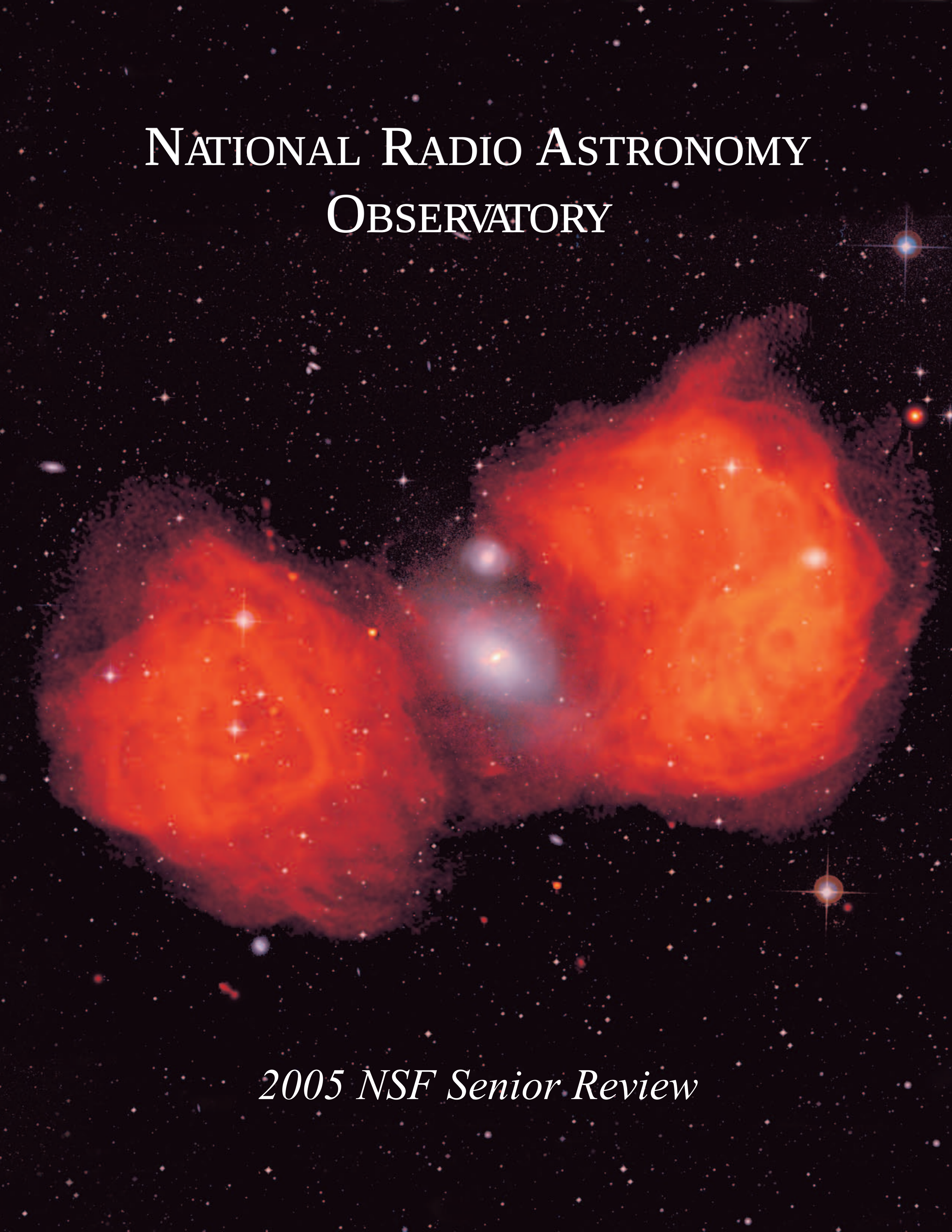
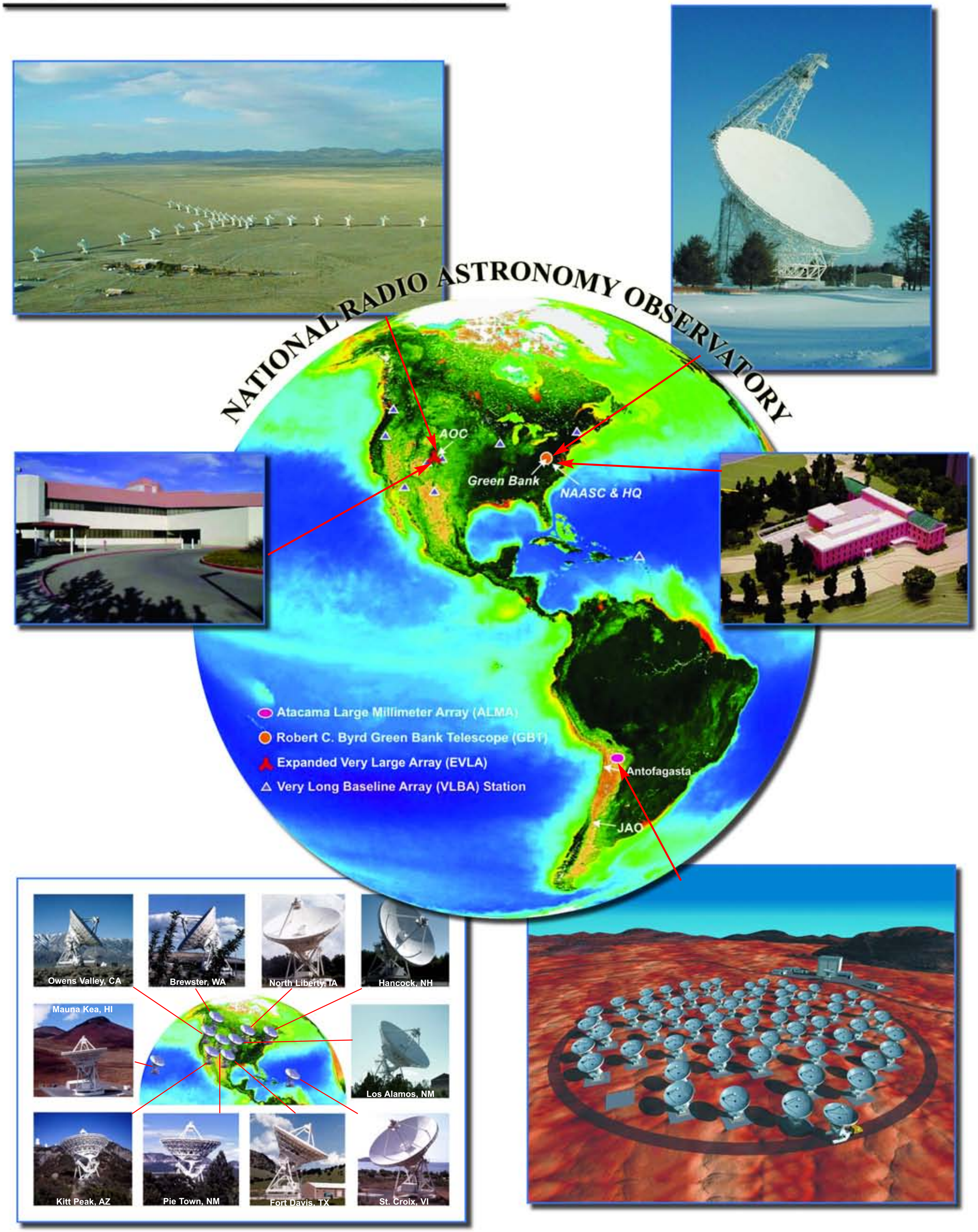
NATIONAL RADIO ASTRONOMY OBSERVATORY



2005 NSF Senior Review

NRAO in 2011


NATIONAL RADIO ASTRONOMY OBSERVATORY
AOC
Green Bank
NAASC & HQ
Antofagasta
JAO
● Atacama Large Millimeter Array (ALMA)
● Robert C. Byrd Green Bank Telescope (GBT)
Expanded Very Large Array (EVLA)
△ Very Long Baseline Array (VLBA) Station
Owens Valley, CA
Brewster, WA
North Liberty, IA
Hancock, NH
Mauna Kea, HI
Los Alamos, NM
Kitt Peak, AZ
Pie Town, NM
Fort Davis, TX
St. Croix, VI

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[1] Additional budget details were provided in this chapter of the document that was submitted to the NSF on July 31, 2005.

1. EXECUTIVE SUMMARY

> Through cooperative agreements, the NSF supports two national centers for radio astronomy: the National Radio Astronomy Observatory (NRAO), operated by Associated Universities, Inc., and the National Astronomy and Ionosphere Center (NAIC), operated by Cornell University. At centimeter wavelengths, NRAO and NAIC facilities are the best in the world, and unlike the situation in optical astronomy, there are no competing private facilities; university astronomers working at centimeter wavelengths rely almost entirely on NRAO and NAIC for their research.—Astronomy and Astrophysics in the New Millennium, National Academy Press (AANM 2001)

The National Radio Astronomy Observatory (NRAO) operates a system of complementary centimeter-wavelength radio telescopes—the Robert C. Byrd Green Bank Telescope (GBT), the Very Large Array (VLA), the Very Long Baseline Array (VLBA)—plus the Central Development Laboratory (CDL). At the same time, the NRAO is building Phase I of the Expanded Very Large Array (EVLA), essentially replacing the VLA by a new facility which has 10 times the sensitivity and 1000 times the spectral capability. Also, the NRAO is responsible for the North American part of the current construction and eventual operation of the Atacama Large Millimeter Array (ALMA), an international facility that will be 100 times more powerful than the present facilities at millimeter (mm) and submillimeter (submm) wavelengths. Both the EVLA and ALMA will be fully operational in 2012.

Soon after 2011, these NRAO telescopes will join current and future major facilities at other wavelengths, such as the Hubble, Chandra and Spitzer Space Telescopes, the Keck, Magellan and Gemini Telescopes, the VLT, the James Webb Space Telescope (JWST), the Constellation X, the Gamma-ray Large Aperture Space Telescope (GLAST) and the next generation ground-based optical/IR telescopes. The suite of NRAO facilities will form the “radio cornerstone” of this system of leading astronomical facilities in addressing the fundamental scientific questions of today and the unexpected ones of tomorrow.

Importantly, the NRAO continues to build on its excellent record of developing forefront radio-astronomical technology and observing techniques. The extensive technology base at the NRAO has been the foundation for developing and building forefront radio-astronomical facilities such as the GBT, EVLA and ALMA. The CDL has designed and built the most sensitive low-noise High Electron Mobility Transistor (HEMT) amplifiers in radio astronomy, and all Cosmic Microwave Background Radiation (CMBR) and related experiments based on heterodyne detectors (e.g., DASI, CBI, VSA, and BIMA) have used amplifiers either built or designed by the CDL. Most notably, the CDL built all of the space-qualified amplifiers in the receiver system of the Wilkinson Microwave Anisotropy Probe (WMAP).

NRAO's priorities for facility development are always set by the astronomical community, and proposals from individual investigators drive the science program. In addition to building and operating facilities, the NRAO provides user support at all stages from proposal preparation through archiving and distributing science-quality images. The NRAO is participating in the National Virtual Observatory initiative to make its archived data and legacy surveys readily available to all astronomers.

1.1 Science with NRAO Facilities

Observations at radio wavelengths address some of the most fundamental questions in astrophysics. The Cosmic Microwave Background Radiation, the Dark Ages before the onset of the first stars or galaxies, the baryonic and dark-matter content of proto-galaxies, the process of reionization of the universe by galaxies, and the earliest stages of star and planet formation are all observed using radio techniques. Combined with observations at other wavelengths, radio observations made with the suite of NRAO facilities—GBT, EVLA, VLBA, and ALMA—will enable astronomers to answer key astronomical questions and contribute to broader scientific progress:

- **How and when did galaxies and supermassive black holes form and evolve in the early universe?**
- **How do stars and planets form, and where did the chemistry of life originate?**
- **What new contributions can radio astronomy make to frontier physics?**

The NRAO facilities working together study a wide range of astronomical phenomena in detail. The 100 m GBT, the largest fully steerable radio telescope in the world, is a very sensitive and highly versatile instrument for surveys, detection, and pathfinder observations. For example, the GBT will easily detect dust emission from highly obscured young star-forming galaxies (submm galaxies) out to epochs of peak cosmic star-formation activity, using the $\lambda = 3$ mm Penn-Goddard bolometer array, complementing shorter-wavelength bolometers such as SCUBA and SHARC. Most weak submm galaxies are heavily obscured by dust, making optical spectroscopy difficult. The GBT will determine their redshifts directly from their millimeter-wave molecular lines using the Maryland Zpectrometer, a very wide-band spectrometer. The excellent surface-brightness sensitivity of the GBT will speed studies of the evolution and structure of cluster gas by mapping the Sunyaev-Zeldovich effect at

~0.1 arcminute resolution, complementing X-ray and optical lensing observations.

Both the EVLA and ALMA can reveal structure within the gaseous components of the earliest galaxies and quasars by imaging redshifted molecular-line radiation and the dust continuum, whereas optical/infrared (OIR) imaging and spectroscopic observations will define stellar components and AGN activities. Together, these observations will provide a complete picture of how stars, galaxies, and quasars form and evolve. The VLBA (and the High Sensitivity Array that combines the VLBA with the GBT and EVLA) can measure accurate distances and proper motions of megamasers in the nuclei of distant galaxies, complementing OIR approaches to determining the Hubble constant and the expansion rate of the Universe. ALMA will resolve details in circumstellar disks as planets form by mapping their mm and submm continuum and line emission, complementing near- and far-IR observations of the later stages of the debris disks and exoplanets.

1.2 Looking Forward: the Observatory in 2011

Looking forward to 2011, both EVLA (Phase I) and ALMA will be approaching full operation and will be working alongside the GBT and the VLBA. This combination of radio facilities will provide astronomers a wide coverage of wavelength, from $\lambda \approx 0.3$ mm to 1 m, and baseline lengths from the filled-aperture GBT (0–100 m), through connected-element interferometers such as the EVLA (0.025–35 km) and ALMA (up to 10 km), to the transcontinental VLBA (200–8,600 km). This range of capabilities is needed to span the “discovery space” of wavelength, angular resolution, and surface-brightness sensitivity for observing both thermal and nonthermal radiation from a wide range of astronomical sources. The resulting scientific breadth of NRAO telescope facilities is enormous, covering topics from cosmology to geodesy.

In addition to providing facilities, the NRAO must also ensure that radio astronomical observations and data are accessible to all astronomers. This requires user support at all stages from proposal preparation through archiving calibrated reference images which are ready for scientific analysis. Such user support will be carried out for the EVLA and VLBA through the Array Operations Center in Socorro, for ALMA through the North America ALMA Science Center in Charlottesville, and for the GBT in Green Bank. Furthermore, the NRAO is participating in the National Virtual Observatory (NVO) initiative to make its archived data and legacy surveys (e.g., FIRST and NVSS) readily available to astronomers worldwide.

Because of the breadth and depth of the expertise of its staff, the NRAO is also an essential resource for developing the next generation of observing facilities, such as the Square Kilometre Array (SKA). Indeed, the existing NRAO facilities may serve as a very cost-effective backbone of the infrastructure required to develop and advance the SKA or other future radio-astronomy facilities beyond 2011.

1.2.1 The Robert C. Byrd Green Bank Telescope (GBT)

The 100 m GBT is a new facility that has been in full operation only since late 2003. It is the most sensitive fully steerable telescope at wavelengths from $\lambda = 1$ m to 5 mm (0.3 to 60 GHz). It is the only large telescope having an unblocked aperture, giving it higher aperture efficiency, lower sidelobe levels, and reduced pickup of ground radiation. Its flexible instrumentation and nearly continuous frequency coverage make it a powerful pathfinder for detecting new sources such as high-*z* galaxies, millisecond pulsars, and new interstellar molecules. The GBT has a computer-controlled active surface which will allow operation at $\lambda = 3$ mm. Early scientific returns from the GBT have been excellent. By 2011, it will have reached maturity with its first generation of instrumentation and capabilities and will be poised for the next generation of upgrades that will include optimized operations in the $\lambda = 3$ mm band and imaging cameras providing factors of 10 to 1000 increase in observing speed. The GBT is, and will remain, the forefront national radio facility on which university groups can develop world-class instruments and retain instrumental expertise. The GBT benefits from and is the prime justification for the National Radio Quiet Zone, a unique and irreplaceable preserve for radio astronomy which protects against radio interference caused by the ever-increasing commercial use of the electromagnetic spectrum. The GBT also supports a very active public-outreach program and is among the most visible of NSF facilities, as it is within a day’s drive of major east-coast population centers. The GBT is the optimal facility for a wide range of current and future research that includes:

- Constraining the equation of state of high-density matter in neutron stars and making the most stringent tests of general relativity in strong gravitational fields by discovering and timing millisecond pulsars in globular clusters.
- Finding the redshifts and molecular-gas masses of “submm galaxies,” candidates for dusty proto-galaxies at high *z,* by spectroscopy instantaneously covering the entire band from $\lambda = 1.15$ to 0.75 cm (26 to 40 GHz), using the Zpectrometer redshift machine recently funded by an NSF ATI grant to the University of Maryland.
- Studying the evolution and structure of cluster gas as a function of redshift by imaging the Sunyaev-Zeldovich effect, using the $\lambda = 3$ mm Penn-Goddard Array bolometer camera now under construction.

1.2.2 The Expanded Very Large Array (EVLA)

The VLA is the most productive ground-based observatory in existence, whose refereed publication rate during the past decade is second only to that of the Hubble Space Telescope. The EVLA is the second-highest-ranked ground-based "major initiative" recommended by the 2001 AANM report. Phase I of the EVLA project will effectively replace the VLA with a new instrument having an order-of-magnitude increased sensitivity, continuous wavelength coverage from λ = 30 cm to 0.6 cm (1 to 50 GHz), and much-improved spectral resolution and observing bandwidth. Phase II of the EVLA project will increase the angular resolution of the VLA by a factor of 10 with the introduction of new stations to fill in the spatial-frequency coverage between the VLA and the VLBA, but this phase has not yet been funded. The continuous frequency coverage of the EVLA will enable the detection and imaging of molecular gas in submillimeter galaxies at $z > 1.3$. The VLA has already detected and imaged the CO(3-2) emission from SDSS 1148+5251 at $z = 6.42$, the highest-redshift quasar known. When both phases of the EVLA are complete, their vastly enhanced sensitivity and resolution will enable astronomers to:

- Detect the galaxies responsible for the bulk of star formation out to $z \sim 4$ from deep-field surveys down to 1 µJy, and trace the formation and evolution of galaxies and active galactic nuclei (AGN) by imaging the molecular lines and continuum emission from such galactic structures at similar redshifts.
- Image the earliest formation and evolution of circumstellar disks and thermal jets in deeply-embedded protostars, where the surrounding envelope is optically thick at ALMA wavelengths, and demonstrate the growth of dust grains to cm-sized planetesimals in debris disks.
- Trace the energy outflow from neutron-star and black-hole binaries, as well as from explosive phenomena like soft gamma-ray repeaters, quasars and AGN, novae and supernovae via high-resolution imaging.
- Study the origins of cosmic magnetic fields by imaging magnetic fields in individual galaxy clusters, in nearby spiral galaxies, and in relativistic jets.

1.2.3 The Very Long Baseline Array (VLBA)

The VLBA, comprising ten 25 m telescopes located from Mauna Kea, Hawaii, to St. Croix, Virgin Islands, is the world's only dedicated very-long-baseline imaging array. It produces images with the highest angular resolution (< 1 milliarcsecond) and astrometric accuracy (10 microarcseconds, 100 times better than Hipparcos) in all of astronomy. The VLBA can resolve high-brightness sources as small as 1 pc and measure their positions with 0.1 pc or better accuracy *anywhere in the Universe*. With enhanced sensitivity through a wider bandwidth, the VLBA, and the High Sensitivity Array (HSA) which combines the VLBA with the GBT, EVLA, and Arecibo for a much larger collecting area, are needed to:

- Image motions and evolution of jets in gamma-ray blazars at high radio frequencies to determine the origin of gamma-ray emission and flares which will be detected by the GLAST satellite.
- Investigate and characterize the role of dark matter in the cosmos by studying gravitational lensing.
- Constrain the mass content and distribution of the Local Group, including the dark-matter halo, by astrometric measurements of the proper motions of the galaxies, as demonstrated for M33 recently.
- Provide a detailed structural and kinematic map of our Galaxy by astrometric measurements of pulsars, circumstellar masers, and binary stars.
- Image the circumnuclear water megamasers in distant AGN and determine directly their black-hole masses and geometric distances out to $z \sim 1$.

