completed, and used to seek funding from foundation, educational, and public sources. The primary goal of the new Visitor Center will be for informal astronomy and science education for the general public, with an emphasis on radio astronomy. In addition, the new Visitor Center will serve as a focal point for astronomy and science education at the K-12 level in New Mexico.

The Visitor Center will be used to provide a hands-on educational experience for students, emphasizing the thought processes and methods of scientific inquiry, while addressing state and national science education standards. An education program will be developed to assist teachers in meeting those standards through curriculum tie-ins and activities available at the Visitor Center. The program will be multi-disciplinary in its approach, including exhibits and activities focusing on local history, archaeology, and natural resources.

The concept for the new Visitor Center envisions approximately 125,000 to 150,000 visitors per year; the current facility serves more than 50,000, and we expect attendance to at least double when a new educational program is in place. There will be approximately 10,000 square feet of space divided into several major areas: an interactive exhibit space; an auditorium for audio-visual presentations; a large classroom for students and/or educators; a gift shop at which various educational materials are available; storage space; and office space for full-time staff.

The outdoor part of the facility will include picnic tables and interpretive areas. It is anticipated that the ongoing operational costs will be covered by education fees and sales from the gift shop, but "up-front" fund raising will be necessary to make the facility a reality.

By mid 2002, we expect to have a specific initiative in place to raise funds of approximately $5M for the new Visitor Center. This initiative will include a detailed description of the center concept, including both its physical plant and the design of the public and school-oriented programs. The schedule for implementation of the new facility will depend on the success in raising funds.

While seeking funding for the new Visitor Center, we will engage in a variety of activities to enhance the effectiveness of the current VLA Visitor Center. These activities will serve as trail blazing efforts for the initial stages of the new facility, and will include formal and informal surveys of client interests, desires, and opinions. Further, in 2002 and 2003, new exhibits will be put in place in a remodeled edition of the current center; these exhibits will be prototypes for those to be available in the more ambitious facility. One or two full-time staff members will be hired, in order to facilitate initial operation of a gift shop and an increase in the number of tours that can be offered to educational groups.

IV.2 Public Outreach

There are many ways the Observatory meets the public besides the education, visitor's center, and tour programs discussed above. It is important that NRAO present itself in these venues professionally, so as to accomplish the goal of informing and educating the public, while conveying the message of scientific research as a worthwhile public investment. This requires a well-managed program of media relations.

The Observatory has Public Information Officers in both Charlottesville VA and Socorro NM. They are responsible for all press releases, press conferences, promotional brochures, conference displays, public events, and the Observatory web site. The public outreach program is centrally organized out of the Charlottesville headquarters.

In fulfilling its role of designing, building, and operating large radio astronomical facilities, the NRAO plays a leadership role in the wider astronomical community. In addition, as a key repository of both technical and scientific expertise, the NRAO serves as a valuable resource to the radio astronomical community. While the NRAO must focus its efforts on large projects, the wider community has initiated several smaller radio astronomy projects to which the NRAO may, in some cases, serve as a partner. In so doing, the NRAO maintains and strengthens its leadership role while, at the same time, enhances ties with and fosters the health of the broad radio astronomical community. Conversely, participation in outside initiatives benefits the NRAO to the extent that it enables the Observatory to keep pace with and exploit technological innovation.

The NRAO has also played a significant role in the MAP mission by providing space-ready receivers and is prepared to assist in other planned and unplanned missions where our in-house technical and scientific expertise apply. Examples of such missions include low-frequency space-based interferometric arrays, low-frequency spectroscopy below the ionospheric cutoff, or the eventual deployment of an instrument on the moon.

Examples of outside initiatives in which the NRAO may play a significant role include design and development of space VLBI, the Square Kilometer Array (SKA), the Low Frequency Array (LOFAR), the Frequency Agile Solar Radiotelescope (FASR).

V.1 Space VLBI

The VLBA antennas and correlator, as well as the Green Bank tracking station, are key ground elements of the VLBI Space Observatory Program (VSOP), the world's first dedicated Space VLBI mission. The HALCA spacecraft for VSOP was developed and controlled by the Institute for Space and Astronautical Science (ISAS) in Japan, which also led the international mission. HALCA was launched in early 1997. As the spacecraft is nearing the end of its useful life, it is expected that U.S. participation in the VSOP mission will come to an end in early 2002. This mission has used an 8-m space antenna operating successfully at observing wavelengths of 6 cm and 18 cm, imaging bright compact radio sources at resolutions up to three times those achievable from the Earth at the same wavelengths.