1.2.4 The Atacama Large Millimeter Array (ALMA)

ALMA will revolutionize the millimeter and submillimeter-wave study of star formation, proto-planetary disks, high-redshift galaxies, nearby galaxies, comets, and many other areas. It will allow rapid imaging of dust continuum and molecular-line emission at angular resolutions down to 10 milliarcsecond with unprecedented sensitivity. When completed in 2012, ALMA will provide astronomers with the ability to:

- Detect spectral-line emission from CO or CII in a normal galaxy like the Milky Way at a redshift of z = 3 in less than 24 hours of observation, and to image the redshifted dust continuum emission from forming galaxies at epochs as early as $z = 10$.
- Image the gas kinematics in protostars and in protoplanetary disks around young Sun-like stars at a distance of 150 pc (roughly the distance of the star-forming clouds in Ophiuchus or Corona Australis). This will enable the study of their physical, chemical and magnetic field structures and the detection of the tidal gaps created by planets undergoing formation in the disks.
- Produce precise images of a wide range of mm/submm phenomena at an angular resolution of 0.02 arcsec.

1.2.5 The Central Development Lab (CDL)

The CDL provides the technology backbone of both centimeter- and millimeter-wave observing at the NRAO and around the world. This laboratory leads the world in designing and building low-noise solid-state amplifiers for wavelengths as short as λ = 3 mm (100 GHz) and will supply them for ALMA, EVLA, GBT and other instruments in the future. In collaboration with the University of Virginia Microelectronics Laboratory, the CDL is among only a few facilities which are consistently able to develop reliable and high-quality superconductor-insulator-superconductor (SIS) mixers for ALMA. The CDL is also a leader in digital signal processing and is presently building the ALMA correlator, the world's fastest supercomputer capable of > 10^{16} calculations per second.

1.3 Performance Metrics

NRAO facilities are demonstrably productive and cost-effective, with broad usefulness to the community. In terms of journal publications, the VLA was the most productive ground-based instrument in the world over the past decade and is surpassed only by HST among all astronomical facilities. All NRAO telescopes observe day and night in most weather conditions and, at an average fully loaded operating cost of ~$2,400/hour, are among the most economical of all national user facilities. The average cost per refereed publication from the VLA is only $80k. More than 1000 different scientists from over 200 different institutions and about 100 PhD students make use of NRAO observing facilities each year.

1.4 Prioritization and Cost-Saving Measures

The 2001 Astronomy and Astrophysics Survey Committee (AASC) reaffirmed the 1991 AASC recommendations by endorsing the completion of ALMA, and it recommended the full EVLA as a new ground-based "major initiative."

Anticipating the need for funding ALMA operations, which are not covered by the MREFC construction budget, the AASC reported:

> It is imperative that the United States maintain its leadership and critical involvement in ALMA. Given the demonstrated effectiveness of the NRAO organization, the panel urges that to operate ALMA, no new institution be created as an entity separate from NRAO. At the same time, NRAO's other unique and vital facilities must be run in synergy with ALMA, not in competition with it. (AANM 2001)

In view of the AST budget constraints and with the AASC recommendations as guidance, the NRAO has responded to the requests of the Senior Review very thoroughly, including a careful description of its scientific vision for 2011 and beyond, performance metrics, business model, operations budget, and priorities for Observatory activities.

Following the direct recommendations of the AASC, the NRAO's top priorities are the construction and operation of ALMA and the EVLA.

The NRAO operates a research and development laboratory, the CDL, which is essential to the long-term future of radio astronomy. The cost of the CDL is very modest, particularly given its great benefits. The NRAO also operates two additional telescopes which are world leaders in producing unique science: the GBT and the VLBA. The GBT is a new telescope with excellent early results and growing scientific potential. The VLBA is critical for some of the most important and fundamental measurements of astronomy. Both facilities provide essential complements to the EVLA, ALMA, and observatories at other wavelengths, and figure prominently in plans for next generation facilities. Both facilities are unique and cannot be replaced by other facilities anywhere in the world. Their priority depends strongly on the direction of all astrophysics, not just radio astronomy, over the next two decades. Because of their unique nature, closing either facility would cause significant long-term damage to the astronomy research infrastructure in the U.S.

Recognizing the need for balancing new initiatives with the ongoing program, the AASC endorsed the completion of ALMA and strongly recommended that a different mode of budgeting be instituted for new initiatives:

> The community and the NSF must commit *at the beginning of a project* to estimate adequately and acquire the funds required to properly utilize the facility for the research of which it is capable. Without clear identification of these monies, new construction should not begin. (AANM 2001)

Accordingly, the NRAO urges that both the construction <u>and</u> operations funding for all new projects be identified prior to their approval. This includes EVLA Phase II, even though it completes the EVLA project as recommended by the AASC in 2001 and its incremental operations costs are unusually low because Phase II is highly leveraged from Phase I.

After 2011, approximately $5.5M per year for the EVLA Phase I construction will be freed from the current NRAO operations budget and will be available for NSF AST use.

The NRAO has always been strongly committed to cost-saving efforts. *It has already closed a number of telescopes and operates only world-leading facilities with AST funds.* The NRAO has limited its development activities through rigorous priority setting, increased operational efficiency through economies of scale, consolidated administrative services, made selective reductions of operations where scientifically tenable, and is actively seeking opportunities for non-NSF/AST funding. Specifically, over the past two years, the NRAO Tucson operations have been phased out, and the ALMA construction efforts there have been consolidated with those in Charlottesville. A voluntary early-retirement program was instituted this past spring, and many other vacated positions have not been filled in an Observatory-wide effort to minimize the personnel budget. Such cost-savings efforts will continue in order for the NRAO to provide the astronomy community a suite of forefront facilities at the minimum operating cost.

1.5 Conclusion

In 2011 the NRAO will be the premier radio observatory providing the astronomy community a remarkable suite of extremely powerful and complementary telescopes to address key astrophysical questions. The open- skies policy it has championed has promoted the best possible science over the years, has led to many important discoveries, and has been in accordance with the strong sentiment of the user community. The exceptional breadth and depth of the facilities, and the expertise and experience in radio-astronomical science and technology have taken 50 years to build up, resulting in an NRAO that is recognized by many as an essential resource for astronomy in the US, and indeed in the world.

A Senior Review of the portfolio of NSF/AST-supported facilities is a necessary process to evaluate the costs and benefits of these facilities and to prioritize spending, especially at this time of budget pressure when many worthwhile new projects are awaiting funding. However, care must be taken to avoid irreparable damage to existing US astronomy infrastructure in this process. The balance between supporting those existing facilities which give U.S. astronomy a competitive advantage and initiating new projects which will maintain that competitive position is a very delicate one.

2. KEY SCIENCE

2.1 How and When Did Galaxies and Supermassive Black Holes Form and Evolve in the Early Universe?

Absorption of $\lambda < 0.0912$ micron ultraviolet radiation by the neutral intergalactic medium (IGM) prior to the Epoch of Reionization (EoR) at $z > 6$ precludes optical studies of the earliest phases of galaxy formation. Near-infrared observations by future large telescopes such as the JWST and the GSMT will reveal stars and ionized gas in the first generations of galaxies. However, dust absorption still obscures both star formation and the growth of supermassive black holes (SMBHs) in AGN. Half of the visible light in the universe (and up to 99% in luminous starburst galaxies) is absorbed and re-radiated by dust. Radio astronomy offers a direct view of the formation and growth of galaxies and SMBHs, unbiased by dust extinction.

NRAO telescopes are well suited to cover the radio and submillimeter window on galaxy formation and evolution back into the EoR. Used in concert with current and future telescopes such as Spitzer, Chandra, JWST, Constellation X, and the GSMT, they can contribute to the panchromatic view of galaxy formation and evolution by helping to reveal the molecular gas, dust, ionized gas, stars, dark-matter content, and star-formation properties in the first galaxies. Figure 2.1.1 shows the frequency coverage and the 12-hour sensitivities of the current VLA, EVLA, GBT, ALMA, Spitzer Space Telescope, and JWST relative to the spectral energy distributions (SEDs) of active star-forming galaxies similar to Arp 220 at redshifts up to $z = 8$, demonstrating the capabilities of these telescopes to probe galaxies well into the EoR.

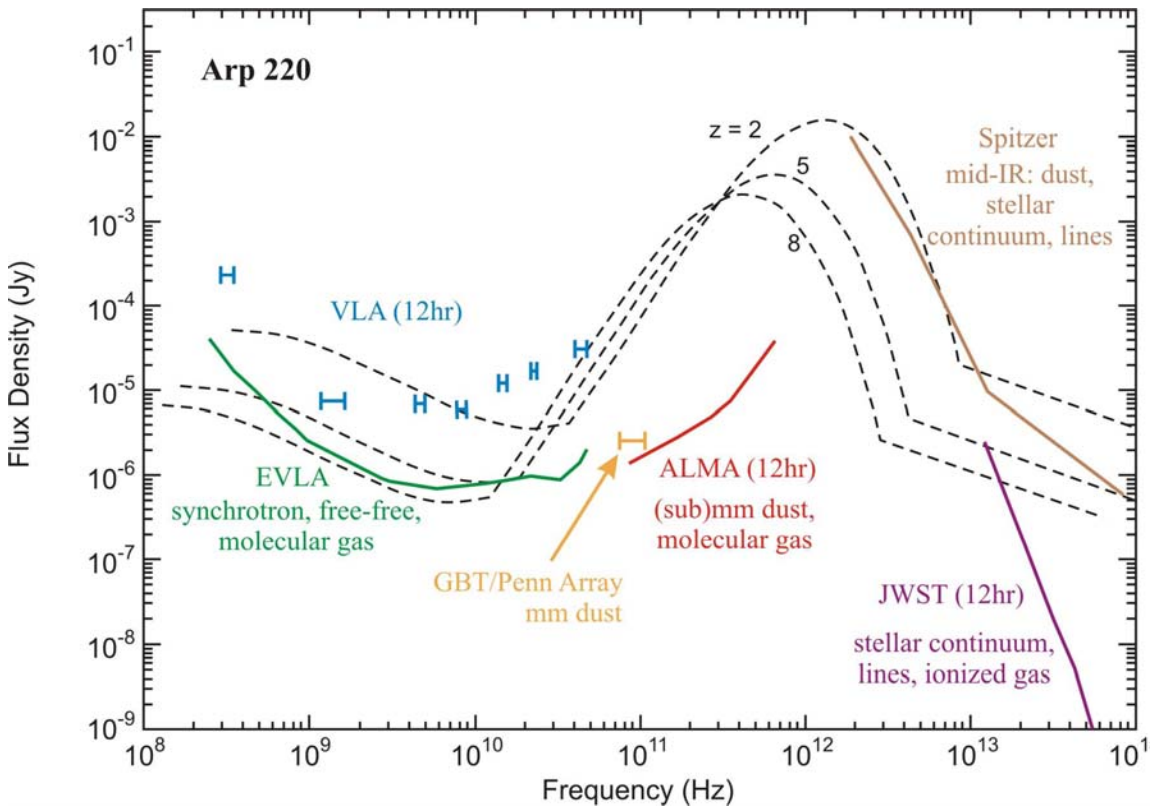


Figure 2.1.1 The continuum SEDs of actively star-forming galaxies similar to Arp 220 at redshifts z = 2, 5, and 8 (dashed curves). Solid curves plot the rms sensitivities in 12 hours for the VLA, EVLA, ALMA, Spitzer (confusion limited at long wavelengths), and the JWST. The rms confusion limit of the GBT, reached after two hours of integration, is also shown. Existing facilities (the VLA and Spitzer) can study galaxies having dust luminosities ~10^{12} $L_\odot$ out to z ~ 2. The EVLA, ALMA, and JWST will be able to image star-forming galaxies an order of magnitude fainter, all the way back to the EoR when the first galaxies formed.

2.1.1 Finding High-Redshift Galaxies

The discovery of “submillimeter galaxies” significantly changed our view of galaxy formation by revealing a population of optically obscured, dusty starburst galaxies that may dominate the cosmic star-formation rate during the peak epoch of star formation at *z* ~ 2 and beyond. Because of its superior sensitivity, ALMA will be able to image the redshifted dust continuum emission from evolving galaxies at whatever epochs they were formed. The inverse K-correction on the Rayleigh-Jeans side of the dust SED (Figure 2.1.1) compensates for dimming at high redshifts, making ALMA the ideal instrument for investigating the origins of galaxies in the early universe, with confusion minimized by ALMA’s high spatial resolution (see Figure 2.1.2).

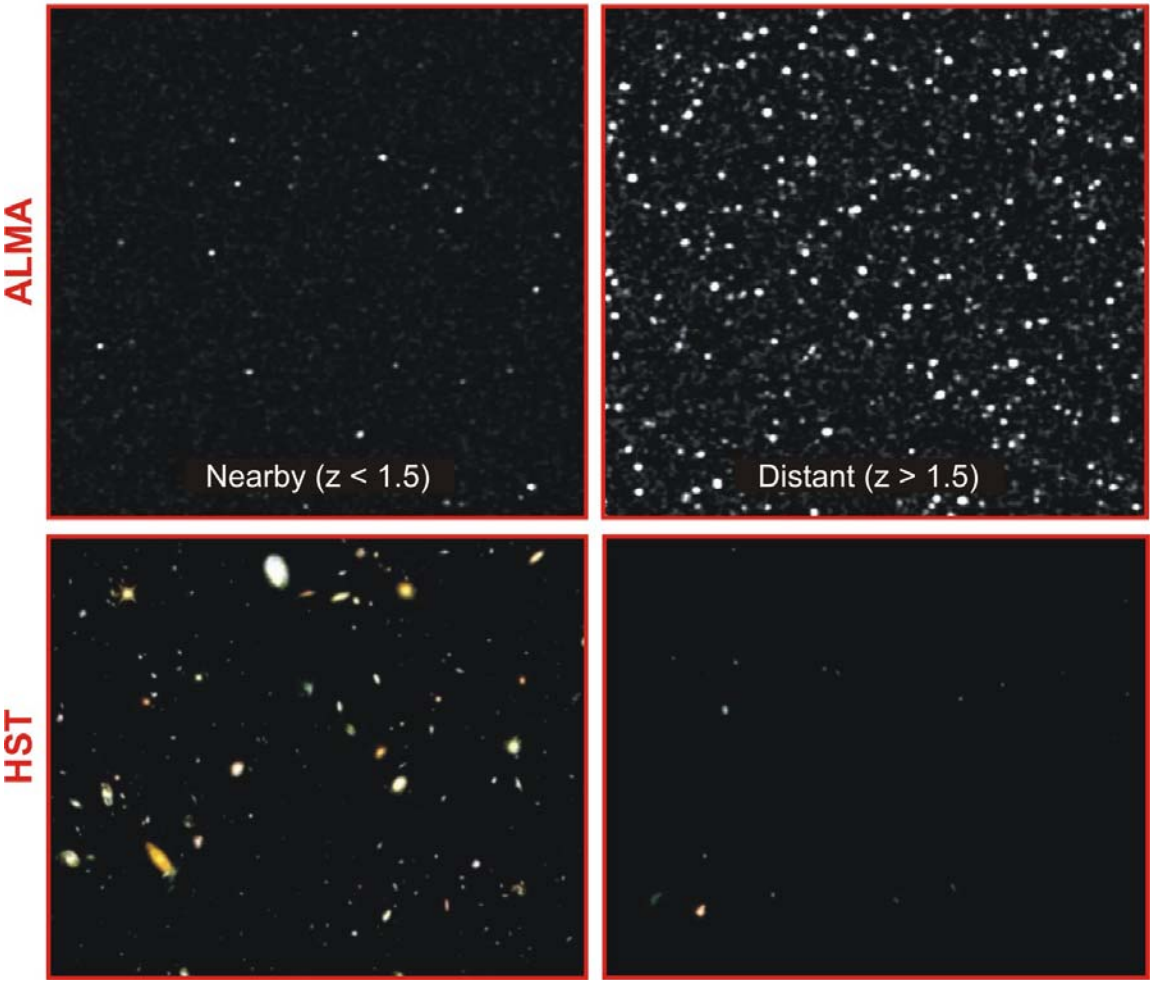


Figure 2.1.2 The top two pictures show simulated deep-field observations of galaxies with $z < 1.5$ and $z > 1.5$. The bottom two show actual Hubble Deep Field galaxies with $z < 1.5$ and $z > 1.5$. ALMA will detect typical Lyman-break galaxies in addition to dusty star-forming galaxies.

The GBT may soon significantly increase the number of dusty starburst galaxies known by making wide-field surveys at $\lambda = 3$ mm (100 GHz) with the Penn Bolometer Array. Operating at a longer wavelength than current bolometer arrays (i.e., SCUBA on the JCMT and MAMBO on the IRAM 30 m telescope), the Penn Array has the potential to find sources at the highest redshifts. When combined with data from other bolometer arrays, the $\lambda = 3$ mm observations will provide the temperature of the dust emission—an important physical parameter that is currently only weakly constrained. The Penn Array project is viewed both as a science pathfinder for ALMA and as a technology pathfinder for future bolometer arrays of 1,000 to 10,000 pixels which will dramatically increase the imaging speed of single-dish telescopes.

In the wavelength range λ = 30 to 3 cm (1 to 10 GHz), the EVLA will make wide-field ultra-sensitive surveys that detect synchrotron radiation from star-forming galaxies. The synchrotron luminosity of a star-forming galaxy is a well-established and dust-unbiased indicator of its star-formation rate. Sensitive VLA surveys now reach source densities of about 3 sources per square arcminute. They typically detect over two thirds of both the X-ray AGN and submillimeter starburst galaxies found in the deepest current surveys, indicating that the VLA is detecting the same population of objects. Deeper surveys with the EVLA at λ = 20 cm may detect ~50 sources per square arcminute stronger than S ~1 μJy, the flux density of galaxies having star-formation rates of only 3 $M_\odot$/yr at $z \sim 1$ or 30 $M_\odot$/yr at $z \sim 3$. Such surveys should yield large samples, unbiased by dust, of these galaxies which can be used in combination with surveys at other wavelength bands to constrain the formation and cosmological evolution of galaxies and AGN.

2.1.2 Tracing the History of Star Formation in the Universe

Star-formation rates at high redshifts remain very uncertain. Obtaining optical and near-infrared redshifts for obscured galaxies has been difficult and time consuming, and it will continue to be a major focus of the JWST and GSMT. The GBT will soon be able to join this effort by determining the redshifts of obscured galaxies by detecting emission lines of CO and other common molecules using the wideband Maryland Zpectrometer, aided by the high spectral dynamic range of the GBT correlation receivers. Figure 2.1.3 illustrates the redshift ranges and CO lines that will be accessible to the GBT, the EVLA, and ALMA.

ALMA observers will be able to use CO emission lines to measure the redshifts of star-forming galaxies throughout the universe. The frequency spacing between successive transitions of CO varies with redshift as $(1 + z)^{-1}$, and the large total bandwidth of ALMA will make possible blind surveys that will establish the star-forming history of the universe without the uncertainties and biases caused by dust extinction.

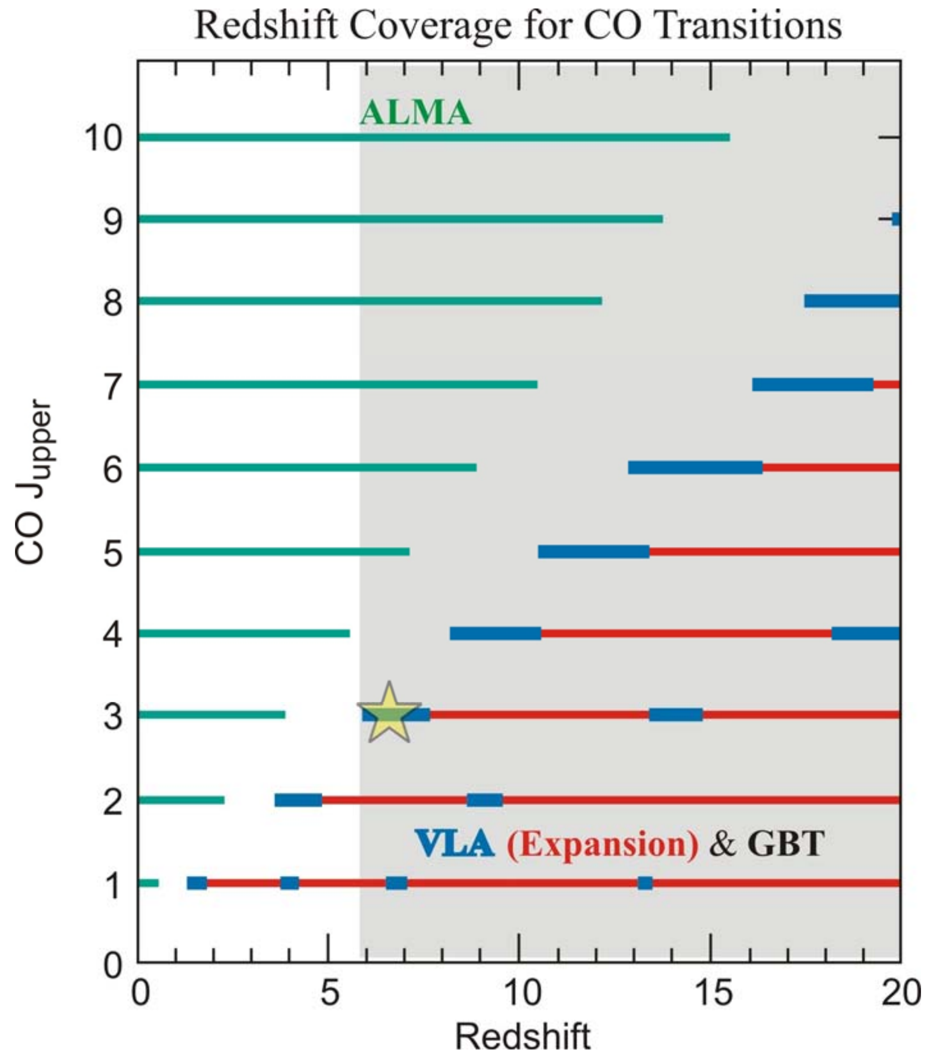


Figure 2.1.3 One or more CO lines at all redshifts are accessible to the GBT (red and blue lines), the EVLA (red and blue lines) and ALMA (green lines). The yellow star denotes the CO(3–2) line from the z = 6.42 quasar J1148+52 already imaged by the VLA (whose limited redshift coverage is shown by the thick blue lines).

The EVLA will detect the low-order transitions from common molecular species such as CO (Figure 2.1.3) and HCN in actively star-forming galaxies. Low-order transitions provide the best estimates for the total mass of cold molecular gas—the fundamental fuel for star formation. Multi-transition studies with ALMA will constrain molecular temperatures, densities, and abundances. Both the EVLA and ALMA will be able to make images of the distribution and dynamics of molecular clouds with sub-arcsecond resolution, thereby constraining the gravitating matter content (both dark and baryonic) of the first generations of galaxies. This capability has already been demonstrated, albeit with some difficulty, by the VLA. The VLA image of molecular gas around the quasar having the highest known redshift, $z = 6.42$, is shown in Figure 2.1.4.

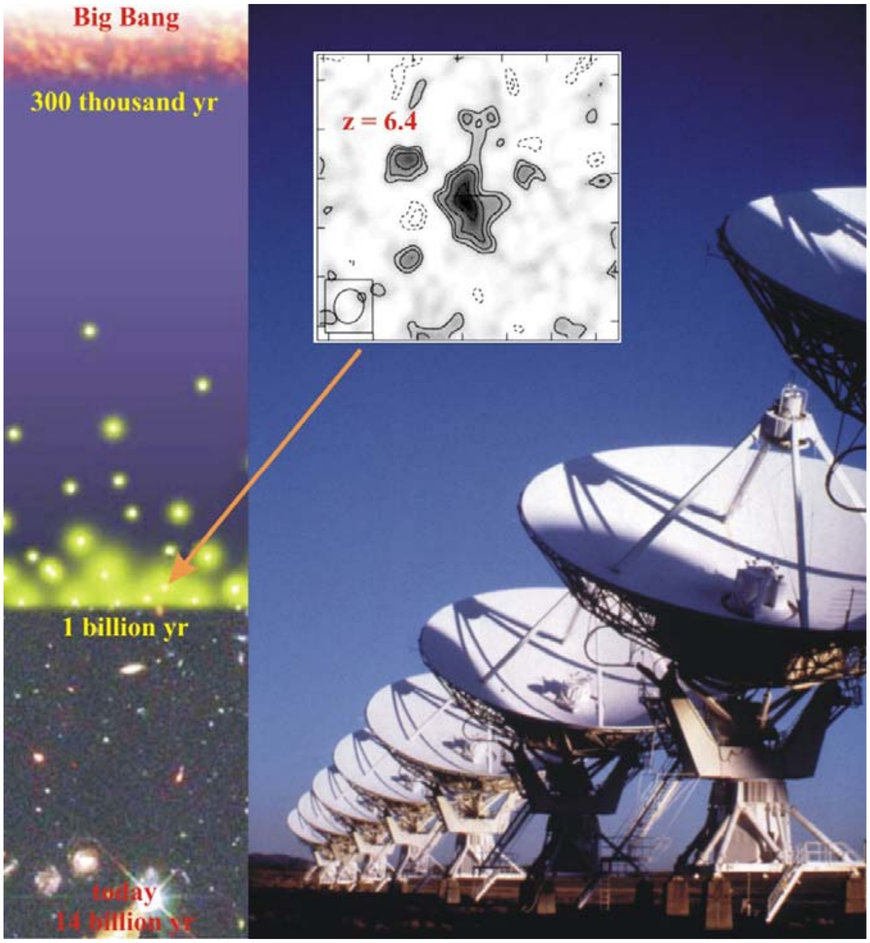


Figure 2.1.4: CO J = 3–2 emission from the quasar J1148+52 at z = 6.42 during the EoR (left panel) was imaged by the VLA with 0.3 arcsec resolution (embedded panel). The host-galaxy dynamical mass within 3 kpc of the quasar, derived from the CO kinematics, is ~5 × 10^{10} $M_\odot$, comparable with the total molecular-gas mass estimated from the CO luminosity. These observations suggest coeval starburst and AGN activity during the EoR.

2.1.3 The Black Hole–Star Formation Connection

The growth of SMBHs is closely linked to formation and galaxy evolution. Nuclear black holes may be ubiquitous, and their masses are roughly proportional to the masses of their host bulges. However, regions of active star formation and black-hole activity are often small (~100 pc) and obscured by dense gas and dust.

Working together, the EVLA and ALMA will lay bare the central region of star formation and the black hole activity. Their broad spectral coverage will probe three continuum processes at high redshifts: synchrotron emission at $\lambda > 3$ cm (< 10 GHz) ultimately powered by supernovae or jets driven by accretion onto black holes, free-free emission from gas ionized by massive stars in the range $1 < \lambda < 3$ cm (10 to 30 GHz), and dust emission at $\lambda < 1$ cm (> 30 GHz). Free-free luminosity is a direct measure of the star-formation rate in galaxies and is tightly correlated with the peak dust emission in the far infrared. With joint ALMA and EVLA observations, it will be possible to separate these components spectrally and estimate the relative importance of star formation and black-hole activity for each galaxy.

Current VLA surveys show that the median angular size of the faint-source population is ~1 arcsec, or 8 kpc at $z \sim 2$. With the high resolution of ALMA and the EVLA it will be possible to image on spatial scales of 50 to 500 pc over a wide range of redshifts. This will help to distinguish between SMBH accretion and star-formation as the dominant energy source and reveal how these phenomena interact in the evolution of galaxies and quasars. With the resolution of EVLA II plus the VLBA, astronomers would have a powerful black-hole finder. Such radio data, combined with data from the JWST and future hard X-ray imaging missions, would provide a dust-unbiased view of black-hole demographics in the early Universe.

2.2 How Do Stars and Planets Form, and Where Did the Chemistry of Life Originate?

High-resolution studies of the earliest dust-enshrouded phases of star formation are the exclusive domain of radio astronomy. ALMA and the EVLA are poised to make breakthroughs in studies of star and planet formation, from AU-scale imaging of the dust and gas in protoplanetary disks and protostellar jets to detailed studies of the astrochemistry in star- and planet-forming environments and the critical role played by magnetic fields. The EVLA and ALMA will deliver at least an order-of-magnitude improvement over existing facilities in sensitivity, frequency coverage, spatial resolution, and spectral resolution. The VLBA provides the highest possible spatial resolution for following the dynamical evolution of masers in winds and jet shocks, while the GBT provides the surface-brightness sensitivity required to detect the weak emission from complex organic molecules, the necessary precursors to life, in dark clouds.

2.2.1 The Formation and Evolution of Protoplanetary Disks

The youngest protostars are completely obscured at visible and near-infrared wavelengths. Only observations at submillimeter to centimeter wavelengths can directly image the deeply embedded early phases of star and disk formation. It is believed that protostars grow by the accretion of material through circumstellar disks and simultaneously drive powerful jets along the disk axis. The disk/jet connection and the mechanism by which material is transported through accretion disks have eluded observational study because of limited spatial resolution. Figure 2.2.1 illustrates the possible structure in a disk, massive enough to be unstable to its own gravity, producing spiral instabilities that might transport matter and angular momentum. Such structures could be imaged directly by ALMA.

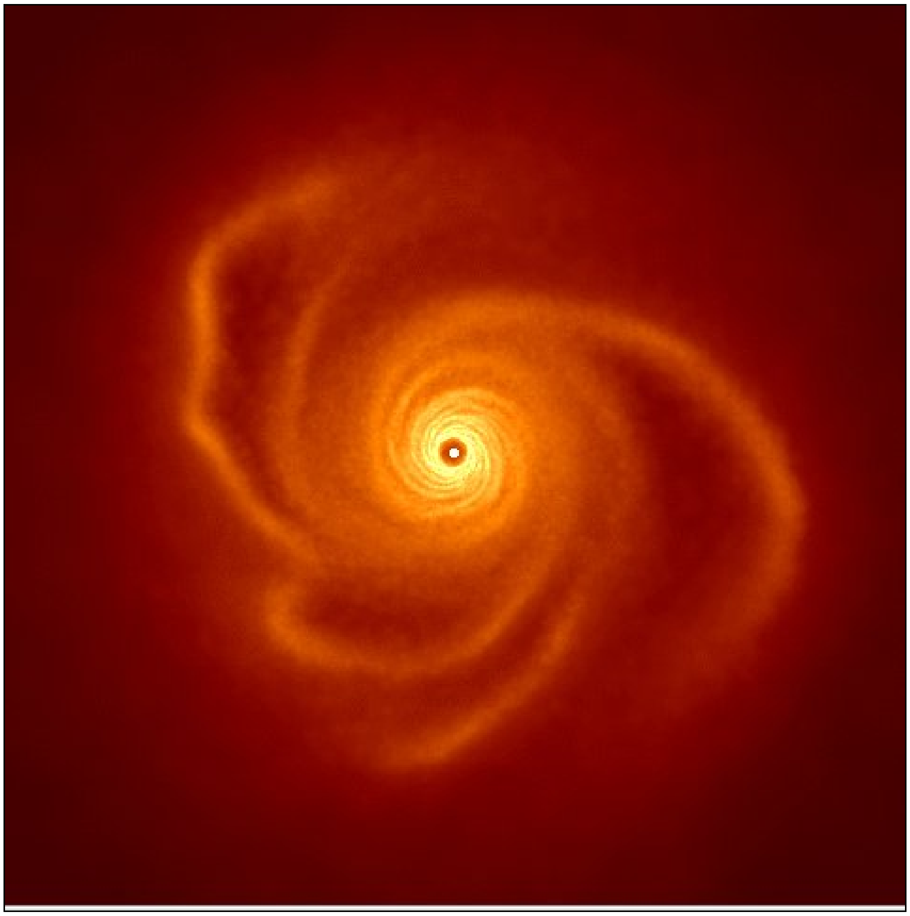


Figure 2.2.1 This frame from a simulation by Lodato & Rice (2005, MNRAS, 358, 1459) shows the molecular hydrogen column-density structure in a disk about half as massive as the central solar-type star. The image is 50 AU on a side. Instabilities, suggested here by the spiral pattern, may be responsible for the transport of both material and angular momentum in protostellar accretion disks, and could be imaged directly by ALMA.

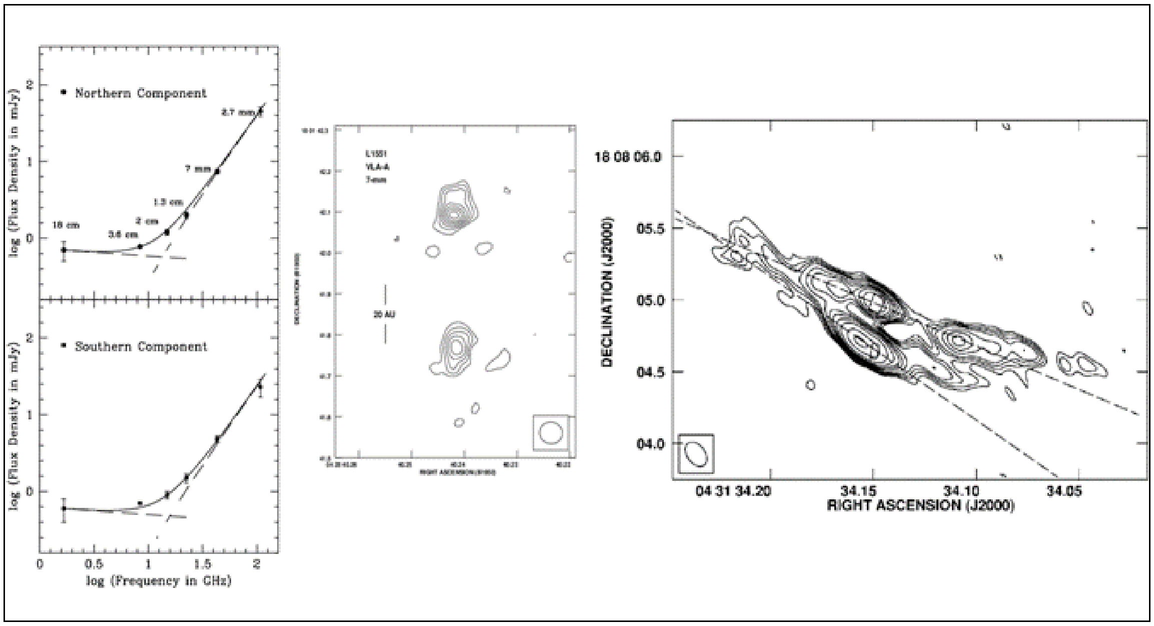
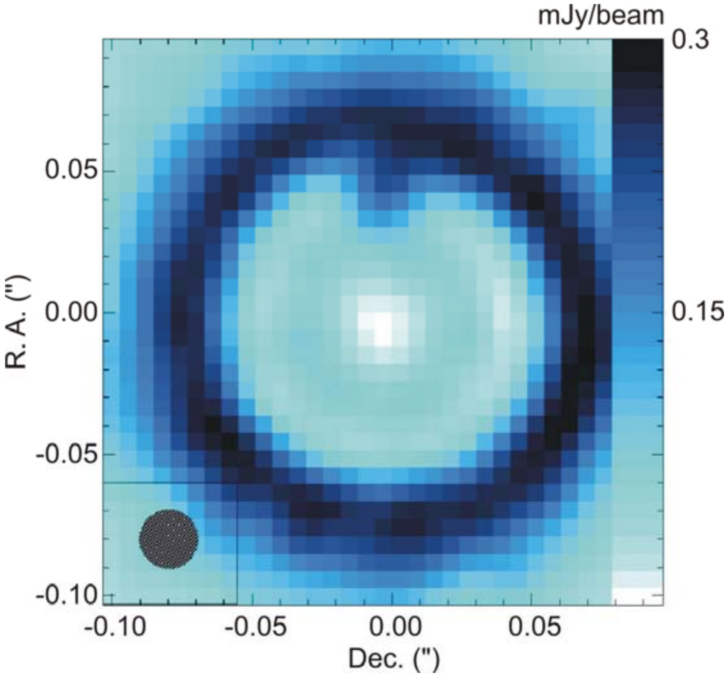


Figure 2.2.2 (Left) The radio spectra of the two components of the embedded protostellar binary system L1551-IRS5 illustrate the transition from emission by ionized gas at frequencies less than 10 GHz (λ > 3 cm) to emission dominated by dust at millimeter/submillimeter wavelengths. (Center) This λ = 7 mm continuum image made with the VLA in its most extended configuration shows that each binary component is surrounded by a dust disk. At its shortest wavelengths ALMA will image these disks with a factor of five better spatial resolution. (Right) At λ = 3.6 cm the ionized gas is resolved into two separate jets oriented perpendicular to the dust disks of the binary components shown as the brightest components near RA = 34.15 seconds (Rodriguez et al. 2003, ApJ, 586, L137). EVLA Phase II could image these jets with ten times the spatial resolution to reveal the relationship between the jets and the disks.

The combination of ALMA and the EVLA will be able to separate the dust emission in the disk from the ionized gas in the accompanying jet (Figure 2.2.2), and at the shortest wavelengths ALMA will have enough resolution to detect the tidal gaps created by planets forming in the disk. Figure 2.2.3 shows a simulated ALMA observation of the dust emission from a disk harboring a 1.0 M_{Jup} protoplanet orbiting a 0.5 $M_{\odot}$ star. This planet would not be discernable in the overall SED but is clearly detectable in the ALMA image.

Figure 2.2.3: From this simulation Wolf and D'Angelo (2005, ApJ, 619, 1114) found that while a planet is not discernable in a region's integrated SED, ALMA could directly image the hot region near the young planet (upper center). The source is at the distance of the dark cloud B68, 100 pc from the Sun, and the image is 0.2 arcsec on a side. A 0.5 $M_\odot$ star has formed at the center, and a Jupiter-mass object resides in the protostellar disk at about 5 AU from the young star. The circle at the lower left shows the beam size.



ALMA will also pioneer high-resolution high-sensitivity imaging of gas kinematics in protoplanetary disks around young Sun-like stars in star-forming regions at the 100–150 pc distances of star-forming clouds in Ophiuchus or Corona Australis, thus enabling studies of their physical, chemical, and magnetic-field structures. ALMA images could reveal evidence of deviations from Keplerian motion in disks and details of the chemistry on size scales relevant for planet formation, including establishing the role of the freeze-out of gas-phase species onto grains, the release of these species back into the gas phase in the warm inner regions of circumstellar disks, and the subsequent formation of complex organic molecules.

Imaging of scattered light from the slightly older T Tauri and debris-disk systems at optical through infrared wavelengths is already providing evidence for the growth of dust grains in disks and the settling of large (micron-sized) grains to disk midplanes. Such processes are vital precursors to the formation of planets. The emissivity of a dust grain peaks at wavelengths near its size, so observations at longer wavelengths are vital for establishing the presence of cm-sized grains and for providing evidence of planetesimal growth. The increase in sensitivity of the EVLA over current facilities brings with it the possibility of investigating dust properties within disks of all ages, from deeply-embedded young protostars to classical T Tauri stars to debris disks around older systems. Observations at wavelengths ~1 cm of large, statistically significant samples of sources having different ages will reveal the timescales for planetesimal growth, thereby providing much-needed constraints on models of rocky planet formation.

2.2.2 The Initial Conditions for Star Formation and the Chemistry of Life

The appearance, evolution, and perhaps even the final mass of a young star are determined by the physical and chemical conditions within its natal molecular cloud. For example, the accretion history of a protostar is expected to depend on whether the cloud begins contracting globally or from the inside out, on the role of turbulence, and on the cloud's initial density profile. The observational appearance of a protostar will depend on the abundances of the key molecules chosen to trace the molecular hydrogen, each of which is subject to chemical processing both in the gas phase and on the surfaces of dust grains. Understanding the properties of starless dark clouds as the sites of future star formation is therefore vital for establishing how protostars and protoplanetary systems form and evolve, and ultimately for revealing the physical mechanisms that determine the Initial Mass Function (IMF).

Starless dark clouds typically exhibit little internal structure on very small scales, so the GBT and the compact configurations of the EVLA and ALMA will be needed to provide the high surface-brightness sensitivity at high spectral resolution required to detect dynamical motions and emission from complex organic molecules in these cold clouds. Indeed, the GBT was recently used to discover the organic molecules propenal and propanal, and the simplest sugar, glycoaldehyde, in just such starless clouds. It therefore appears that significant chemical processing takes place prior to the onset of star formation, raising the question: How much did chemistry in interstellar and protosolar gas clouds contribute to the origin of life on Earth and perhaps elsewhere? More than 135 molecular species have already been identified in interstellar and circumstellar sources, most through observations with NRAO telescopes. Many of these are complex species of ten or more atoms, and they include biologically significant molecules such as formic acid (HCOOH), acetic acid (CH_3COOH), ethylene glycol ($HOCH_2CH_2OH$), and the simplest member of the sugar family, glycolaldehyde (CH_2OHCHO). The evident complexity of interstellar chemistry and the existence of plausible delivery mechanisms such as comets and meteorites lend increasing support to the hypothesis that some part of prebiotic chemistry on the early Earth may have originated in interstellar and protosolar gas clouds.

Molecular lines at radio frequencies are produced by rotational transitions between angular-momentum states separated by multiples of $\hbar$. For any molecule, the lowest line frequency is inversely proportional to the moment of inertia, so simple molecules radiate only at millimeter wavelengths (e.g., CO radiates at λ = 2.6, 1.3 mm, … or ν = 115, 230, … GHz) while complex molecules radiate at short centimeter and long millimeter wavelengths, albeit more weakly because the Einstein emission coefficient is proportional to ν^3. The GBT, EVLA, and ALMA provide the ideal combination of instruments for detecting and studying the chemistry of complex prebiotic molecules in the cold interstellar medium thanks to their sensitivity, frequency coverage, and ability to cover wide bandwidths with high spectral resolution in a single observation. Their frequency coverage allows a large range of molecular masses and excitation conditions to be explored, and their wide bandwidths typically allow simultaneous observations of multiple molecular transitions, which greatly facilitates later analysis. Furthermore, the combination of the synthesis instruments EVLA or ALMA with the filled-aperture GBT enables structure to be measured on all possible spatial scales. When the radio data are combined with mid- and far-infrared spectroscopy of ices in these clouds, it will be possible to develop a full picture of the complex chemical processes taking place both in the gas phase and on the surfaces of dust grains, and to relate this picture to the final outcome of star formation: a young star surrounded by a planet-forming disk.