Throughout the VSOP mission, the NRAO has operated a tracking station for VSOP at Green Bank, under contract with NASA. This tracking station provides a maser frequency standard uplink, a data downlink, and VLBI recording back-ends. Much of the hardware for the station, as well as hardware for other stations in the tracking network was designed and built by NRAO staff. This has been a highly successful operation that has better than a 99 percent success rate for data recording passes—far better than any other tracking station which has supported VSOP. Issues relating to the closure of the station at the time the NASA mission support terminates are under discussion with NASA at this time.

More than half of investigator observations from VSOP was obtained in conjunction with NRAO telescopes and was correlated at the VLBA; NRAO scientists have played a major role in the planning, scheduling, tracking, and data analysis. All of our participation in the VSOP Space VLBI program has been supported by NASA, including correlator upgrades and software enhancements that have contributed materially to the operation of the VLBA. Without this support from NASA, our very strained operation budget would not have allowed the development of the extensive software tools which observers use for the reduction of their VLBA data.

We are currently involved in planning for the next generation of Space VLBI missions. The two main candidates currently under consideration are VSOP-2 and ARISE (Advanced Radio Interferometry between Space and Earth). VSOP-2 is a Japanese initiative; it would consist of a single spacecraft, with a radio antenna of 10 m in diameter, observing wavelengths from 7 mm (43 GHz) to 6 cm (5 GHz), and a data rate of 1 Gbps. If VSOP-2 is approved, the predicted launch date is 2008. The more ambitious NASA ARISE mission was recommended by the U.S. decade committee, but is unlikely to be launched before 2015. ARISE would consist of a space antenna with capabilities roughly equivalent to a VLBA antenna–a diameter of 25 m, maximum frequency of 86 GHz (3 mm wavelength), and a maximum data rate of 8 Gbps. While primarily a JPL initiative, the ARISE Project Scientist is a member of the NRAO scientific staff. If either, or both, of these missions are implemented, we foresee a continuing role for the NRAO comparable to that which we played for VSOP.

The current VLBA will not be capable of supporting the sustained data rate envisioned for VSOP-2, to say nothing of ARISE. Therefore, new data transmission, recording, and correlation systems, such as those discussed in Section II.3, will be essential for NRAO participation in VSOP-2 or ARISE. It appears that the most inexpensive route for VSOP-2 will be to increase the EVLA correlator from its minimum of 32 stations to 40 stations with a 16 GHz capability. This enhancement will be needed not only to support space VLBI, but also for the real-time operation of the EVLA and VLBA by exploiting the flexibility of the correlator to trade stations for bandwidth. Such an increase, together with low-cost S3 or MOTS recording/playback units for the NRAO telescopes, and upgraded signal channel hardware, will cost approximately $8-11 M. Some part of this enhancement could be funded as part of the North American Partnership for Radio Astronomy, between Canada and the U.S. or from NASA. The major part of the upgrade would need to be designed and funded by 2004, in order to be implemented and tested in time for a 2008 launch date. Here, it is worth noting that the expansion of the EVLA correlator and either of the new recording systems would be on the path not just to VSOP-2, but also to a much higher bandwidth ARISE-like mission.

The NRAO has developed considerable expertise in satellite earth stations through VSOP, and also has several antennas on the Green Bank site that could be used in support of future space VLBI missions or other astronomical satellite tracking programs, as opportunities arise. It also has been proposed that NRAO design and build one or two low-cost tracking and data-transmission stations for VSOP-2. The current concept for these stations includes the possibility of two ground antennas at each station, a small (3-m class) antenna for a two-way timing link with the spacecraft, and a larger (10-m to 34-m) antenna for receiving the wideband data downlink. Indeed, it is conceivable that a VLBA antenna might be used for tracking the spacecraft during observations made in conjunction with the VLBA. If a common tracking-station design is selected, it is anticipated that several identical copies of the stations might be produced, but funded and operated by several different agencies.

V.2 The Square Kilometer Array

In recent years there has been increasing discussion within the international radio astronomy community about developing radio telescopes which have several orders of magnitude improved sensitivity compared with existing instruments. Because current receivers are close to their theoretical limits, the only way to achieve significant improvement in sensitivity is to greatly increase the collecting area. However, any simple extension of conventional approaches to obtaining large collecting area will be prohibitively costly, hence the need to "break the cost curve" to achieve a collecting area equivalent to one square kilometer. The development project is known as the Square Kilometer Array (SKA). The NRAO is a member of the U.S. SKA Consortium and is represented on the International SKA Steering Committee; these two bodies are charged with the coordination of national and international efforts, respectively, to develop the next generation of radio astronomy instrumentation needed to address the scientific questions of future decades. NRAO staff have been active in developing the scientific case for the SKA, in organizing meetings to focus the attention of the U.S. radio astronomy community on the challenges presented by the SKA, and in working with the SETI Institute to develop the Allen Telescope Array. In cooperation with the university community we will continue and expand these activities to involve more of the NRAO staff during the next five years.