2.3 What New Contributions Can Radio Astronomy Make to Frontier Physics?

In this World Year of Physics marking the 100th anniversary of Einstein's most seminal work, radio observations are critical for studying phenomena that constrain frontier physics. GBT timing observations of the relativistic binary pulsar J0739-3039 are providing the most stringent tests of Einstein’s General Theory of Relativity (GR) in strong gravitational fields. The high masses and short rotation periods of pulsars recently discovered by the GBT in the globular cluster Terzan 5 are providing constraints on the equation of state (EOS) of matter at supra-nuclear densities, which may be a quark-gluon plasma. Distances and proper motions of galaxies in the Local Group are being measured directly by high-precision astrometry with the VLBA, which can yield geometrical distance measurements of distant quasars that could constrain the Hubble constant and perhaps even the dark-energy EOS.

Pulsars, relativistic jets from black holes and neutron stars, gamma-ray bursts and soft-gamma-ray repeaters reveal themselves via emission from electrons accelerated to ultrarelativistic energies. Radio emission can trace energetic events at milliarcsecond resolution and on millisecond timescales even through dense gas and dust. Synoptic observations constitute a frontier area of astrophysics with close symbiotic links between radio and current and planned high-energy astrophysics missions (Chandra, Swift, GLAST, Constellation X, etc). All of NRAO’s telescopes are being configured for dynamic scheduling to take full advantage of these opportunities.

2.3.1 Pulsars–Extremes of Gravity and Density

The GBT is an outstanding telescope for detecting and timing pulsars because it is the largest fully steerable radio telescope, it is protected from radio-frequency interference (RFI) by the National Radio Quiet Zone (NRQZ) and the surrounding mountains, and it has an excellent suite of pulsar backends. It is being used to make precision tests of Einstein's General Theory of Relativity (GR) in the strong-field regime and to constrain the EOS of neutron-star interiors by determining the moments of inertia of neutron stars. In less than two years, GBT observations of the relativistic binary pulsar J0737-3039 have provided higher-precision tests of GR than those obtained from three decades of monitoring the Hulse-Taylor system PSR B1913+16 which first showed gravitational radiation. GBT timing data have determined the five principal post-Keplerian (PK) parameters, the mass ratio of the two pulsars, and their individual masses with an unprecedented accuracy of 0.1%. The neutron stars in J0737-3039 will merge in only 85 Myr. This short lifetime multiplies by four the expected detection rate for ground-based gravitational-wave interferometers such as the Laser Interferometer Gravitational-Wave Observatory (LIGO). The Shapiro delay calculated from GR for the measured masses agrees with the observed delay within one part per thousand, making this the most stringent check yet on the validity of GR in the strong-field limit.

GBT observations in the near future will increase the accuracy of these PK parameters to the point that second-order terms will be constrained for the first time, and completely new phenomena (relativistic deformation of the A-pulsar orbit and parameters characterizing aberration and geodetic precession) will be seen. GR predicts that relativistic spin-orbit coupling will cause the spins of both pulsars to precess about the total angular momentum (primarily orbital angular momentum) vector with periods ~70 yr. GBT observations of this phenomenon should also yield the first measurement of the moment of inertia for a neutron star.

At very high temperatures or densities, matter undergoes a phase transition to a new state, the quark-gluon plasma (see Figure 2.3.1), also present in the early Universe. Combining mass and inertia measurements constrains the EOS of matter at pressures and densities much higher than those found in atomic nuclei. Massive and/or rapidly rotating pulsars recently discovered in dense globular clusters by the GBT increasingly constrain the EOS of high-density matter, by being too massive to be supported by a "soft" EOS or by rotating too rapidly to be stabilized by a soft EOS. The GBT has been uniquely successful in finding millisecond pulsars in globular clusters thanks to its wide sky coverage (including the Galactic Center region richest in dense globular clusters), its high sensitivity, and the 600 MHz of RFI-free bandwidth near λ = 15 cm (2 GHz) available only in the NRQZ.

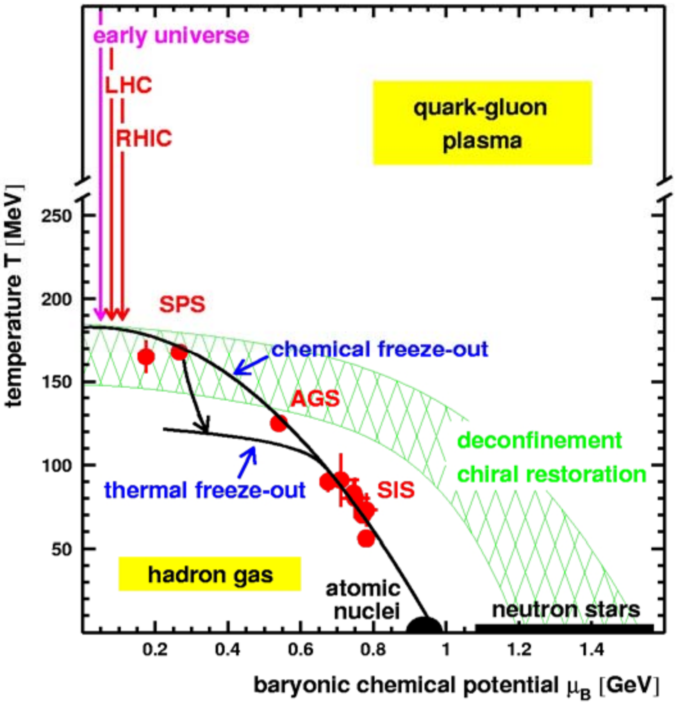


Figure 2.3.1 Neutron stars may contain the only high density (high chemical potential or Fermi energy) quark-gluon plasmas in the Universe (see Rho 2000, nucl-th/0007073).

2.3.2 Imaging a Massive Black Hole

NRAO telescopes, using the technique of VLBI, offer the best prospect for directly imaging the black hole in the center of our Galaxy, Sgr A*. Although existing VLBA observations at λ = 7 mm (43 GHz) are limited by sensitivity and interstellar scattering, they reach down to 24 times the Schwarzschild radius of the Galactic Center black hole, a factor >100 smaller than the innermost stellar orbit measured in the near infrared. These observations already provide a critical constraint to the many models that attempt to explain the accretion and radiation processes near low-luminosity black holes. However, with the increased bandwidth that will soon be available at the VLBA plus the addition of the GBT to the array, a definitive measurement of the structure of the radio source Sgr A* is likely at λ = 3 mm (86 GHz) within the next few years. VLBA measurements will be a pathfinder toward future high-frequency VLBI experiments (including ALMA as an element) which will be capable of making images of Sgr A* at 2–3 Schwarzschild radii. The existence of a singularity may be revealed by the gravitational "shadow" which the black hole casts by bending light in the strong-field limit.

2.3.3 Extracting Energy and Momentum from Black Holes

Black holes, despite their names, are among the brightest objects in the universe. Gravity must be the energy source, and direct accretion can indeed explain the X-ray emission from stellar-mass black-hole binaries as well as the UV and (through reprocessing) optical, IR, and millimeter-wave emission from massive AGN. This accretion is almost always associated with outflow, with relativistic jets observed from sources ranging from X-ray binaries to SMBHs. These outflows are now believed to carry away as much energy as the accreting matter emits through radiation. Furthermore, recent observations of galaxy clusters indicate that the outflows may disrupt the infalling gas on megaparsec scales, while correlations between the masses of SMBHs and their host-galaxy bulges suggest a tight connection between black holes and their surroundings. Together these observations imply that outflows are fundamental to the accretion process and that there may be an important feedback between the outflows a black hole creates and the infalling material which feeds it.

Radio observations remain the only unambiguous tracer of relativistic outflows in these systems. Radio images were the first to connect the central object directly (through a jet) to the large-scale radio lobes. VLBA observations have produced the most detailed and reliable time-dependent images of the central few parsecs, and they have provided direct evidence for the accretion torus in a few systems. Within the Milky Way, radio images of X-ray binaries, primarily made with the VLA and the VLBA, have shown convincing connections between X-ray states (and state changes) and radio outflows, and they have led to a major paradigm shift in the modeling of all such systems, with jets now being invoked to explain even the X-ray emission (through inverse-Compton scattering or direct synchrotron emission). Radio images of interaction regions have provided some of the best determinations of the total kinetic energies in jets, thereby constraining jet composition and acceleration mechanisms. Suggestive links have been claimed between jet speed and black-hole spin in Galactic sources, and radio data remain fundamental to interpretations of black-hole SEDs. X-ray binaries in particular have allowed detailed comparisons between the X-ray and radio emission for a wide range of X-ray states, with corresponding implications for radio/X-ray loud and quiet quasars.

Much remains to be done. In the Milky Way, for example, SS433 is the only relativistic jet whose composition is directly known. Only a few neutron-star binaries have been imaged; a detailed comparison of neutron-star and black-hole binary jets would give unique insight into jet acceleration mechanisms. The statistics of Galactic jets remain poor, and we do not yet understand why the same black-hole binary can behave very differently during consecutive accretion events. The versatility and flexible scheduling of the VLBA have made it ideal for studies of these very transient sources. The advent of the EVLA will produce a real revolution, leading to the detection and imaging of an order of magnitude more galactic objects and allowing much more complete coverage of those we already know. As with pulsars, more objects will lead to a qualitative improvement in the science, both because of the discovery of a few key sources such as SS433 and GRS 1915+105 and because of the improved statistics, leading to more believable correlations between black-hole spin and jet speed, radio and X-ray luminosity, etc. Pushing deeper also means observing sources in different X-ray states, with direct implications for models of radio-quiet quasars.

2.3.4 Extremes of Speed and Energy: Highly Relativistic Outflows

One of the great discoveries of VLBI observations was the highly relativistic and apparently superluminal bulk motions associated with AGN. The most extreme of these sources are the blazars, ejecting matter almost directly towards us with Doppler factors $\Gamma \sim 20$ or higher. These sources provide unique probes of the most extreme bulk velocities known in the Universe. About one hundred were detected by the Compton Gamma Ray Observatory (CGRO), and we expect thousands to be found in all-sky surveys made by NASA's Gamma-ray Large Area Space Telescope (GLAST), due for launch in 2007 or 2008 (see Figure 2.3.2). The gamma-ray emission mechanism is thought to be inverse-Compton scattering of lower-energy photons, but is otherwise poorly understood. GLAST will revolutionize gamma-ray astronomy by achieving regular short-timescale sampling of blazars. Repeated high-frequency VLBA imaging of these sources (especially at $\lambda = 7$ mm) on sub-milliarcsecond scales will be used to correlate changes in the radio flux densities and structures of individual components with the expected rapid gamma-ray variability. The radio images will constrain or reveal the locations of particle acceleration, the probable origins of the seed photons, and physical conditions (magnetic fields, pressures, etc.) in the particle acceleration regions. Only this combination of VLBA imaging and gamma-ray variability can provide the necessary constraints to the models for the most powerful particle accelerators in the Universe.

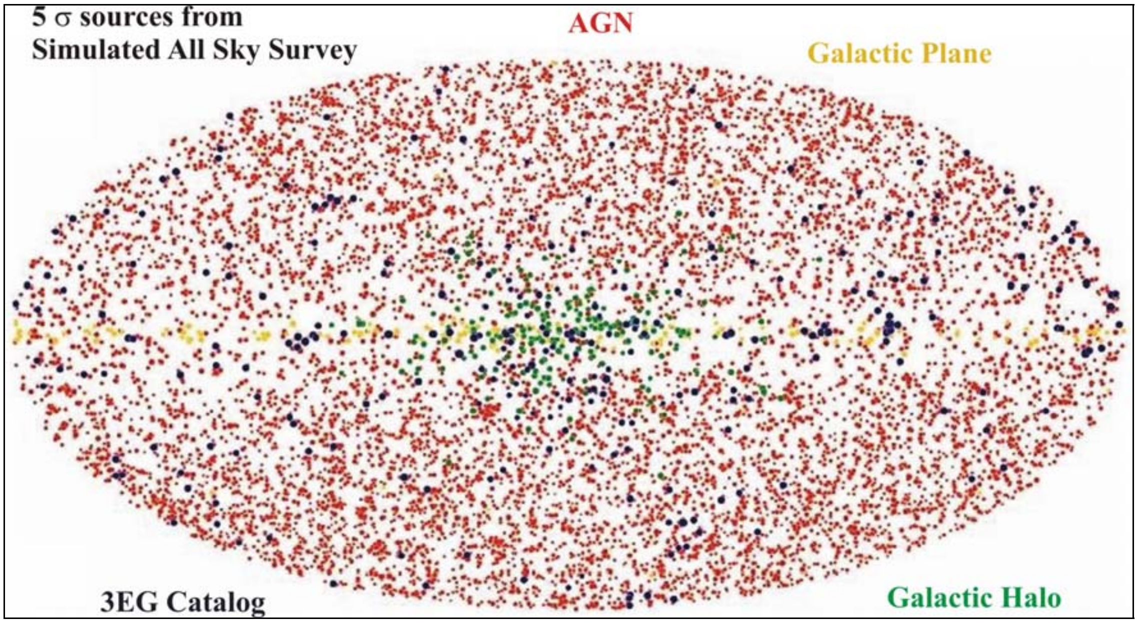


Figure 2.3.2 Simulated All-Sky Survey from GLAST indicating an increase of up to two decades in the number of new gamma-ray AGN (red dots) compared to the previous (3EG) survey. It is expected that the VLA will be critical for the identification of counterparts to the gamma-ray blazars, while repeated high-resolution VLBA imaging combined with gamma-ray variability will be critical for understanding the physics of the gamma-ray emission.

2.3.5 Dark Matter and Dark Energy

Dark matter and dark energy contribute more than 95% of the mass-energy of the Universe. Dark matter is revealed by its gravitational influence on luminous matter via orbital motions within galaxies, relative motions of galaxies in groups and clusters, and on light itself via gravitational lensing of distant galaxies and quasars by intervening objects along our line of sight. Dark energy was discovered through the effects of acceleration on the apparent brightnesses of distant Type Ia supernovae (assumed to be “standard candles”) and its contribution at the redshift of recombination was measured via its effects on the CMBR power spectrum (assumed to be “standard rulers”) by WMAP. Precision (microarcsecond) astrometric measurements with the VLBA can yield direct measures of distances and proper motions that can provide important checks and independent constraints on indirect measurements.

The distribution of dark matter in the local universe can be probed using the VLBA, the most accurate astrometric telescope in existence. For example, the VLBA recently measured angular motions of water masers in the nearby galaxy M33 with 3 microarcsec yr^{-1} accuracy (Brunthaler et al. 2005, Science, 307, 1440). Together with the maser radial-velocity distributions determined by both the VLA and the VLBA, these provide the first measurement of the three-dimensional velocity of a galaxy in the Local Group and determine the distance of M33 (0.8 Mpc). Measuring this distance and velocity is an important step toward understanding the relationship of M33 to the neighboring Andromeda Galaxy, M31. Future measurements of other nearby galaxies may lead to an improved understanding of the dark-matter distribution in and around the Local Group, which may in turn constrain the process of condensation of our local mass out of the lumpy Early Universe.

To explore the nature of dark energy there are plans for projects such as a Large Synoptic Survey Telescope and the NASA/DOE Joint Dark Energy Mission. Understanding dark energy is so critical that astronomers must use completely different methods subject to independent (or minimal) systematic errors for checks and verifications. The value of independent checks was made apparent when the VLBA measured the geometric distance (7.2 Mpc) to the water megamasers in the Seyfert galaxy NGC 4258. This measurement led to an adjustment of 10% in the zero-point of the Cepheid distance scale and hence in the determination of the Hubble parameter by the HST Key Project. The suite of NRAO telescopes in 2011 will be well placed to determine geometric distances to objects farther out in the Hubble flow and thus perform independent checks of extragalactic distances, the Hubble constant, and perhaps even the acceleration at cosmological distances. Recent searches with the GBT already have doubled the number of extragalactic water-megamaser galaxies to more than 40, including a dozen having the high-velocity satellite lines revealing the

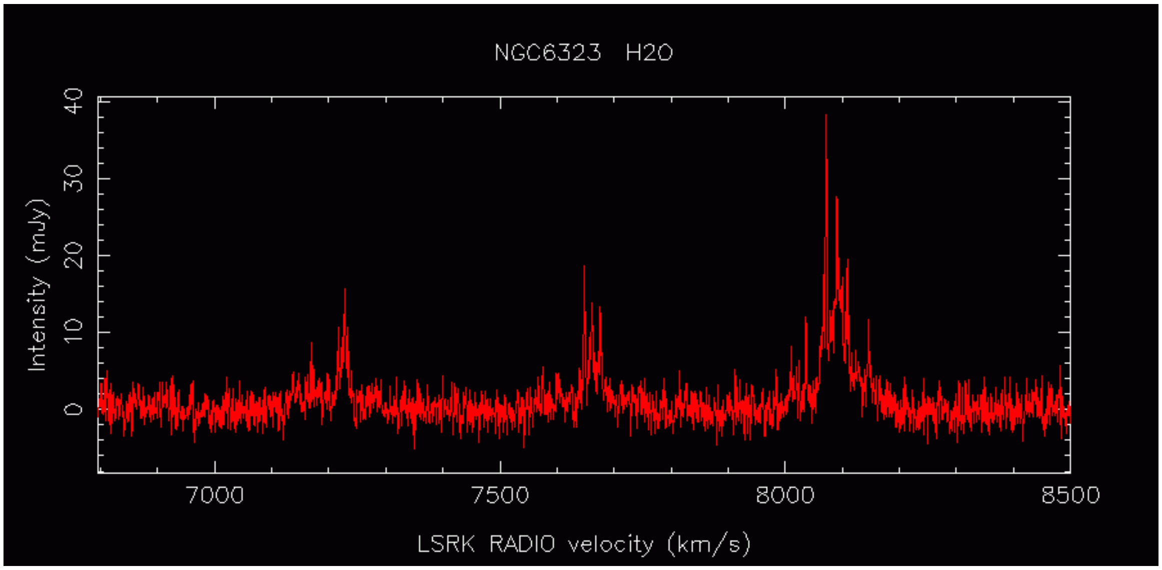


Figure 2.3.3 GBT discovery spectrum of the circumnuclear water maser in NGC 6323 at ~100 Mpc distance (Braatz et al. 2004, ApJ, 617, L29).

circumnuclear disk emission needed for VLBA distance measurements. Figure 2.3.3 shows the GBT spectrum of NGC 6323 at a distance of ~100 Mpc. NGC 6323 will be observed with the High Sensitivity Array (HSA) combination of the VLBA, EVLA, and GBT for direct and accurate measurements of its geometric distance and black-hole mass over the next few years. The recent GBT discovery of a gigamaser in the Sloan quasar J0804+3607 at $z = 0.66$ strongly suggests that other cosmologically distant masers will be discovered and raises the hope that geometric distance determinations at redshifts relevant to the EOS of dark energy will take place in the next decade.

3. LOOKING FORWARD: NRAO IN 2011

In 2011, the NRAO will operate four state-of-the-art telescopes for the NSF that span the discovery space of radio astronomy and uniquely complement ground- and space-based observatories at other wavelengths. The EVLA and ALMA—two major NSF construction projects—will be nearing full operation and will bring, respectively, a ten-fold and hundred-fold improvement in sensitivity relative to existing comparable arrays. The GBT will be mature in first-generation capabilities and will be poised to exploit the technological breakthroughs of large-format imaging systems. Such systems will have comparable flux sensitivity to the interferometer arrays while providing the capability to conduct surveys of larger area and to make images of larger structures. The VLBA will have marked sensitivity gains from wider bandwidth hard-disk recording systems and will be prepared for real-time fiber-connected operation that will greatly improve sensitivity and ease of use.

These facilities will thus have greatly improved scientific capabilities compared to the present. The four telescopes: GBT, EVLA, VLBA, and ALMA, will operate with great synergy, covering a range of resolution and sensitivity to image structures from degree to sub-milliarcsecond scales, in the submillimeter to meter wavelength range. The facilities will be complementary to gamma-ray, X-ray, optical, and infrared facilities for multi-wavelength research ranging from gamma-ray bursts to galaxy formation to studies of star-formation.

The NRAO telescopes will support the innovative experiments of specialists as well as the imaging observations of generalists. Observers will specify their projects through a proposal submission tool and have them executed via a queue-based dynamic scheduling system. Science images will be processed and archived automatically. Support to facilitate the access to and the utilization of NRAO telescopes by all astronomers will be provided for the EVLA and VLBA through the Array Operations Center in Socorro, for the ALMA through the North American ALMA Science Center in Charlottesville, and for the GBT through Green Bank Operations. The astronomy community will use and reuse the archived images through the National Virtual Observatory.

The NRAO will carefully maintain and manage its facilities, preserving the NSF's capital investment for continuing reliability and future upgrade. The NRAO will equip its telescopes with instruments defining the state-of-the-art today, and conduct the research and development required for the innovations of tomorrow through the CDL.

Very importantly, the NRAO will work closely with the university community to foster the vitality of its scientific and instrumentation groups via an active exchange and visitor program, and through partnerships for instrument development and construction. The NRAO will support students through grants and pre-doctoral programs, and provide radio astronomy training to young astronomers through its postdoctoral and Jansky Fellowship programs.

The NRAO will promote scientific excellence by continuing its long-standing *open-skies* policy which awards telescope time on the basis of merit, not affiliation or national origin. To ensure that the NRAO can provide the best possible science capabilities for the astronomy user community, it will continue to maintain an excellent scientific and technical staff. Furthermore, the NRAO will continue its tradition of planning for the next generation of forefront telescopes. In this regard, NRAO facilities can form a cost-effective infrastructural backbone of a North American Array, a vision of the Square Kilometre Array operating to wavelengths of 1 cm and shorter.

4. TECHNICAL CAPABILITIES OF NRAO FACILITIES

4.1 GBT

4.1.1 Technical Overview

The Robert C. Byrd Green Bank Telescope (GBT) was dedicated in 2000 and recently began full-time operation as the world's most sensitive fully steerable radio telescope. Located in the National Radio Quiet Zone (NRQZ) and shielded by mountains, the GBT (Figure 4.1.1) enjoys unique protection against radio-frequency interference (RFI). In addition, the 100 m diameter GBT is the only large radio telescope having a clear aperture. Eliminating blockage by feed-support structures increases its aperture efficiency, greatly reduces sidelobe responses to stray radiation from extended radio sources and RFI, and lowers the noise pickup from ground radiation. The GBT surface consists of 2,004 high-precision panels which are continuously adjusted by computer-controlled actuators to remove deformations caused by gravity, thermal gradients, and setting errors. The rms surface error of the GBT is currently 0.32 mm ($\lambda/16$ at $\lambda = 5$ mm, or $\nu = 60$ GHz) in benign conditions, and initial operation at $\lambda = 3$ mm ($\nu = 100$ GHz) should be possible within two years.

GBT receivers provide nearly continuous frequency coverage from $\lambda = 1$ m to 6 mm (0.29 to 52 GHz) with on-sky system temperatures as low as 20 K. A single-pixel correlation receiver for $\lambda = 3$–4 mm (68–92 GHz) and the Penn Array 64-element bolometer camera for $\lambda = 3$ mm (100 GHz) are under construction. The GBT spectrometer is a multilevel digital correlator providing 2,048 channels in each of eight 800 MHz spectral bands or up to 262,144 channels at 50 MHz bandwidth. The Zpectrometer, a redshift machine for the GBT having a 14 GHz instantaneous bandwidth at 26–40 GHz, was recently funded by the NSF ATI (Advanced Technologies and Instrumentation) program. Three fast-sampling backends provided by university collaborations are available for pulsar observers.

Unique characteristics of the GBT include:

- Largest fully steerable single-dish telescope in the world.
- The only large telescope having an unblocked aperture.
- Low elevation limit makes 85% of the entire celestial sphere accessible and allows long observations for monitoring transient events, pulsar timing, and VLBI.
- Low-RFI environment thanks to terrain shielding and the unique National Radio Quiet Zone, allowing unique HI and pulsar observations. This offers access to frequencies which might not otherwise be observable, gives greater sensitivity for continuum and pulsar observations, and greater

opportunity to observe spectral lines both at rest and redshifted throughout the spectrum.

- Highest pulsar sensitivity of any fully steerable telescope.
- Continuous frequency coverage from 290 MHz–52 GHz (λ = 6 mm to 1 m) currently, to 115 GHz (λ = 2.6 mm) in the future.
- Large effective collecting area (~2,000 m^2) and focal plane capable of accepting feed arrays having thousands of pixels at λ = 3 mm.
- Possibly the best imaging capability of any single-dish radio facility owing to the offset optics; high-fidelity wide-field HI imaging capability.
- The large diameter (in wavelengths) of the filled aperture results in a unique combination of high sensitivity and resolution for point sources plus high surface-brightness sensitivity for faint extended sources.

Figure 4.1.1 The Robert C. Byrd Green Bank Telescope has a 100 m diameter unblocked aperture and a computer-controlled active surface.

Table 4.1.1 GBT Technical Specifications

Location	Green Bank, West Virginia
Coordinates	79d 50' 23.406" Longitude 38d 25' 59.236" Latitude
Telescope Diameter	100 m (effective)
Elevation Range	5–90 degrees
Slew Rates	35 deg/min (az), 17.5 deg/min (el)
Optics	110 m x 100 m unblocked section of a 208 m parent paraboloid Off-axis feed arm
Available Foci	Prime and Gregorian f/D (prime) = 0.29 (referred to the 208 m parent paraboloid) f/D (Gregorian) = 1.9 (referred to the 100 m effective aperture)
Frequency Coverage	290 MHz – 52 GHz (current) 290 MHz – 115 GHz (target)
Main Reflector	2004 actuated panels (2209 actuators); average panel rms 68 μm
Surface rms	320 μm (current) 210 μm (target)
Offset pointing	2.7” (current) 1.3” (target)
FWHM Beamwidth	12.4 arcmin/ν (GHz) = 740 arcsec/ ν (GHz)
Sensitivity (Penn Array)	3.2 μJy rms in 2 hours

4.1.2 GBT Science Highlights

Although the GBT has been in full scientific operation only since late 2003, it has already made a number of major contributions, including:

- Discovery of 27 new millisecond pulsars in the globular cluster Terzan 5, several of which are exotic objects that constrain general relativity and the physics of superdense quark-gluon plasmas.
- Discovery of molecular line emission from high-redshift galaxies, including HCN emission at $z = 2.3$, CO emission from $z > 4$ objects, and water-maser emission from a Type 2 quasar at $z = 0.66$.
- Discovery of discrete neutral hydrogen (HI) clouds in the Galactic halo and the remnants of building blocks for M31 that refine theories of Galactic structure and the origin of high-velocity clouds.

- Discovery of new pre-biotic interstellar molecules and a cold repository of the simplest member of the sugar family, shedding light on the origin of the chemistry of life.
- Determining the nature of the core of Mercury, through bistatic radar observations with Goldstone.

4.1.3 The GBT in 2011

Although the GBT is still very new, it has established itself as a major facility for astronomical discovery. This discovery potential of the GBT accrues from its large collecting area and resultant sensitivity, its extensive sky coverage, its versatility in frequency coverage and observing modes, the image fidelity afforded by its unblocked aperture, and its location in the unique National Radio Quiet Zone.

The GBT is the most advanced single-dish radio telescope in operation, and it is the only NRAO single-dish telescope. Single dish (filled aperture) telescopes have special properties that make them complementary to synthesis interferometers such as the Expanded Very Large Array (EVLA) and the Atacama Large Millimeter Array (ALMA). They are inherently sensitive to the extended low-surface-brightness emission which tends to be resolved out by interferometers. Single dishes can thus supply data on extended emission for combination with interferometric data to yield images having both high resolution and high fidelity. Single dishes also bring all of the received energy to a single focal plane, offering flexibility for instrumentation and observing modes. This facilitates innovation in instrumentation, especially by external university groups. There are seven user-built instruments installed on, or under development for, the GBT. Only a single data stream is required for point sources, so very wide bandwidths can be analyzed at low cost. The University of Maryland "Zpectrometer" now being built for the GBT is a wideband spectrometer that will cover the λ = 1.15 to 0.75 cm (26 to 40 GHz) band instantaneously and detect CO (1–0) emission lines from galaxies anywhere in the redshift range $1.9 < z < 3.4$.

The most exciting long-term development for the GBT will be the creation of large-format focal-plane arrays of bolometers or monolithic microwave integrated circuit (MMIC) devices. Bolometer arrays of up to 10,000 pixels are now technically possible, as are MMIC spectroscopic arrays having 100 to 1,000 pixels plus digital spectroscopic processors. Few areas of astronomy have witnessed such rapid technological advances in recent years. These instruments will revolutionize the imaging capabilities of single-dish radio telescopes. First-generation arrays such as the λ = 3 mm 64-pixel Penn Array bolometer camera are nearing completion for the GBT. The NRAO anticipates starting work on much larger-format imagers in the next few years, with the possibility of operational availability in 2011.

Science opportunities with large-format arrays on the GBT include:

- Making high-resolution images of young star-forming regions and starless cores. These sources often show unique features only at certain wavelengths, such as clumps of N_2H^+ that reveal the presence of cold material not seen in the continuum by interferometers.
- High-resolution imaging of Sunyaev–Zeldovich (SZ) clusters at redshifts $z > 1$ to help determine their dynamical states, important for mass estimation and subsequent cosmological tests.
- Searching for SZ signatures from large X-ray cavities in cluster cores or in AGN jets.
- Deep surveys for high-redshift star-forming galaxies. Galaxies similar to Arp 220 in the redshift range $5 < z < 8$ should have flux densities ≈ 100 μJy at λ = 3 mm. The Penn Array will be able to cover 10 arcmin^2 with 10 μJy beam^{-1} rms noise in 5 hours. A 6,400-pixel array would cover 1 deg^2 in 18 hours, making the GBT among the fastest telescopes for finding $z > 7$ galaxies.

The GBT anchors the NRQZ, a 33,000 km^2 region which is protected by the Federal Communications Commission against fixed, licensed transmitters that might otherwise emit harmful RFI. Thanks to the NRQZ, the GBT is able to observe redshifted λ = 21 cm (1.42 GHz) neutral hydrogen and make sensitive wide-band searches for low-frequency pulsar emission, observations which are extremely difficult or impossible at many observatories elsewhere in the world. The NRQZ is a unique and irreplaceable scientific preserve whose critical importance will grow as radio “light pollution” becomes more intense and extends to higher frequencies in the future. *If the GBT ceases operation, this scientific preserve will vanish forever.*

4.2 EVLA

4.2.1 Technical Overview

The Very Large Array (VLA) is a 27-element interferometer whose 25 m parabolic antennas can be deployed in four principal configurations to synthesize diffraction-limited apertures having diameters d ≈ 1, 3.4, 11, and 36 km (Figure 4.2.1). It operates full-time with seven discrete frequency bands ranging from λ = 1 m to 6 mm (0.3 GHz to 50 GHz) and part-time at λ = 4 m (74 MHz). It’s imaging resolution of 50 milliarcseconds at λ = 7 mm (43 GHz) is comparable with the highest resolution of the Hubble Space Telescope. The VLA was dedicated in 1980. Since the mid-1980s it has produced an average of 170 refereed papers per year (see Appendix A for detailed statistics since 1998), a rate of productivity that continues even as the VLA celebrates the 25th anniversary of its dedication.

Figure 4.2.1 The smallest VLA configuration spans 1 km on the Plains of San Augustin at 2,100 meters (7,000 ft) elevation.

Over the years, the VLA has added significant capabilities including:

- The λ = 3.6 cm (8.4 GHz) receiving system funded by NASA in the late 1980s.
- The recently completed λ = 7 mm (43 GHz) receiving system jointly funded by Mexico, Germany, and the NSF.
- Beam-forming capability for observing as an element of a VLBI array.
- A fiber-optic link to the Pie Town VLBA antenna, providing an improvement by a factor of two in resolution.

However, the fundamental data-processing electronics of the VLA remained essentially unchanged for 25 years, preventing it from reaching its current potential as the world's most versatile radio telescope. The Expanded VLA (EVLA) will revolutionize its ability to make high-sensitivity and high-resolution images, ensuring that NSF centimeter-wave facilities will stay at the forefront of discovery in modern astronomy for the next two decades. With this potential in mind, the 2001 National Academy of Sciences decadal survey recommended the EVLA as the second-ranked major ground-based project for the current decade:

> *The EVLA—the revitalization of the VLA, the world's foremost centimeter-wave radio telescope—will take advantage of modern technology to attain unprecedented image quality with 10 times the sensitivity and 1000 times the spectroscopic capability of the existing VLA. The addition of eight new antennas will provide an order-of-magnitude increase in angular resolution. With resolution comparable to that of ALMA and [JWST], but operating at much longer wavelengths, the EVLA will be a powerful complement to these instruments for studying the formation of proto-planetary disks and the earliest stages of galaxy formation.*—Astronomy and Astrophysics in the New Millennium, National Academy Press (AANM 2001)

The EVLA project has been divided into two phases for administrative and scheduling purposes: EVLA I and EVLA II. Construction on the international EVLA I began in 2001 with contributions from Canada and Mexico; it will be completed in 2012. The incremental cost to the NSF approved by the National Science Board is $55M in FY 2003 dollars. The current total cost, including NRAO contributed effort, is $73M in FY 2005 dollars. By 2011 all but a few receivers will be completed, so the VLA will have been completely transformed into the EVLA I.

The EVLA I preserves the large existing investment in VLA antennas and civil infrastructure, and it adds new wideband receiver systems, a state-of-the-art correlator, a fiber-optic data-transmission system, digital electronics, and a new on-line control system to yield a new instrument with the following improvements over the present VLA:

- Continuum sensitivity improvements from up to a factor of 5 for $\lambda > 3$ cm (< 10 GHz) to more than 20 between $\lambda = 3$ and 0.6 cm (10 and 50 GHz).
- Operation at any wavelength from $\lambda = 0.6$ to 30 cm (1.0 to 50 GHz) yielding two pairs of signals, each pair with opposite polarizations and up to 4 GHz bandwidth, independently tunable to any frequency within any given band.
- A flexible new correlator which will provide over 16,384 frequency channels, process the full EVLA bandwidths, and give frequency resolution better than 1 Hz if necessary.

The basic technical specifications of EVLA I, which is expected to be complete in 2011, are listed in Table 4.2.1.

Table 4.2.1 EVLA I Technical Specifications

Location	Near Socorro, New Mexico
Coordinates	107d 37’ 03.819” Longitude 34d 04’ 43.497” Latitude (significant ALMA declination overlap)
Telescope Properties	27 25-m antennas
Elevation Range	8–125 degrees (over the top)
Slew Rates	40 deg/min (az), 20 deg/min (el)
Frequency Coverage	Continuous 1.0–50 GHz (0.6–30 cm), plus 74 and 327 MHz
Pointing Accuracy	6 arcsec rms blind pointing, 2 arcsec rms reference pointing
Field of View of Antennas	40 arcmin / ν (GHz)
Maximum Baselines	1, 3.4, 11, or 36 km
Number of Baselines	351
Spatial Resolution	2 arcsec / ν (GHz); n.b., 50 milliarcseconds at 40 GHz
Maximum BW, each pol.	8 GHz
Point Source rms, 12 hr	0.8 μJy
Maximum Freq. Channels	16,384

Phase II of the EVLA will add eight new antennas spread across New Mexico to increase the angular resolution of EVLA Phase I by a factor of ten, filling the spatial-frequency gap between the EVLA I and VLBA and completing the project recommended by the National Academy decadal survey. The EVLA II proposal was submitted to the NSF in 2004 and is currently under review.

4.2.2 VLA Scientific Highlights

Its combination of sensitivity, flexibility, and spatial and spectral resolution has made the VLA the world’s most productive ground-based astronomical telescope as measured by publication rates. The great strength of the VLA has always been its ability to contribute across the entire range of modern astrophysics by making fundamental discoveries in areas ranging from proto-stellar cores to galaxy-cluster magnetic fields to gamma-ray burst afterglows. Most of these discoveries could not have been predicted at the time the VLA was built. They include:

- The presence of ice at the north pole of Mercury
- Images resolving the extended coronae of supergiant stars such as Betelgeuse.
- Discovery of superluminal motion in galactic microquasars.

- The fundamental structures at the center of the Milky Way galaxy on many different scales.
- Physics and images of a wide variety of jets in radio galaxies and quasars.
- Numerous gravitational lenses, including Einstein rings.
- Afterglows, hosts, and energetics of gamma-ray bursts.

The VLA has been a productive scientific user facility for more than 25 years. Some of the highest-impact science can be noted from its ten most-cited papers of all time, listed in Table A9.1, while a sampling of the science that is important in a particular era can be seen from the most-cited papers from 1998 and 1999, listed in Table A4.5. Key contributors to VLA science in recent years have been legacy surveys, including wide-field surveys such as the NRAO VLA Sky Survey (NVSS), Faint Images of the Radio Sky at Twenty centimeters (FIRST), and a number of deep integrations covering the leading optical, infrared, and X-ray deep fields (e.g., the Hubble Deep Field, the Spitzer First Look Survey, and the Chandra Deep Fields). The NVSS and FIRST survey papers are the most-cited publications in the lifetime of the VLA.

Prospective EVLA science is discussed in Section 2 of this report.

4.2.3 The EVLA in 2011

The EVLA (Phase I) is expected to be in full operation in 2011 as the successor to the VLA, which has made fundamental scientific contributions since 1980. This new telescope will provide 10 times more sensitivity and greatly improved spectral capabilities along with full dynamic scheduling. This will enable deep imaging that complements (or leads) imagers in other wavebands, such as the James Webb Space Telescope (JWST) in the optical and near-infrared bands. The EVLA and ALMA will make an especially powerful pair, with the same bandwidth, similar sensitivities and spectral resolution, and similar ranges of angular resolution. The EVLA and ALMA together will provide sub-arcsecond imaging over the three decades in wavelength from 0.3 m to 0.3 mm (1 GHz to 1 THz). Although the two telescopes are separated by 57 degrees in latitude, they both can observe objects ranging from -26 degrees declination to +37 degrees declination (more than half the sky) at elevations above 30 degrees.

Some of the unique characteristics of the EVLA in 2011, which will enable new scientific discoveries, include the following:

- The only full-time astronomical interferometer combining a complete coverage of centimeter wavelengths down to $\lambda = 0.6$ cm, sub-arcsecond resolution, and a large number of antennas. This provides excellent instantaneous two-dimensional aperture-plane coverage for outstanding snapshot imaging in addition to Earth-rotation aperture synthesis.

- Continuous wavelength coverage from λ = 6 mm to 30 cm (1 to 50 GHz).
- Sampling of all angular scales from 50 milliarcseconds through many arcminutes by means of the wide wavelength span and the use of the four principal configurations.
- Beam-forming capability providing the sensitivity of a 130 m single dish for VLBI observations.
- Sky coverage ranging from +90 degrees to -47 degrees declination, 87% of the sky.
- Scientific observing day and night, year-round, with dynamic scheduling.
- Three proposal opportunities per year plus rapid-response capability for the most time-critical astronomical observations.
- Production of calibrated data and reference images for all observations made in straightforward "standard modes".

4.3 VLBA

4.3.1 Technical Overview

The Very Long Baseline Array (VLBA) is a transcontinental interferometer consisting of 10 identical 25 m antennas on baselines up to 8,000 km (see Figure 4.3.1). The VLBA can resolve high-brightness sources as small as 1 pc and measure their positions with 0.1 pc (or better) accuracy *anywhere in the Universe*. The VLBA was the leading ground-based project recommended by the 1980 decadal survey of the National Academy of Sciences, and it was dedicated in 1993. It relies on the techniques of Very Long Baseline Interferometry (VLBI) first demonstrated nearly 40 years ago. During that 40-year period, the VLBA has been the only facility designed specifically for and dedicated to full-time astronomical VLBI. The design includes:

- Ten identical antennas.
- A distribution of antenna locations specifically chosen to optimize aperture-plane coverage and to take advantage of the large additional collecting area of the VLA.
- Routine operation of the array on an unattended basis, with minimal staff (two site technicians) required to perform routine maintenance at each antenna location.
- A dedicated data processor (correlator) matched to the characteristics of the antennas and their recording systems.
- An overall maintenance/operations plan that exploits economies of scale using VLA staff located in Socorro, New Mexico.

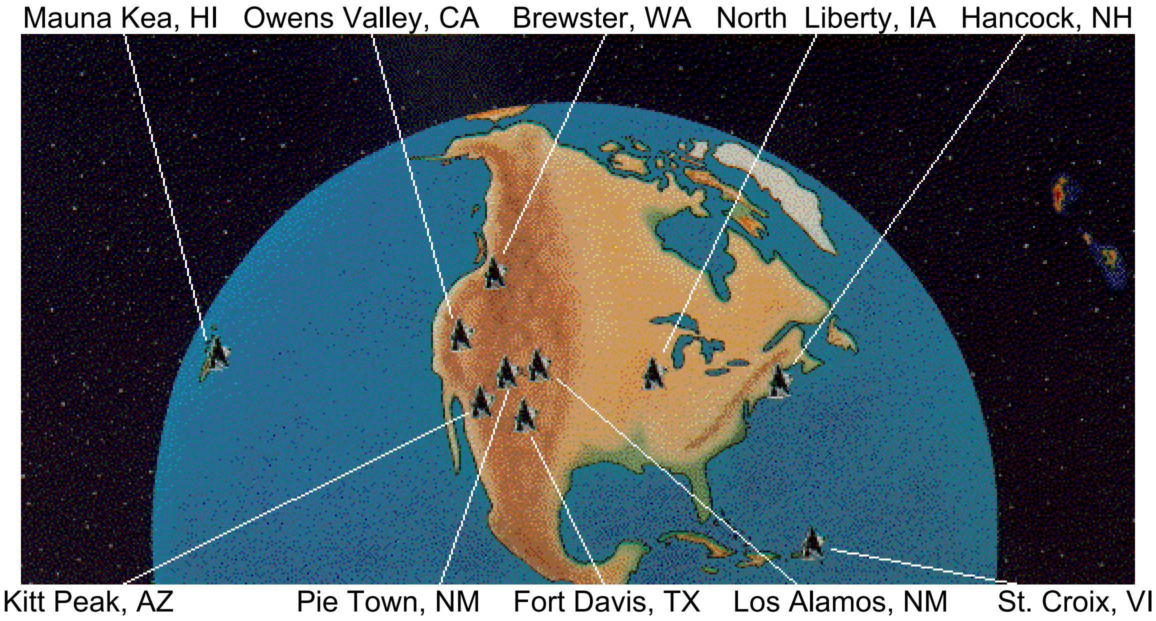


Figure 4.3.1 The VLBA is a system of ten radio telescopes between Mauna Kea on the Big Island of Hawaii and St. Croix in the U.S. Virgin Islands. It has the resolving power of a single radio telescope 8,000 km in diameter.