In addition, many of the techniques and instrumentation being developed for the EVLA will be important in the planning for the SKA. This includes wideband low noise receivers and feeds, an advanced correlator designed to minimize the impact of RFI, the use of broad band fiber optic transmission systems, configuration optimization, advanced data management techniques including multiple-field calibration in the presence of non-isoplanatic screens, non co-planar and high dynamic range imaging, the effective use of data archives, and real time imaging from complex data acquisition.

In order to obtain sufficient angular resolution to avoid the effects of confusion at the high source density corresponding to the SKA sensitivity, as well as to adequately image, rather than just detect, distant galaxies and other weak radio sources, overall SKA dimensions of hundreds to thousands of kilometers will be needed. The EVLA will constitute a critical first step toward developing such an array as well as toward defining the SKA scientific program. The main challenge of the SKA is to reduce the cost of building large collecting areas by an order of magnitude or more. As soon as this is accomplished, even if only over a limited frequency range, the new technology can be used to increase the collecting area and corresponding sensitivity of the EVLA including each of the ten sites of the New Mexico Array. As described in Section II.3, a possible next step will be to extend the real-time operation of the EVLA to each of the other eight VLBA antennas and to perhaps increase the collecting area at each station. In this way it will be possible to approach the full capability of the SKA in a deliberate fashion, and at the same time maintain the viability of the radio astronomy user community during the long SKA development and construction period which may extend over several decades.

V.3 The Low Frequency Array

In addition to the SKA, there is currently considerable interest in another proposed radio array, also with physical scales comparable to that of the Phase II EVLA—the LOw FRequency Array (LOFAR). LOFAR is intended to exploit the relatively unexplored region between 15 MHz and 240 MHz. Although all of the pioneering work in radio astronomy was done at these meter wavelengths, the emphasis later moved toward shorter wavelengths to obtain better angular resolution and to exploit the opportunities created by the plethora of spectral lines at microwave and millimeter wavelengths. Only recently has it been possible to extend the techniques for high dynamic range imaging with arcsecond resolution to meter wavelengths, and the LOFAR initiative is designed to exploit this opportunity. The EVLA, the SKA, and LOFAR all require real-time correlation of data taken at sites separated by hundreds of kilometers. Given that real-time wide-bandwidth signal transmission is a major cost for all of these arrays, it clearly makes good sense to consider a plan for development of EVLA Phase II which would encourage these projects to co-locate their sites. Not only would this save considerable resources in data transmission, but it would also reduce the expense of establishing new infrastructures for these projects. Our planning for Phase II will take into account the needs of these other projects, in the hope that a joint development project, beneficial to all three, will ultimately emerge.

More specifically, the VLA has been instrumented at 74 MHz with receivers and feeds provided by the Naval Research Laboratory (NRL). As part of the LOFAR development program, NRL may construct new low frequency stations in New Mexico which might coexist with EVLA sites. This may permit LOFAR and the EVLA to exploit common infrastructure including the fiber optic communication system. The LOFAR prototypes also will extend the frequency coverage of the present 74 MHz VLA system as well as provide increased sensitivity and resolution at meter wavelengths. We look forward to working together with NRL scientists and engineers to jointly develop the EVLA and LOFAR sites and to provide the high speed data links between the sites and the central control/processing facility.

V.4 The Frequency Agile Solar Radio Telescope

For several years there has been discussion in both the U.S. and international solar physics communities about the need for a high-performance, solar-dedicated radio array designed for broadband imaging spectroscopy. From these discussions, plans for the Frequency Agile Solar Radiotelescope (FASR) emerged. The U.S. astronomy and astrophysics community, as embodied by the NAS/NRC Astronomy and Astrophysics Survey Committee, recently endorsed the solar physics community's plans to design and build FASR, a radio array designed to image the Sun in an optimum fashion from centimeter to meter wavelengths on very short time scales. FASR will probe the solar atmosphere from the chromosphere up into the corona. It is designed to address an ambitious science program, including the physics of flares, the structure and evolution of solar active regions, the measurement of magnetic fields above the photosphere, eruptive phenomena (filaments, coronal mass ejections), space weather, the structure of the quiet solar atmosphere, and coronal heating. FASR will bring unique capabilities to bear on these problems, capabilities that are highly complementary to existing and planned space- and ground-based facilities.