The VLBA covers λ = 28 cm to 3 mm (1.2 GHz to 96 GHz) in eight discrete bands plus two narrow sub-gigahertz bands, including the primary spectral lines that produce high-brightness maser emission. Its unique high-frequency capabilities enable the VLBA to image features within tens of Schwarzschild radii of the massive black holes in the Galactic Center and in the radio galaxy M87. The VLBA can be scheduled dynamically on a full-time basis, although about 30% of its observing time is allocated on fixed schedules to accommodate the requirements of other co-observing telescopes. Since the data from the VLBA are transported via magnetic media, its observing time has been restricted to about 50% to 55% of the hours in a year by limited tape-recorder capacity. Observing time will increase to 65% or more by the end of 2006, once the full transition is completed to direct recording on transportable high-capacity computer disks. Table 4.3.1 summarizes some of the key technical specifications of the VLBA as a stand-alone instrument. The continuum sensitivity can be improved by a factor of more than 5 by adding the GBT and the phased VLA to the VLBA.

Table 4.3.1 VLBA Technical Specifications

Location	Spanning North America; see Figure 4.3.1
Coordinates	Various
Telescope Properties	10 25-m antennas
Elevation Range	2–90 degrees
Slew Rates	60 deg/min (az), 40 deg/min (el)
Frequency Coverage	Ten discrete bands from 90 cm to 0.3 cm (0.3 to 96 GHz)
Pointing Accuracy	6 arcsec rms blind pointing
Field of View of Antennas	40 arcmin / ν (GHz)
Number of Baselines	45
Angular Resolution	10 milliarcsec / ν (GHz); n.b., 1 milliarcsec at 8 GHz
Maximum BW, each pol.	64 MHz now, 500 MHz in 2011
Maximum Data Rate	512 Mbit/s now; 4 Gbit/s in 2011
Point Source rms, 12 hr	20 μJy at 512 Mbit/s, 8 μJy at 4 Gbit/s, at 1–15 GHz
Maximum Freq. Channels	2,048 now; 16,384 with the EVLA correlator in 2011

4.3.2 VLBA Scientific Highlights

The dedicated VLBA is unique among VLBI arrays for its ability to monitor the evolution of radio sources over all time intervals from days to years. At the high spatial resolution of the VLBA, source morphologies often evolve rapidly, and studies of the physical processes associated with such evolution motivate many of the primary VLBA observing programs. No other set of VLBI antennas in the world combines this capability with the well-designed aperture coverage and systematic common calibration of the VLBA which permit making “movies” of time-varying phenomena ranging from stellar pulsations to galactic microquasar flares to explosive jet ejection in gamma-ray blazars. The ability to make repeated observations at regular intervals also makes the VLBA the leading astrometric instrument in the world. Its astrometric accuracy, as good as 10 microarcseconds, is a factor of 100 better than that of Hipparcos and nearly equals that of the prospective SIM PlanetQuest (formerly the Space Interferometry Mission) likely to launch no earlier than 2013.

These observational capabilities of the VLBA have enabled many of the following scientific highlights:

- Measurement of the geometric distance to the Seyfert galaxy NGC 4258 and a direct measurement of the mass of its central black hole.

- Imaging the superluminal motions of gamma-ray blazars, and relating them to their gamma-ray emission, with full polarization capabilities.
- Detection of the proper motion and measurement of the three-dimensional velocity of the galaxy M33 in the Local Group.
- Direct imaging of the expansion of several supernovae and one GRB afterglow in external galaxies, as well as imaging the distributions of individual recent supernovae in obscured starburst galaxies such as Arp 220.
- Measurement of the proper motion of Sgr A* and demonstrating its coincidence with the massive black hole at the center of the Milky Way.
- Imaging the collimation of a radio jet within 100 Schwarzschild radii of the massive black hole in an AGN.
- Measurements of parallaxes and proper motions of pulsars and X-ray binaries (microquasars), providing their distances and inferences about their birthplaces and the physics of their formation in supernova explosions.
- Anchoring the orientation of the universal quasar inertial reference frame with 20 microarcsecond accuracy.

4.3.3 The VLBA in 2011

Like the present VLA, the VLBA is currently "sensitivity-starved" by electronic limitations: its bandwidth is constrained by the tape-recording and correlator technologies of the late 1980s. By 2011 the VLBA will combine the ongoing implementation of disk-based recording systems with the ability to use the spare capacity of the EVLA correlator. This will increase the maximum data rate of the VLBA from 512 Mbit/s to 4 Gbit/s (the sustained data rate will increase from 128 Mbit/s to 4 Gbit/s), thus increasing observing speeds by factors of 8–32 or multiplying sensitivities by factors of three to six. In addition, both now and in the future, the sensitivity of the VLBA can be increased by adding combinations of the GBT, the phased VLA, Arecibo, and Effelsberg to the VLBA; this High Sensitivity Array (HSA; see http://www.nrao.edu/HSA/) can multiply the sensitivity of a VLBA observation by up to factor of ten.

In summary, the VLBA in 2011 will maintain and enhance these unique features:

- Only full-time telescope imaging objects on sub-milliarcsecond scales.
- Only VLBI instrument with antenna locations chosen for optimal imaging capability over a wide variety of scales.
- Only VLBI instrument that can repeat identical observations on time scales from days to years.
- Only VLBI instrument with identical, commonly calibrated antenna and telescope systems, permitting relatively easy image production.

- Time sampling and common calibration permitting both global and local astrometry with accuracies as good as 10 microarcseconds.
- Only VLBI instrument with excellent sensitivity and imaging characteristics at short wavelengths (1.3 and 0.7 cm, or 22 and 43 GHz), with some imaging capabilities at $\lambda \approx 3$ mm (86 GHz).
- Only VLBI instrument with full-time dynamic scheduling, enabling access to high radio frequencies under the best conditions plus rapid response to time-critical targets such as outbursts of galactic microquasars.
- Sky coverage ranging from the North Pole (90 degrees declination) to about -45 degrees declination for most telescopes, 85% of the sky.

4.4 ALMA

The Atacama Large Millimeter Array (ALMA) will be the premier millimeter and submillimeter telescope in the world. It is under construction in the Altiplano region of northern Chile and, when completed in about 2012, will combine an array of up to 64 12-m antennas (see Figure 4.4.1 and detailed information at http://www.alma.nrao.edu/ALMAHandoutApr05.pdf) with an additional compact array supplied by Japan. ALMA will study many fundamental problems in astronomy such as the origins of planetary systems and the nature of early galaxies.

The ALMA project is an international partnership among Europe, North America, and Japan, in cooperation with the Republic of Chile. The project is funded in North America by the NSF in cooperation with the National Research Council of Canada, in Europe by the European Southern Observatory (ESO) and Spain, and in Japan by the National Institute of Natural Sciences. ALMA construction and operations are led on behalf of North America by the NRAO, on behalf of Europe by ESO, and on behalf of Japan by the National Astronomical Observatory of Japan.

ALMA will be a truly transformational instrument for studying the cool universe—the relic radiation of the Big Bang and the molecular gas and dust that constitute the very building blocks of stars, planetary systems, galaxies, and life itself. This material typically has temperatures of 3 K to 100 K, resulting in spectral-energy distributions peaking at submillimeter to far-infrared wavelengths. Most of the electromagnetic energy in the Universe lies in two thermal components—the cosmic background and the far-infrared background—within the ALMA wavelength range λ = 1 cm to 0.3 mm (30–950 GHz). Indeed, the peak of the spectral-energy distribution for dusty objects in the distant universe is redshifted entirely to submillimeter wavelengths.

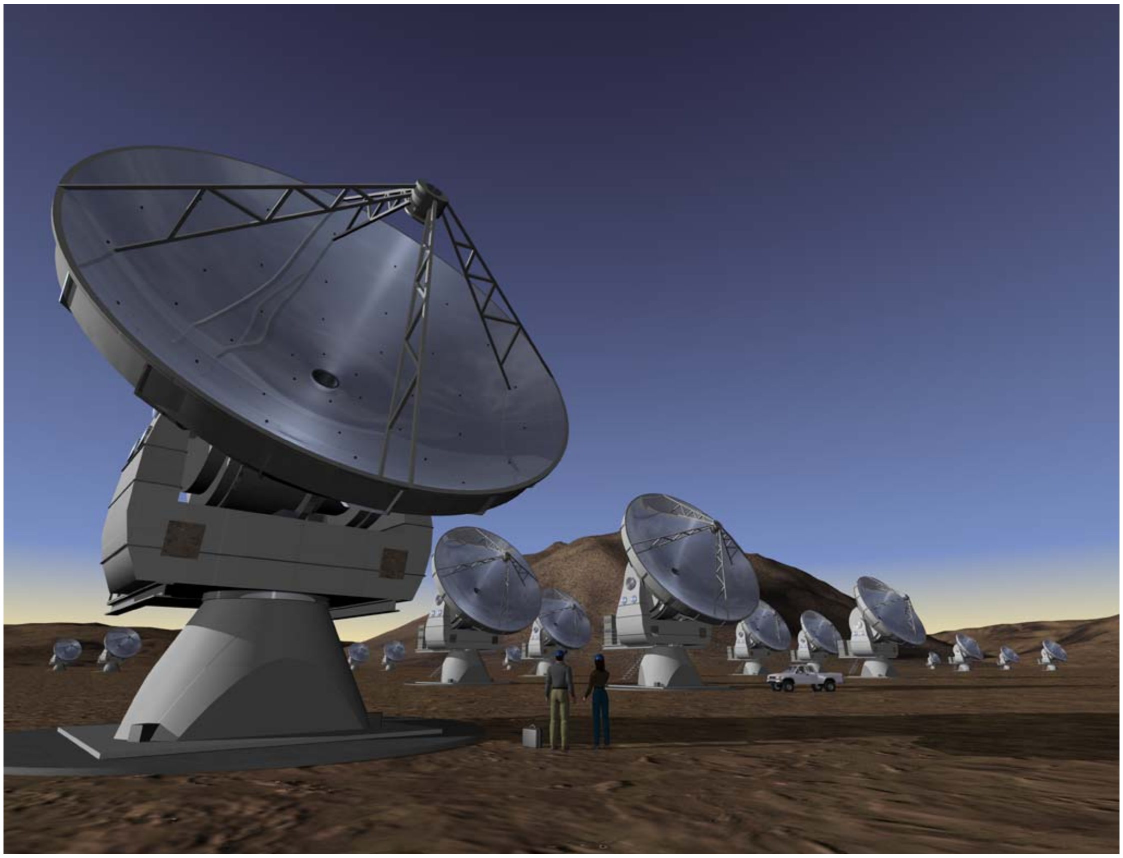


Figure 4.4.1 Artist's conception of ALMA.

4.4.1 ALMA Key Science Objectives

- The ability to detect spectral-line emission from CO or CII in a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation.
- The ability to image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as $z = 10$.
- The ability to image the gas kinematics in protostars and in protoplanetary disks around young Sun-like stars at a distance of 150 pc (roughly the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling the study of their physical, chemical, and magnetic-field structures and to detect the tidal gaps created by planets undergoing formation in the disks.
- The ability to provide precise images at an angular resolution of 0.1 arcseconds. Here the term "precise image" means being able to represent correctly, within the noise level, the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness.

ALMA's sensitivity to thermal emission from warm dust is extraordinary. At a fixed wavelength of observation, cosmic dimming with increased redshift is naturally compensated by the strongly increasing dust emissivity as a function of emitted frequency. Thus, ALMA takes us from the current regime where we can study only exceptionally luminous and rare objects to the point where we can image the dust in typical galaxies having star-formation rates of just a few solar masses per year well into cosmic reionization, in a manner complementary to and competitive with JWST. ALMA represents a step forward of orders of magnitude over current facilities in terms of sensitivity, frequency coverage, spatial resolution, and spectral capabilities. It will be 10–100 times more sensitive and have 10–100 times better angular resolution than any current mm/submm telescope. Part of this comes from the quality of the site, clearly the best in the world for submillimeter astronomy.

4.4.2 ALMA Technical Specifications

ALMA will be 10–100 times more sensitive and have 10-100 times better angular resolution than current mm/submm telescopes. ALMA's technical specifications are listed in Table 4.4.1.

4.4.3 ALMA Operation in 2011

In the era of ALMA, the NRAO will have been transformed: Charlottesville will become the headquarters for the North American part of the ALMA project and will host the North American ALMA Science Center (NAASC).

The flexibility and power of ALMA will bring to the NRAO users new to millimeter and submillimeter astronomy. The user community has demanded workshops and training schools to enable these new users to make the most of this unique instrument, while at the same time providing data products (i.e., calibrated images and data cubes) which can be manipulated and interpreted by non-experts. Provision of these services will increase the productivity and cost effectiveness of ALMA by expanding its user base and by ensuring that scientific results will be published in a timely fashion.

Table 4.4.1 ALMA Technical Specifications

Location	Atacama desert, Northern Chile, 5,000 m elevation
Coordinates	67d 45’ 16” Longitude -23d 01’ 22” Latitude (significant EVLA overlap)
Telescope Properties	64 12-m antennas, plus compact array of 12 7-m antennas and 4 12-m antennas
Elevation Range	2–90 degrees
Slew Rates	6 deg/sec (360 deg/min)
Frequency Coverage	31–950 GHz (λ = 1 cm to 0.3 mm) in ten bands (six bands available at first light, ranging from 3 mm to 0.45 mm)
Pointing Accuracy	0.6 arcseconds offset pointing, 2.0 arcseconds absolute
Field of View of Antennas	19 arcminutes/ ν (GHz)
Baseline Range	15 m to 15 km
Number of Baselines	2,016
Spatial Resolution	4 arcseconds/ ν (GHz), largest config.; 40 milliarcseconds at 100 GHz or 5 milliarcseconds at 950 GHz
Maximum BW, each pol.	8 GHz
Point Source rms, 350 GHz	1.6 mJy in 1 second; 8 µJy in 8 hr
Maximum Freq. Channels	8,192

The NAASC will serve as the portal to ALMA for the North American scientific community. It will be the point of contact for North American ALMA users from proposal submission to calibrated-data distribution and analysis. The heart of this end-to-end data system will be an automatically generated data archive. The core of the Center’s activity will be the development, maintenance, and refinement of the pipeline reduction, data archive, and software systems that surround the archive. Very importantly, the NAASC will foster community development to optimize the science use of ALMA and guide the future evolution of ALMA. To achieve these goals, the Center will conduct a program of ALMA Fellows and promote the establishment of grant support for data analysis by users on behalf of the NSF. It will be the focus for ALMA affairs in North America, sponsoring workshops, schools, and events that will stimulate the scientific activities appropriate to ALMA. Many ALMA development projects, both hardware and software, will be conducted by the NAASC and university collaborators. The NAASC will be responsible for the ALMA component of the NRAO program of education and public outreach.

4.5 User Access and Support

A primary goal for all NRAO telescopes in 2011 is improved access and support for users. The NRAO has always provided open access to its telescopes and the data they generate. This history includes the invention of the Astronomical Image Processing System (AIPS), which has been ported to universities and institutions worldwide for more than 20 years, and collaboration in the invention of the Flexible Image Transport System (FITS), the standard data-interchange and archival format of the worldwide astronomy community. More recently, the entire VLA data archive has been placed on-line, contributing to at least 25 refereed publications per year, and the legacy sky surveys FIRST and NVSS were cited by 250 publications last year (see Appendix A). In an era of limited funding for ground-based astronomical research, the NRAO continues to facilitate access to its telescopes by all U.S. astronomers, supplying full page-charge support to all astronomers eligible for NSF grants, paying airfares for successful proposers to make observing and data-reduction trips to NRAO facilities, providing stipends for student dissertation work on the GBT (now) as well as on the EVLA and VLBA (near future), and providing additional travel and housing support for student observers.

In future years, the issues of user access to NRAO facilities will become qualitatively different. For example, the sheer volume of data that will emerge from ALMA (initially 100 Tbytes per year, ultimately reaching 100 Tbytes per day) and the EVLA (expected to be at least 1000 Tbytes per year by mid-decade) leads to the requirement that the interaction between the NRAO and the North American astronomy community must follow a different model from that used in the past. In order to maximize the science output from ALMA and the EVLA, it will be vital to provide extensive archive and data-reduction support (such as help with processing of large and/or complex datasets) and sophisticated tools for data analysis (such as automated spectral-line identification programs and astrochemical models). Many of these tools will be developed in collaboration with colleagues at universities.

An example of the NRAO vision for user access is the NAASC described in Section 4.4.3 above. The NRAO will strive to maximize such access for all its telescopes, particularly the EVLA, which will supersede the VLA as the world’s flagship centimeter-wavelength radio telescope.

The optimal use of the resulting archives of calibrated and imaged data is best facilitated for the worldwide community through the interface to be provided by the National Virtual Observatory (NVO). The NRAO is committed to NVO efforts, with its participation in the NVO technical design, the NVO Science Steering Committee, and strong AUI participation in the upcoming proposal for NVO operations. NRAO has played a vital role in development of the “World Coordinate System” that is critical to NVO. It is the intention of the NRAO to make all the data from its telescopes publicly available via the NVO, with as much emphasis as possible on processed data products that can be utilized by all segments of the astronomical community. Currently, the NRAO is carrying out a pilot project to image a subset of historical VLA archive data and make the resulting calibrated data and images available to the NVO. We anticipate that this may result in the availability of images from 10% to 50% of the archival VLA data by 2011 (depending on results of the pilot project) and certainly will result in an increased understanding of the optimal approach for the NRAO to make ALMA and EVLA images available as these instruments come on line fully at the turn of the decade.

Figure 4.5.1 is a conceptual view of the NRAO facilities that may be accessed by the user community in 2011. NRAO will strive to operate the GBT, EVLA, VLBA, and ALMA as a unified system of telescopes so that the scientific community may (1) access any of the suite of telescopes, (2) take advantage of the numerous NRAO services to the user community, (3) create state-of-the-art images from a combination of automated pipelines and expert assistance, and (4) get to work on writing the scientific papers. The calibrated data and images then will be stored in archives for continued scientific use by other astronomers, perhaps for scientific goals not envisioned by the original proposers.