Recognizing the importance of this initiative by the wider solar physics community, the NRAO plans to assist with the design and development of critical components of FASR. As a solar-dedicated instrument designed to perform broadband imaging spectroscopy on short time scales, the NRAO will bring its expertise to bear on problems associated with broadband signal transmission, signal correlation for large numbers of stations, and real time calibration, imaging, and archiving. Some of these requirements are closely aligned with those of the EVLA and SKA development.

VI.1 Organization and Management

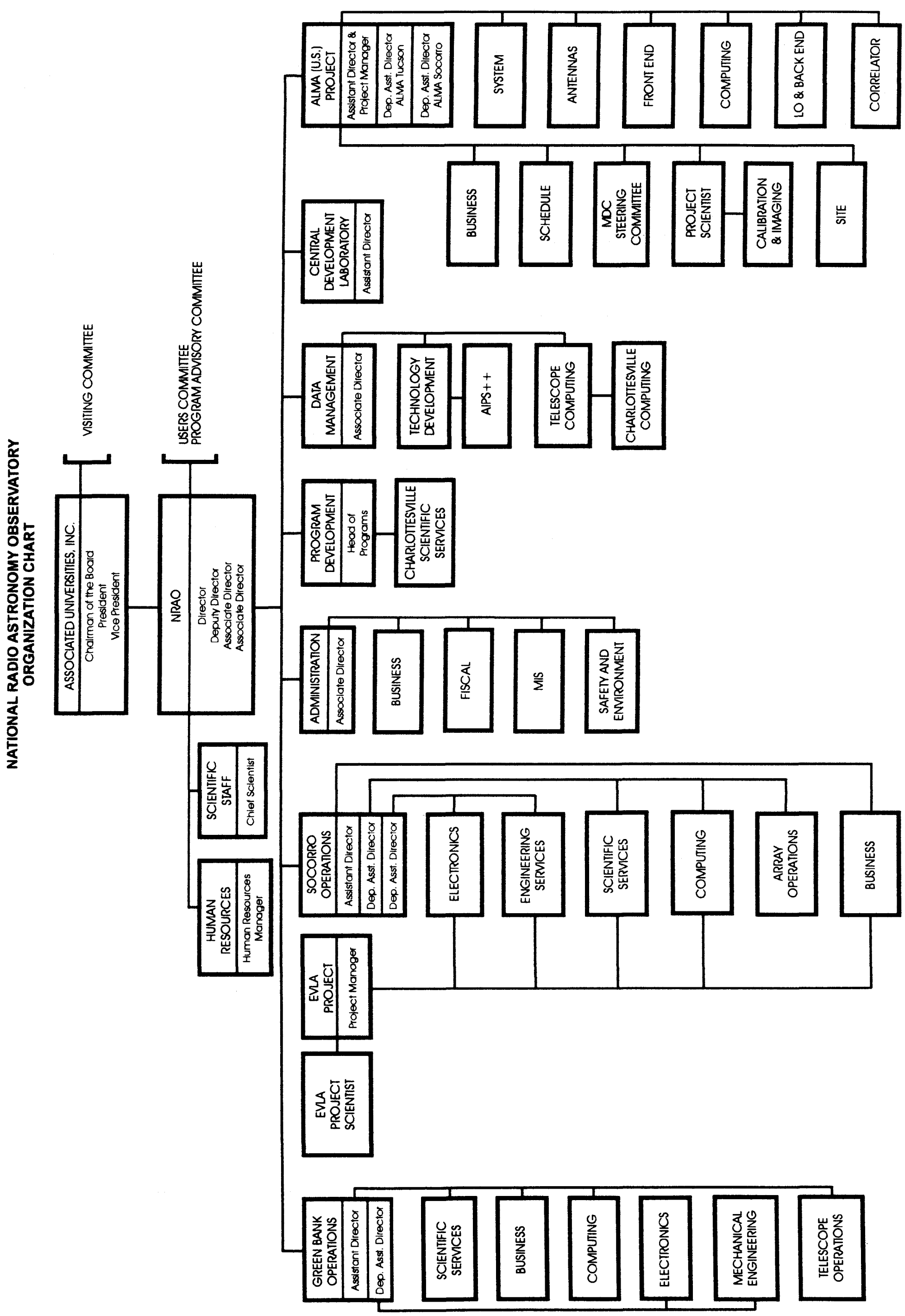


Figure VI.1 NRAO organization chart showing the organization of activities for three telescopes/projects (GBT, VLA/VLBA, and EVLA project), four central functions (Administration, Data Management, Central Development Laboratory, and Education and Public Outreach), and the ALMA project.

The functions shown in the organization chart above are managed using standard management tools. The primary tool is a work breakdown structure (WBS) that defines for all activities of the Observatory the scope, resources, schedule, and person responsible. The establishment of an effective WBS is iterative and evolutionary. The 2000 Program Plan was the first to present a crude WBS for operations. The Program Plan for 2001 had an improved WBS. The Program Plan for 2002 will be using WBS as a management tool. And by 2003, we expect to have a smoothly running system for creating, updating, and tracking Observatory activities by WBS. The Observatory WBS for operations, together with those for the projects, ALMA and EVLA, define all Observatory activity.

At the same time we are developing a WBS, we are improving the Management Information Systems (MIS). This consists of two parts: an upgrade to the Payroll system, to be completed by mid-2001, that combines all Payroll and Human Resource functions into a single software system: and an upgrade to the Business Software system (general ledger, financial reports, purchasing, budgeting, etc.), to be completed by the mid 2002, that brings the hardware up to date and software into a more robust windows interface. With the completion of these upgrades, it will be possible to implement a web-based reporting system to track the progress of activities against schedule and budget.

The salaries for Scientists, Engineers, and Computer Scientists at the NRAO are not competitive with the outside market. This is a result of years of relatively flat budgets leading to salary increases that did not keep up with other R&D organizations. The situation is further exacerbated by the unprecedented growth in the economy that has led to extremely low unemployment rates throughout the country and dramatic increases in the salaries for technical personnel. This lack of competitiveness has resulted in increased turnover in these classifications as well as an impairment of our ability to attract new talent. If this situation is not addressed, it will lead to increased employee dissatisfaction and turnover of critically needed and talented staff. The following analysis demonstrates the severity of the problem.

Table VI.1 NRAO Salaries vs. Watson Wyatt Survey of R&D Scientists and Engineers

Electrical Engineers			
Current Salaries	W/W Survey	Difference	% Difference
$3,963,734	$4,461,500	($497,766)	-13
Mechanical Engineers			
Current Salaries	W/W Survey	Difference	% Difference
$330,352	$359,708	($29,356)	-9
Computer Scientists			
Current Salaries	W/W Survey	Difference	% Difference
$2,103,810	$2,535,742	($431,931)	-21
Astronomers			
Current Salaries	W/W Survey	Difference	% Difference
$2,657,293.16	$3,230,988	($573,695)	-22
Scientific Supervisors			
Current Salaries	W/W Survey	Difference	% Difference
$1,963,496	$2,384,898	($421,401)	-21
Grand Total			
Total Current	Survey (w/3.5%)	Difference	% Difference
$11,018,687	$12,972,836	($1,954,149)	-18

The National Survey of Research and Development Scientists and Engineers is conducted annually by the Watson Wyatt Company and is recognized as the benchmark survey for scientists and engineers in research organizations. The survey has been conducted for more than 35 years and provides data on compensation paid to a broad cross section of researchers from educational institutions, industrial organizations, nonprofits and federal contract research centers. Information is gathered from more than thirty organizations for more than six thousand incumbents.

The comparison of NRAO salaries to the survey data reveals NRAO salaries for scientists, engineers, computer scientists and scientific supervisors lag the current market by 18 percent. The cost to raise our salary levels to a competitive level with a one-time raise would be almost $2M. Within the existing budget levels, this correction cannot be realistically accomplished in a single year; therefore, we have developed a 5-year plan to bring our salaries in line with the market. The plan requires the allocation of a $ 400,000 special adjustment fund each year for the five-year period to be used to raise the S&E salaries at the Observatory. Should funding increase, this plan will be accelerated to correct the salary deficiency in fewer years.

There are indications that salary levels for other groups at the Observatory are also falling behind the market and we plan to engage a professional compensation consultant to assist us in measuring these markets and instituting a performance/market-based compensation system for the entire Observatory.

VI.2 Advisory Structure

The operation and management of the NRAO is supported by a range of standing advisory committees reporting to the Director or to AUI. In addition, there are ad-hoc groups which are convened as needed to advise on specific new instrumental and software initiatives.

The **Visiting Committee** is appointed by the AUI Board of Trustees to review the management and research programs of the Observatory. The Visiting Committee met in Tucson in 1998, in Socorro in 1999, and in Green Bank in 2000.

The **Users Committee** is made up of users and potential users of NRAO facilities from throughout the scientific community. It advises the Director and the Observatory staff on all aspects of Observatory activities that affect the users of the telescopes. This committee, which is appointed by the Director, meets annually in May or June.