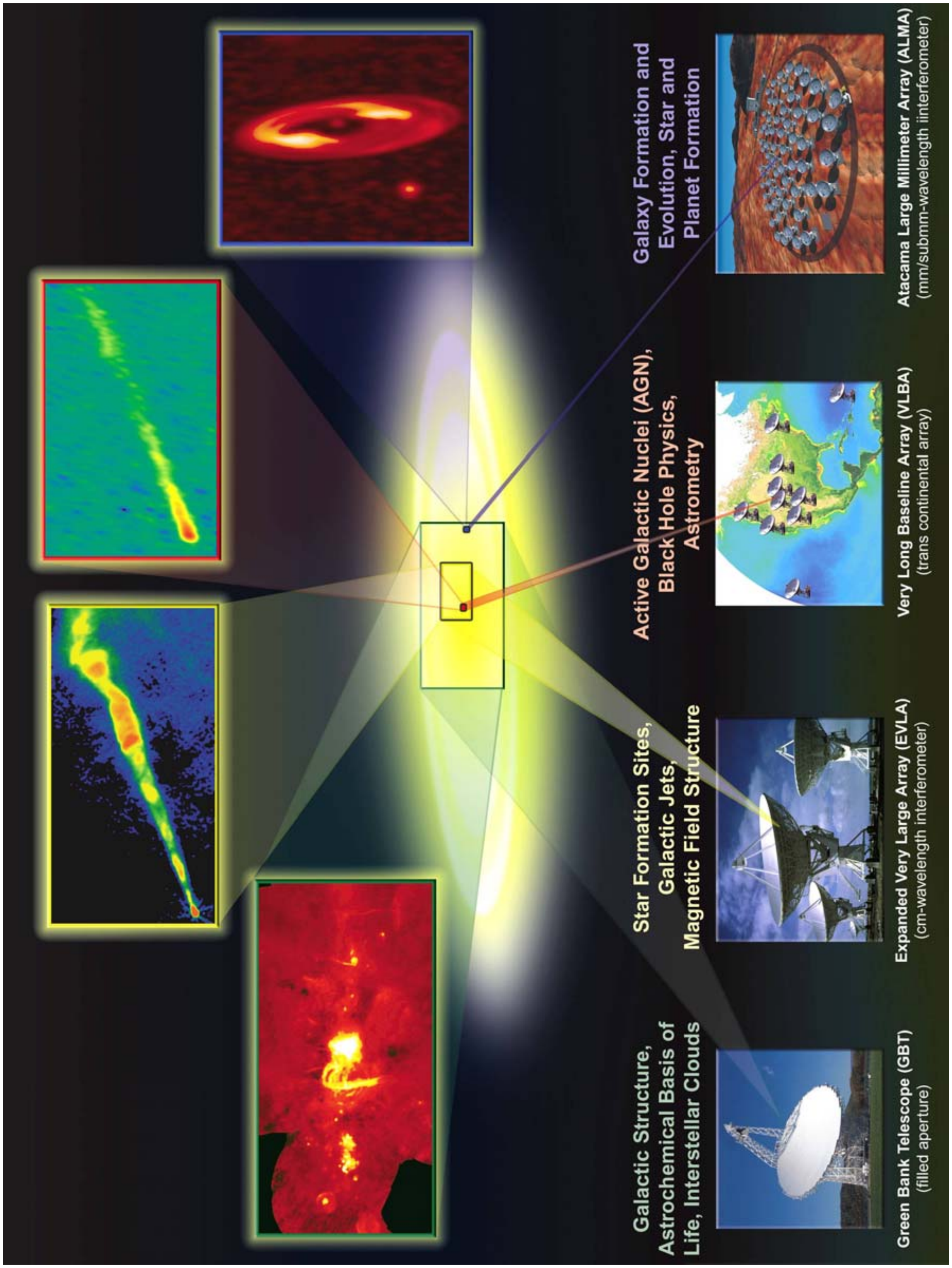


Figure 4.5.1 Conceptual view of the system of NRAO telescopes in 2011 and the scientific results that they are expected to produce.

4.6 *Lo*ng-term Vision for Radio Facilities

The overall design of any system of facilities for radio astronomy is largely determined by two facts:

- The radio band spans five decades in wavelength from 0.3 mm to 30 m, a range wider than the near-IR, optical, UV, and X-ray bands combined.
- Radio sources span more than seven decades in angular size and 14 decades in surface brightness, with emission on scales from microarcseconds to degrees.

Figure 4.6.1 illustrates in a schematic way the breadth of scientific investigations that may be carried out over the ranges of wavelength and angular scale covered by radio astronomy. The science ranges from sub-milliarcsecond imaging near supermassive black holes at cosmic distances, through imaging of star formation and proto-planetary disks in the Milky Way, to exquisite timing of binary pulsars in our Galaxy.

Different parts of the radio band require different sites (e.g., for protection from RFI at low frequencies or for low atmospheric absorption at higher frequencies) and telescope technologies. Phased arrays of nearly isotropic antennas such as dipoles yield the highest collecting area per dollar at frequencies below about 100 MHz (e.g., http://lwa.nrl.navy.mil/). Efficient reflector antennas must have rms surface errors $< \lambda/16$ and pointing errors $< \lambda/10d$. A large fully-steerable radio telescope that is strong enough to withstand the environmental stresses of ice loading and high winds can be made efficient to wavelengths as short as 7 or even 3 mm with little additional cost. Thus the large GBT, EVLA, and VLBA dishes are cost-effective solutions providing ~30,000 m^2 of aperture between about 100 MHz (λ = 3 m) and 100 GHz (λ = 3 mm). The high-precision ALMA antennas needed to reach 1000 GHz (λ = 0.3 mm) are relatively small and expensive, and they must be located at extremely high, dry sites. At centimeter and longer wavelengths, ALMA is not competitive with the larger GBT, EVLA, and VLBA for sensitivity and resolution.

Aperture-synthesis imaging is uniquely important to radio astronomy. It is (i) necessary because the diffraction-limited resolution $\theta \approx 1.2\lambda/d$ is poor at long wavelengths λ even for the largest practical diameter $d \approx 100$ m of a single fully-steerable dish; and (ii) practical because the sensitivity of coherent amplifiers is not badly degraded by quantum noise at radio frequencies. Ground-based aperture-synthesis arrays routinely achieve resolutions $\theta \approx 10^{-9}$ rad at $\lambda \approx 1$ cm by using baselines $d \sim 10^4$ km approaching the diameter of the Earth.

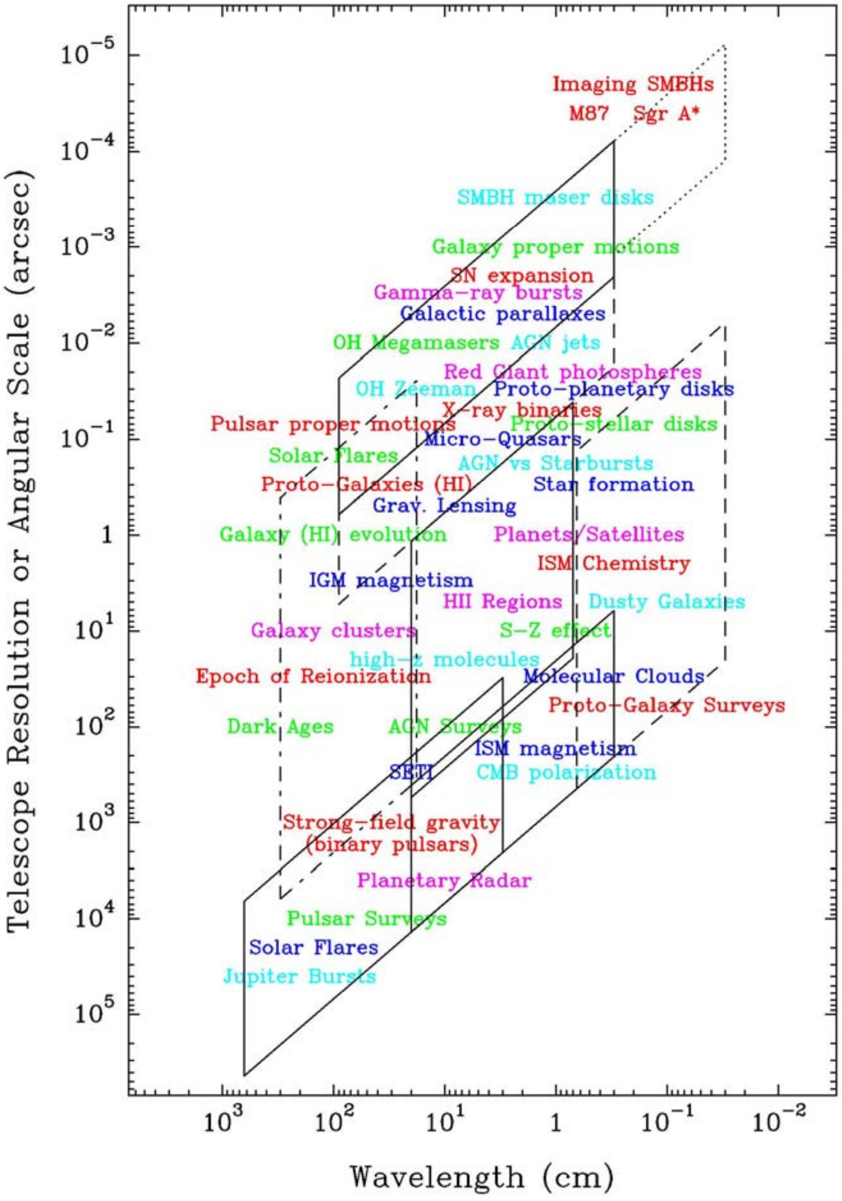


Figure 4.6.1 Radio phenomena span wide ranges of wavelength and angular size (Reid, M. 2005, private communication). Parallelograms bound the areas covered by individual existing (solid lines) NSF telescopes (Arecibo and the GBT at the bottom, the VLA/EVLA-I in the center, and the VLBA at the top) or future ones (dashed lines) such as ALMA (dashed parallelogram on the right) and EVLA-II (between VLA/EVLA-I and the VLBA).

Detailed imaging of faint complex sources with interferometers is impossible in the optical and higher-frequency bands because the sensitivity of any coherent amplifier is ultimately limited by quantum fluctuations whose amplitude hν/k is proportional to frequency. Signals from a large number N of array elements can be amplified coherently before distribution and combination, so the sensitivity of a radio interferometer with N identical elements is nearly N times the sensitivity of each element. Without coherent amplification, the signal from each element must be divided (N-1) ways before combination, so the sensitivity of an incoherent optical interferometer is less than that of a single element. Thus optical interferometers have small N and are used on morphologically simple, bright objects, to measure stellar diameters for example.

The surface-brightness sensitivity of an array is inversely proportional to its filling factor, which scales as d^{-2} for a given total collecting area. A wide range of baseline lengths d is needed to detect and resolve radio sources spanning many decades of angular size and surface brightness. No single telescope or array can do this; a system of facilities is required. The optimum distribution of baseline lengths for matching the wide range of source sizes and brightnesses is approximately logarithmic, and achieving this distribution has been the primary design driver for the suite of NRAO facilities (Figure 4.6.2). The d = 100 m filled-aperture GBT has the highest brightness sensitivity and lowest angular resolution. The VLA/EVLA-I is really four instruments in one, having four configurations with sizes d ≈ 1 km, 3.4 km, 11 km, and 36 km. The proposed 0.3 km E configuration of the EVLA II (http://www.aoc.nrao.edu/evla/) will provide excellent brightness sensitivity in the gap between 100 m and 1 km. Reconfigurable arrays much larger than 35 km are impractical; long-baseline arrays must use fixed antennas. The proposed New Mexico Array (d = 350 km) of the EVLA II is intended to span the gap between the VLA and the VLBA, which provides baselines up to 8,600 km. Although the GBT, VLA/EVLA, and VLBA were constructed at different times and often operate as independent facilities, they are all essential components of one system.

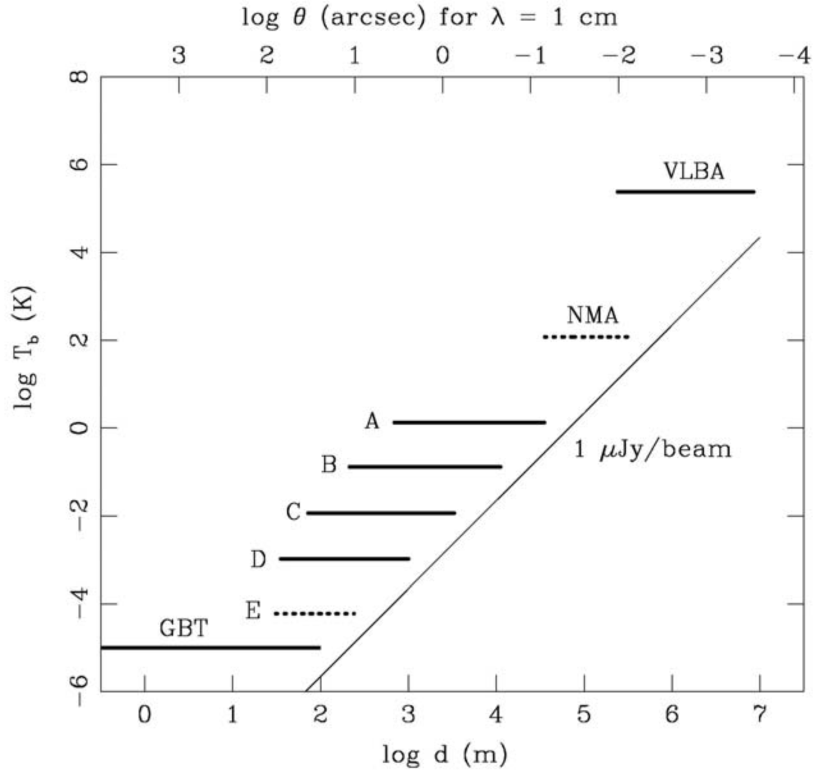


Figure 4.6.2 The system of NRAO facilities (see text) was designed to provide nearly uniform coverage in the logarithmic (log d, logT_b) plane. Only the upper abscissa of this plot, showing angular resolution at λ = 1 cm, is wavelength-dependent. The diagonal line indicates a peak flux density of 1 μJy per beam, the rms noise expected in sensitive EVLA images.

This system design is so fundamental that it will guide plans for centimeter-wavelength telescopes of the future. For example, the "Vision for cm/m Radio Astronomy in the US" white paper http://www.astro.cornell.edu/~cordes/RPG/AdhocRadioWhitepaper.pdf recommends "building upon EVLA and VLBA infrastructure for a (possibly) reduced-collecting-area [0.1 to 0.3 km^2] SKA [Square Kilometer Array] above ~1 GHz . . . ." Thus existing facilities (whose capital costs are about $100M for the GBT, $250M for the VLA/EVLA, and $150M for the VLBA in 2005 dollars) would not be abandoned, but rather reused as part of a future instrument.

5. BROADER IMPACT OF THE NRAO

While the primary mission of the National Radio Astronomy Observatory (NRAO) is to design, build, and operate world-class facilities for scientific research at radio wavelengths, the Observatory also undertakes a range of activities designed to broaden its impact on society. The NRAO considers these activities high-priority components of its role as a national observatory.

The NRAO strives to advance discovery and understanding while also promoting teaching, training, and learning, and supporting graduate students, post-doctoral researchers, and university faculty. To enhance the research and education infrastructure, the NRAO has established collaborative instrumentation programs and educational partnerships with the university-based astronomical community.

The NRAO maintains its commitment to the development of a scientifically literate, diverse society by keeping the public informed of its scientific and technological research, and by broadening the participation of under-represented groups. The NRAO supports an ambitious education and public outreach (EPO) program to communicate its mission and science to a broad international audience and has established a progressive diversity program.

The Central Development Laboratory (CDL) participates in technology development and routinely transfers its unique technology and instrumentation to radio telescopes and astronomical institutions around the world. The Frequency Agile Solar Radiotelescope (FASR), a ground-based interferometric array dedicated to solar research, is a recent direct spin-off of NRAO activities. NRAO facilities also make contributions to research in fields outside astronomy, such as geodesy and transportation safety.

5.1 Graduate Student, Postdoctoral, and Faculty Programs

Pre-doctoral student support is a high Observatory priority. Despite recent reductions in the NRAO operating budget, the successful and popular Green Bank Telescope (GBT) Student Support Program which funds GBT research by graduate students at U.S. universities and colleges (http://www.gb.nrao.edu/gbtprops/gbtstudentsupport.shtml) has been continued at its $200k/yr level, and an additional $100k/yr has been allocated to start a similar program at the Very Long Baseline Array (VLBA). Like its GBT counterpart, the new VLBA program covers student stipends, computer hardware purchases for student use, and student travel to domestic meetings to present VLBA results. Awards of up to $35,000 are available. In addition, the Pre-Doctoral Research Program (see http://www.nrao.edu/students/pre-docs-research.shtml) funds six Ph.D. students with NRAO mentors acting as thesis research advisors.

Several NRAO programs (see http://www.nrao.edu/students/) offer students extended opportunities to work closely with Observatory scientific and technical staff:

- Undergraduate Summer Student Research Assistantships partially funded by the National Science Foundation (NSF) Research Experiences for Undergraduates (REU) program. This program is open to U.S. undergraduates and graduating college seniors.
- Graduate Summer Student Research Assistantships funded by the NRAO. This program is open to first-year and second-year graduate students.
- The NRAO Co-op Program supports undergraduate engineering and computing students spending two or three semesters working in cooperation with their academic institution and the NRAO technical staff on projects at the forefront of technology.
- The NRAO Graduate-Student Internship Program supports first-year and second-year graduate students interested in pursuing research in radio astronomy and related fields.

The Jansky Fellowship program (http://www.nrao.edu/administration/directors_office/jansky-postdocs.shtml) is widely recognized as one of the most prestigious astrophysics postdoctoral programs in the world. The program was recently expanded to support Fellows at external institutions while continuing the successful program for fellows resident at NRAO sites. Its success is confirmed by the fact that over 90% of the previous fellows remain in astronomy, with prominent positions at universities and other research institutions, both in the U.S. and abroad. One of the goals of the external fellowship program is to foster radio astronomy research at U.S. universities. External Fellows are fully incorporated into the NRAO community through frequent video conferences, funded visits to NRAO sites, and an annual symposium at an NRAO site.

The NRAO Visitor's Program for faculty is extremely flexible with regard to support (computers, salary, etc.), starting date, and visit duration, all of which are negotiated to match individual needs. This program supports several visitors each year (see http://www.nrao.edu/astrores/visitors.shtml).

The NRAO has recently established what is envisioned as a long-term collaboration with the West Virginia University Department of Physics, assisting with the creation of an astronomy program and a nationally competitive research program in radio astronomy. The NRAO also has active long-term collaborations with the University of Virginia and the New Mexico Institute of Mining and Technology.

5.2 University-Built Instrumentation and Software Programs

The NRAO actively seeks collaborations with universities to develop telescope instrumentation and software. Despite budget pressures, the NRAO intends to continue funding these university-centered programs, given their importance in educating the next generation of astronomical instrument builders. Major university projects currently receiving NRAO support (funding and/or personnel effort) are:

- University-built pulsar backends at the GBT, including the Berkeley-Caltech Pulsar Machine, the Coherent Green Bank–Berkeley Pulsar Processor, the Pulsar Spigot Card, and the Caltech–Green Bank–Swinburne Recorder II. (http://www.gb.nrao.edu/GBT/MC/doc/GBTprojects/pulsarSupport/index.html).
- The Penn Array Receiver is a 64 pixel Transition Edge Superconductor bolometer array that will operate in the λ = 3 mm (86–94 GHz) window. It is being built by a collaboration involving the University of Pennsylvania, NASA GSFC, NIST, and NRAO and will provide fully sampled images of a 32 x 32 arcsecond region of sky at 8 arcsecond resolution. With the GBT's large aperture, the Penn Array Receiver will be a premier instrument for studying high-redshift galaxies, Galactic star formation, and for high-resolution imaging of the Sunyaev-Zeldovich Effect.
- The Caltech Continuum Backend is being built to support the GBT's current λ = 1 cm (26–40 GHz) and future λ = 3 mm (68–92 GHz) receivers. This instrument will instantaneously cover the full receiver band with separate detectors in 3 to 4 sub-bands on both feeds and both polarizations using the 12 to 16 direct RF detectors the receiver provides.
- The "Zpectrometer" is an analog correlation spectrometer which instantaneously covers the entire bandwidth of the GBT 26–40 GHz (λ = 1 cm) receiver. Andrew Harris (University of Maryland), Andrew Baker (Jansky Fellow at the University of Maryland) and Philip Jewell (NRAO) recently obtained an NSF ATI grant for its construction. The Zpectrometer spectral resolution is sufficient to make initial detections and rough determinations of line widths of high-redshift galaxies. Since the receiver covers the entire band, this instrument is ideal for searching for galaxies with uncertain redshifts. The 26–40 GHz band is well matched for this science because it includes the 115 GHz (λ = 2.6 mm) J=1–0 CO line at redshifts between 1.9 and 3.4, the peak epoch of star formation in the universe.
- The Long Wavelength Array (LWA) is being developed by a collaboration of many institutions including the Naval Research Laboratory (NRL) and universities of the Southwest Consortium (SWC). The LWA is a low-frequency radio telescope designed to produce high-sensitivity, high-resolution images at 10–88 MHz (λ = 30–3.4 m), opening a new astronomical window on a poorly-explored region of the electromagnetic spectrum. This will be accomplished with a large collecting area spread over an interferometric

array having baselines up to at least 400 km. The LWA project plans to site the instrument in New Mexico, possibly near the VLA. The LWA would encompass interferometer stations spread throughout and possibly beyond New Mexico. Phase 0 of the LWA added 74 MHz (λ = 4 m) capacity to the VLA by installing half-wave dipoles and 74 MHz receivers at each antenna's prime focus. The NRAO is assisting with the LWA development primarily through its participation in Phase 0. Completed in 1998, the Phase 0 system has already produced outstanding scientific results and is now being used to conduct the VLA Low-frequency Sky Survey (VLSS) which has mapped most of the sky visible to the VLA at 74 MHz. LWA Phase 1, which began in mid-2005, consists of the construction of two "development" LWA stations near the VLA. This Long Wavelength Development Array (LWDA) can be used in stand-alone mode or in combination with the VLA 74 MHz system.