The **Program Advisory Committee** reviews and provides advice on the long range plan of the Observatory, on new programs and projects being considered for implementation, and on the priorities among Observatory program elements.

The Atacama Large Millimeter Array (ALMA) project has formed a new committee to provide scientific advice to the project and outreach to the wider community, the **ALMA Scientific Advisory Committee**.

The EVLA Scientific Advisory Committee is to be appointed later in 2001.

VI.3 Budget Projections for FY2002 - 2006

The following is a table and a collection of graphs to illustrate budget projections for the period of this Long Range Plan.

Table VI.2 Budget Summary

($ in 000s)

	2002	2003	2004	2005	2006
Observatory Wide Activities	$12,139	$13,227	$14,120	$14,841	$15,480
GBT Ops	8,562	9,101	9,739	10,472	11,254
VLA/VLBA Ops	16,234	17,006	17,793	18,725	19,623
Total Operations	$36,935	$39,334	$41,652	$44,038	$46,357
ALMA *	26,000	36,000	46,000	42,000	42,000
EVLA I (7-year plan)	5,000	9,000	10,530	10,950	11,390
EVLA II	0	0	1,000	2,000	2,000
COBRA (NSF/IT-R)	650	425	450	475	500
Total Projects/New Initiatives	$31,650	$45,425	$57,980	$55,425	$55,890
CDL/Computing	450	450	450	500	500
GB Instrumentation	800	1,155	1,720	1,650	1,000
VLA Instrumentation	200	200	0	0	0
VLBA Instrumentation	0	0	1,000	2,000	3,000
Total Instrumentation	$1,450	$1,805	$3,170	$4,150	$4,500
Total	**$70,035**	**$86,564**	**$102,802**	**$103,613**	**$106,747**

**All categories include inflation, except ALMA which is in 2001 dollars.*

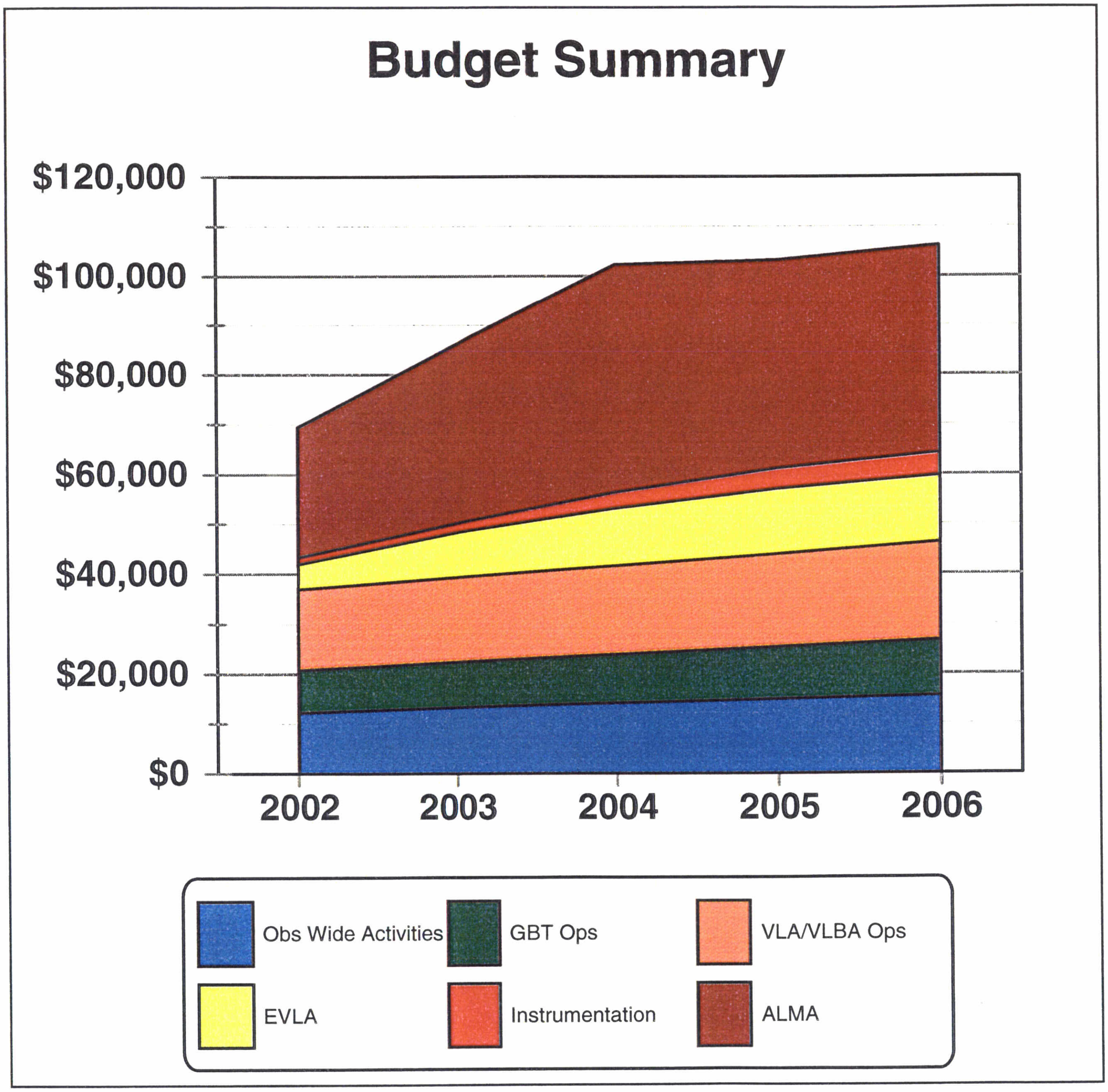


Figure VI.2 (Budget $ in 000s.) A graphical presentation of Table VI.2 showing projected growth in major budget categories over the period of this Long Range Plan. The change in slope is due to the ramp-up in ALMA cosntruction that levels off starting in 2004.

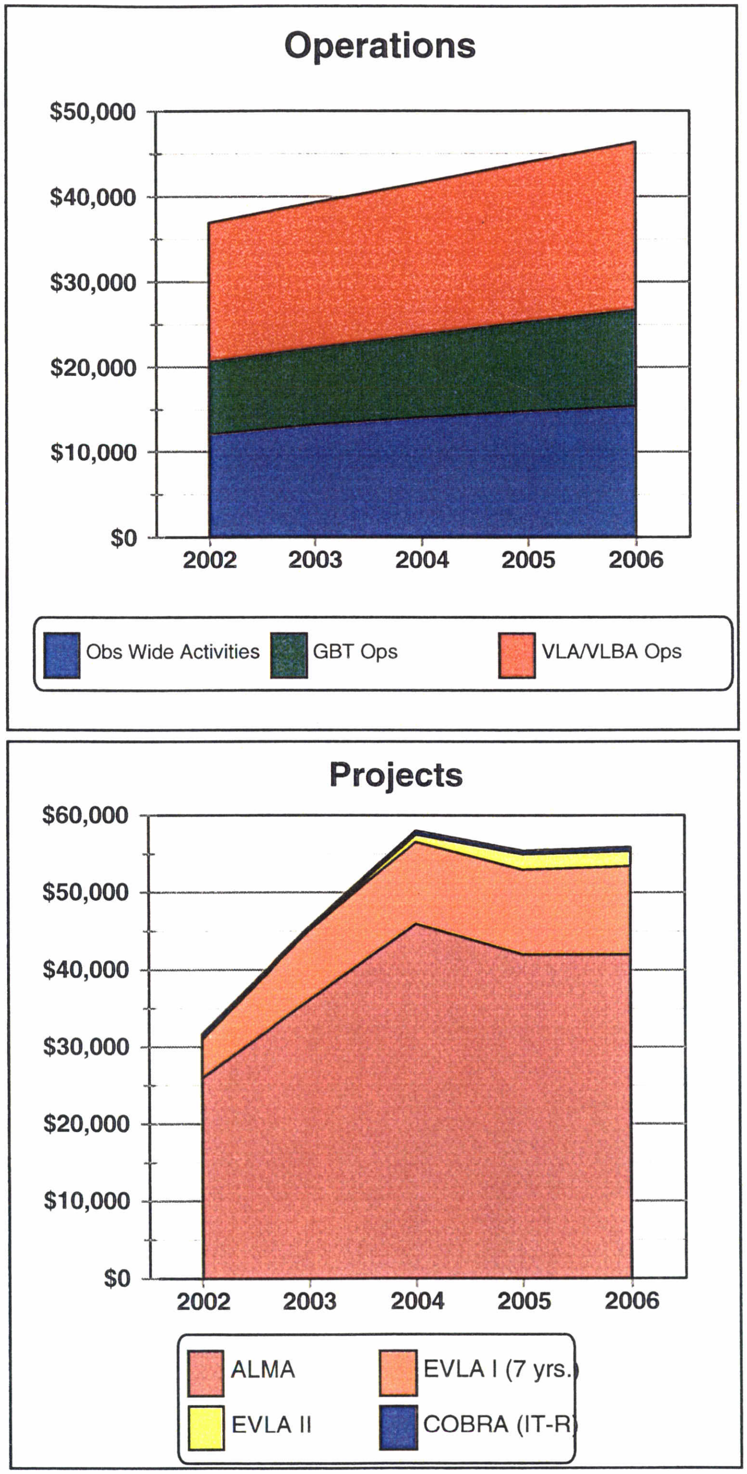
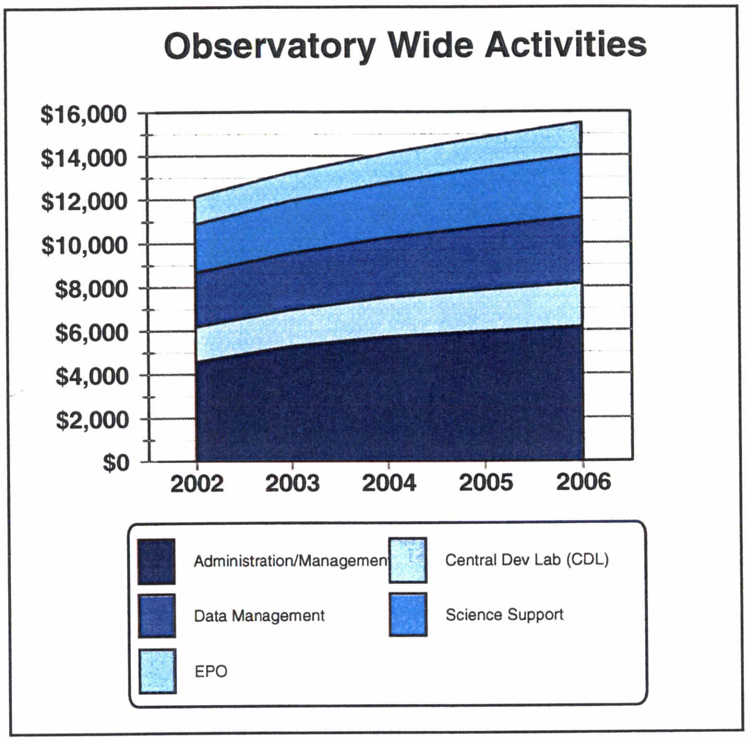


Figure VI.3 (Budget $ in 000s.) Two plots of projected operations budgets for the VLA/VLBA, GBT, and Observatory-wide activities (top), and project budgets (bottom). As in Figure VI.2, the change in slope is due to the leveling off of ALMA construction funding in 2004.



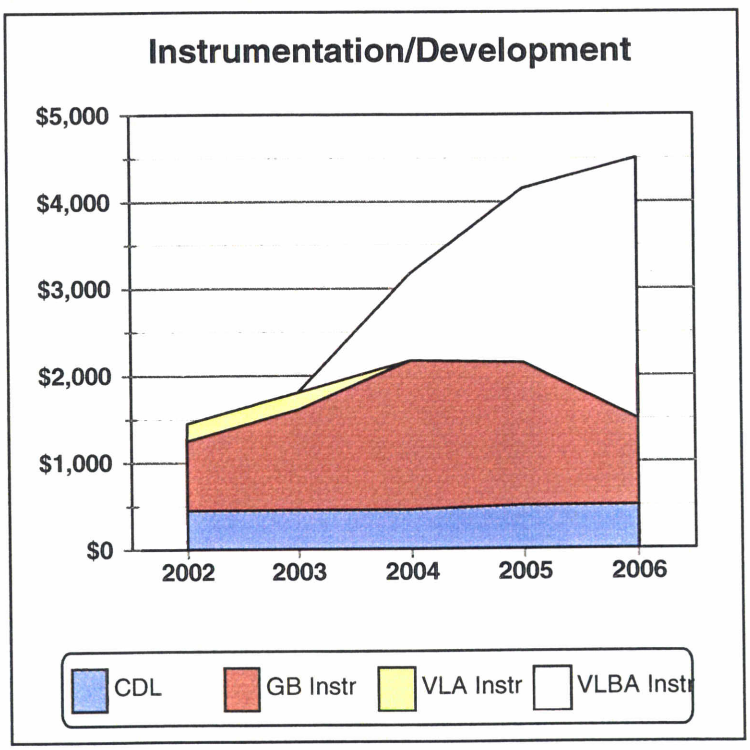


Figure VI.4 (Budget in 000s.) Two plots of projected Observatory-wide Activities by sub-category (top), and Instrumentation/Development by telescope and the CDL (bottom). The VLBA projection is only a rough estimate. Final budget figures are dependent on technical studies to be made in the next several years. There is a possibility of NASA funding this program if there is a follow-on space VLBI mission to HALCA.