- Astronomers at the Smithsonian Astrophysical Observatory (SAO), Harvard University, and NRAO are working to outfit the VLA to detect and image HI emission during the epoch of reionization. The VLA VHF Refit project (see http://cfa-www.harvard.edu/dawn/) will equip each VLA antenna with a crossed-dipole feed and λ = 1.6 m (190 MHz) receiver. The SAO is providing hardware and engineering services. The goal is to complete deployment in time for acquisition of first science data during the 2005 D-configuration cycle of the VLA.
- University-initiated software collaborations have made valuable contributions recently, especially for the Green Bank Telescope (GBT). University-provided pulsar backends traditionally arrive at the NRAO with basic software, and collaborations with NRAO staff extend the utility and user base for that software. During the past year, IDL-based data-reduction software for spectroscopy at the GBT (see http://www.bu.edu/iar/research/dapsdr/) was developed following the intellectual leadership of Tom Bania (Boston University), and polarization software development has been led by Carl Heiles (Berkeley) and Berkeley Ph.D. student Tim Robishaw, with funding from the GBT Student Support Program.

5.3 Education and Public Outreach

The NRAO contributes to the development of a scientifically literate, diverse society and is strongly committed to keeping the public informed of its research, programs, and activities. To achieve these goals, the NRAO supports an ambitious and forward-looking education and public outreach (EPO) program.

The NRAO EPO program communicates the Observatory's mission and science through the World Wide Web, electronic and print news and media, public Science Center programs and activities, and carefully planned educational programs. The Observatory's EPO program portfolio is designed to reach a large and diverse international audience: the general public, the professional and amateur astronomical communities, the media, K–16 students and teachers, and

EPO professionals. Each NRAO EPO program incorporates the most recent scientific results from the GBT, VLA, and VLBA, and discusses the scientific promise of the Expanded Very Large Array (EVLA) and the Atacama Large Millimeter Array (ALMA). NRAO EPO programs also describe how radio astronomy complements and connects to astronomical research at optical, infrared, ultraviolet, X-ray, and other non-radio wavelength regimes.

5.3.1 World Wide Web

The World Wide Web is an important outreach and communication channel. The NRAO is investing significant resources to improve the usability, structure, navigability, content, content management, and design of its web site. This effort will enhance the Observatory's web pages that serve the astronomical user community, EPO-related constituents, and the NRAO/AUI staff and guarantee that the web will remain a vital resource.

5.3.2 Astronomical Community

NRAO EPO staff actively participate as exhibitors, press-room and event coordinators at major meetings of the astronomical community, interacting with graduate and undergraduate students, astronomy and physics faculty, post-doctoral fellows, and research staff. EPO personnel lead the planning and coordination of special outreach events such as the "Town Meetings" that periodically communicate the progress and scientific promise of the EVLA and ALMA construction projects. EPO staff are also participants in the activities of IAU Commission 46 (Astronomy Education and Development), the IAU Division XII Working Group (Communicating Astronomy with the Public), the American Astronomical Society, the Astronomical Society of the Pacific, the Southwest Consortium of Observatories for Public Education, and the State of the Art Telescope Educational Consortium. Through their long-term and proactive participation in these organizations, EPO staff communicate the Observatory's mission, science, opportunities, and facilities to a world-wide audience.

Figure 5.3.1 EPO Public Information Officers Andrea Gianopoulos and Dave Finley staff the NRAO – ALMA exhibit at the summer 2005 American Astronomical Society meeting in Minneapolis, Minnesota.

5.3.3 Legacy Imagery Project

Recently inaugurated and envisioned as a long-term program, the Legacy Imagery Project is developing the Observatory's capability to process astronomical data acquired at radio wavelengths into compelling visual images, and to use these images in conveying the Observatory's mission and science to its constituencies. Images generated by each of the existing (GBT, VLA, VLBA) and future (EVLA, ALMA) NRAO research facilities will typically be combined with images from other wavelength regimes and observatories (Hubble Space Telescope, James Webb Space Telescope, Spitzer, Chandra X-ray Observatory, Keck, Gemini etc.), creating multi-wavelength composite images that offer unique, synergistic views of our Universe.

The annual NRAO/AUI Image Contest is a key component of this project (see http://www.nrao.edu/imagegallery/image_contest/image_contest.shtml). This image contest engages the astronomical community in the Observatory's efforts to increase the number of high-quality and EPO-effective radio astronomy images. These images will be made widely available via the Observatory's on-line Image Gallery, which will grow year-by-year and become increasingly valuable as a resource for teachers, students, scientists, the media, and other EPO programs. These images will also be distributed via well-designed EPO products such as DVDs, posters, and annual calendars.

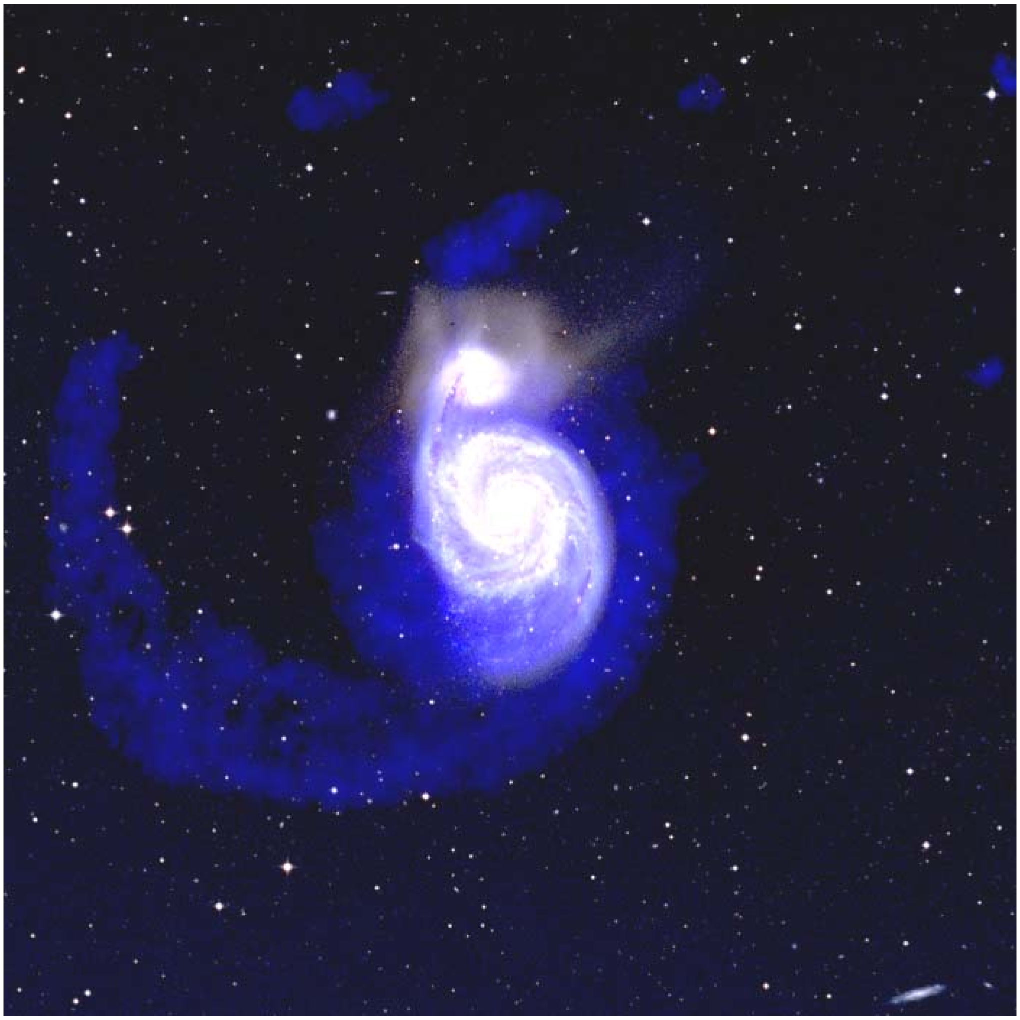
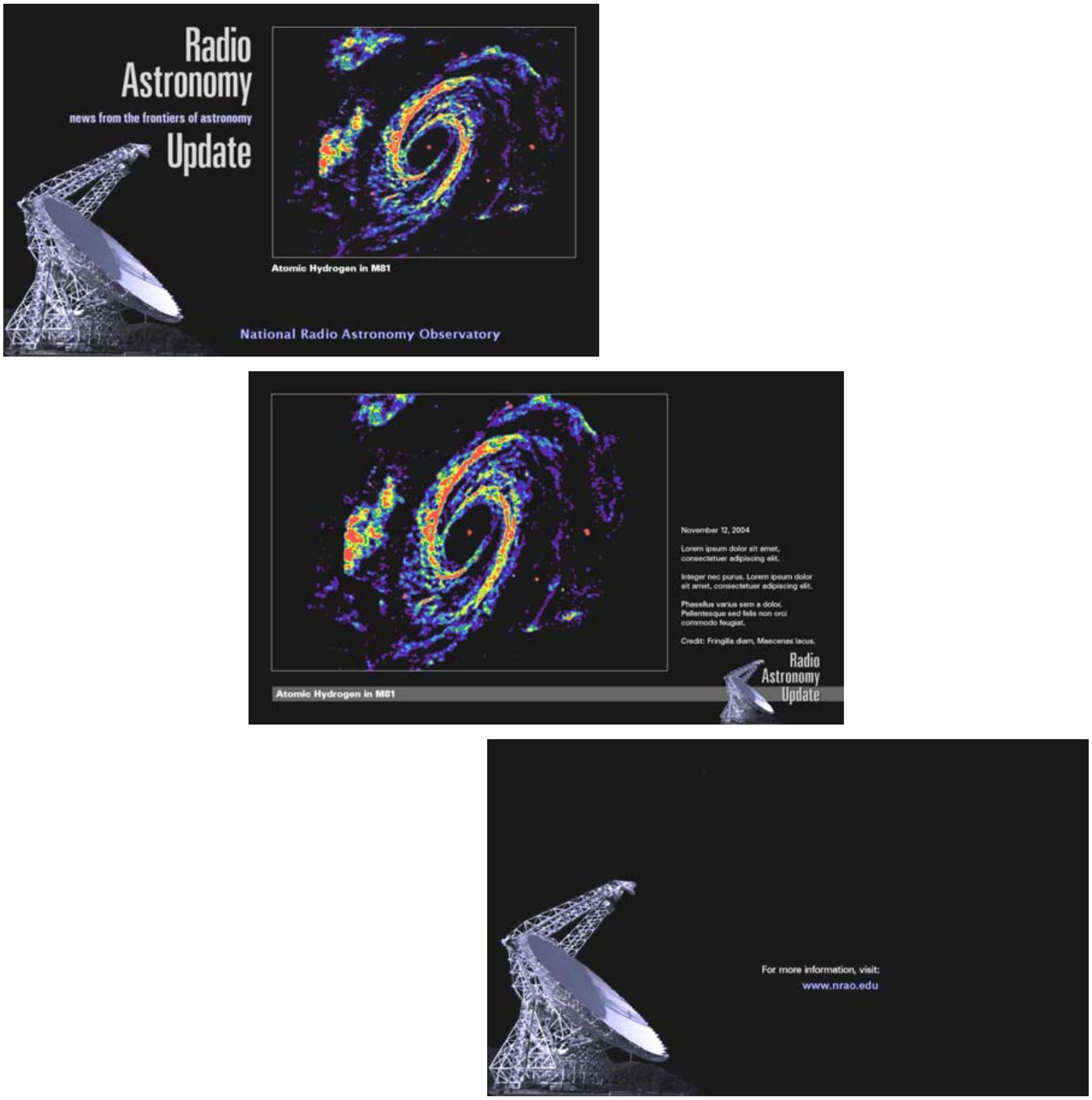


Figure 5.3.2 Legacy Imagery Project optical-radio composite image of the Whirlpool Galaxy, Messier 51. Neutral hydrogen 21 cm VLA radio data courtesy A.H. Rots (NRAO), A. Bosma (O. Marseille), J.M. van der Hulst (Groningen), E. Athanassoula (O. Marseille), and P.C. Crane (NRAO). Optical data courtesy STScI/POSS-II.

5.3.4 Science Museum Outreach

The Observatory's Science Museum Outreach initiative is a long-term program that is bringing radio-wavelength scientific research and the NRAO into more than 70 major science museums and planetariums in North America. The Observatory's goals for this program are being accomplished through its participation in *ViewSpace,* a free multi-media electronic exhibit developed and managed by the Space Telescope Science Institute's Office of Public Outreach (http://hubblesource.stsci.edu/exhibits/viewspace). NRAO scientific research press releases are now distributed via the *ViewSpace* network, and EPO staff envision future program modules that discuss the scientific richness of radio astronomy and the NRAO, including the transformational science and capabilities of the EVLA, GBT, VLBA, and ALMA.



Radio Astronomy

news from the frontiers of astronomy

Update

Atomic Hydrogen in M81

National Radio Astronomy Observatory

November 12, 2004

Lorem ipsum dolor sit amet, consectetuer adipiscing elit.

Integer nec purus. Lorem ipsum dolor sit amet, consectetuer adipiscing elit.

Phasellus varius sem a dolor. Pellentesque sed felis non orci commodo feugiat.

Credit: Fringilla diam, Maecenas lacus.

Radio Astronomy Update

Atomic Hydrogen in M81

For more information, visit:
www.nrao.edu

Figure 5.3.3 Lead, content, and credit templates for the NRAO ViewSpace program module that convey GBT scientific press releases to more than 70 science museums and planetariums.

5.3.5 News and Media

Ensuring that scientific research conducted at the NRAO receives excellent international news and media coverage is another important long-term EPO responsibility. NRAO public information officers (PIOs) write and issue 20 to 30 press releases per year, working closely with scientists who have used NRAO telescopes. Joint press releases are often generated in collaboration with PIOs at other universities and research institutions. NRAO press releases are electronically distributed to more than 1,500 science journalists world-wide and via *ViewSpace* (see http://hubblesource.stsci.edu/exhibits/viewspace/). This distribution will increase, especially via web-based news organizations.

5.3.6 Public Science Centers

The Green Bank Science Center in West Virginia and the VLA Visitor Center in New Mexico are increasingly popular and offer numerous educational programs designed for the general public. The visual impact of the GBT and the VLA and the intriguing, well-publicized accomplishments of modern astronomy are major draws for the general public. The self-directed and guided tours enabled by the on-site EPO staff in West Virginia and New Mexico made visiting these NRAO facilities an enjoyable and enriching experience for more than 63,000 people in 2004, and visitation is expected to show continued increases. The Observatory recently commissioned a study by the University of New Mexico School of Architecture & Planning for a larger VLA Visitor Center that would enable education and tour programs comparable to those offered at the Green Bank Science Center. This architectural study, the Green Bank Science Center construction, and the VLA Visitor Center expansion, were all funded outside the Observatory's NSF-AST budget.

Figure 5.3.4 Opened in May 2003, the NRAO Green Bank Science Center in West Virginia attracts more than 40,000 visitors per year.

5.3.7 Education

The Observatory's education programs in New Mexico and West Virginia are healthy and growing. The NRAO Education Specialists at these sites host multiple educational opportunities for K–16 teachers and students each year. Chautauqua Short Courses have been a fixture at the NRAO for eighteen years and have served more than 580 undergraduate science faculty who visited the Observatory to update their science course content and pedagogy. The Research Experiences for Teachers (RET) program, funded by the National Science Foundation (NSF), is another mainstay of the education program, annually funding secondary-school teachers for an eight-week summer program in West Virginia, New Mexico, and/or Virginia. New education programs are regularly added to the EPO portfolio. For example, a Master of Science Teaching class in observational radio astronomy was planned and offered for the first time at New Mexico Tech in 2004 and will again be featured in 2006. In West Virginia the Governor's School for Mathematics and Science (GSMS), a collaboration with the National Youth Science Foundation, is debuting in 2005, offering unique science-ducation opportunities to the 60 gifted eighth-grade students who were selected from more than 300 applicants.

5.4 Under-Represented Groups

The Observatory is strongly committed to broadening the participation of underrepresented groups in its activities, increasing the number of women and minorities in astronomy and within its scientific, professional, and managerial organizations. An Observatory Diversity Committee was formed in 2004 by the Director to promote and enable these important Observatory goals. In its first year, the committee was extremely successful in increasing the number of underrepresented groups applying for and hired onto the scientific staff. The continuing activities of this committee include the active recruitment of underrepresented groups to open positions at the NRAO and the implementation of the "Pasadena Recommendations" of the American Astronomical Society Committee on the Status of Women in Astronomy.

5.5 Technology Development and Transfer

The Central Development Laboratory (CDL) of the NRAO is a center of excellence which provides engineering development and production of unique instrumentation for radio astronomy and physics research. Components and devices produced by the CDL are central to achieving the sensitivity of modern radio telescopes, and they have been incorporated into most radio telescopes around the world. Without these developments, improvements in radio-telescope instrumentation would drastically decline.

Successful development by the CDL of an InP-based low-noise amplifier at 90 GHz (λ = 3.3 mm) was crucial to Goddard Space Flight Center's obtaining funding for the Wilkinson Microwave Anisotropy Probe satellite (WMAP). The CDL developed and produced all 80 space-rated amplifiers (plus 40 prototypes and spares) covering the five WMAP bands, and these were the core technology which enabled this highly successful mission. Other CMB instruments using NRAO low-noise amplifiers include the Degree Angular Scale Interferometer (DASI), the Very Small Array (VSA), the Cosmic Background Imager (CBI), and the Berkeley Illinois Maryland Association Sunyaev Zeldovich Array (BIMA SZA).

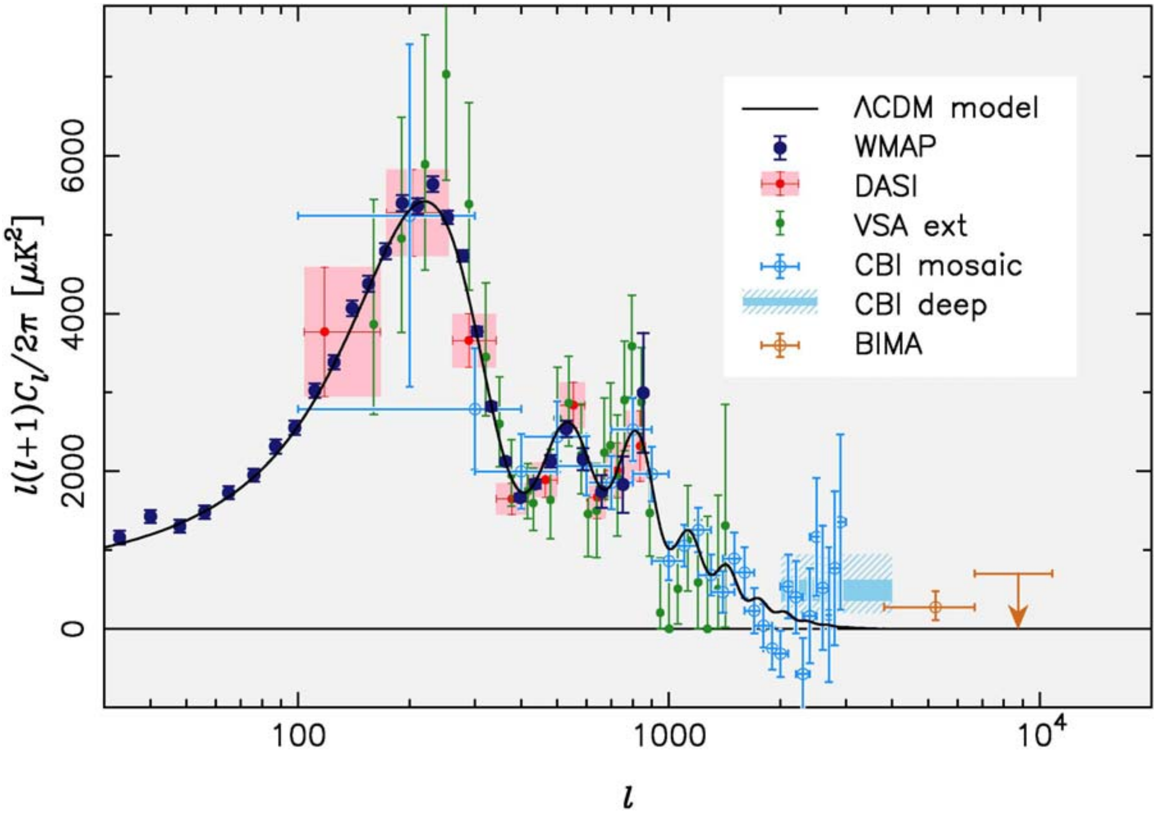


Figure 5.5.1 All of the data shown in this plot of the CMBR power spectrum were obtained using low-noise HEMT amplifiers designed and/or built at the CDL.

At frequencies below 1 GHz (λ > 0.3 m) CDL balanced HEMT amplifiers have been used in the investigation of single-electron transistors (http://marcuslab.harvard.edu/jc/reilly0505.pdf) and in the ongoing search for axions (http://www.phys.ufl.edu/~tanner/PDFS/Axion04prd-DYu.pdf).

Superconductor-Insulator-Superconductor (SIS) tunneling junctions configured as mixers to convert mm- and sub-mm waves to intermediate frequencies are the foundation of all sensitive receivers above 115 GHz (λ < 2.6 mm). CDL staff led the development of Nb-based junctions, which are now the standard for SIS devices of all types, not only low-noise mixers. The CDL has produced large numbers of SIS mixers for many radio telescopes. Years of work have led to SIS mixer designs that are inherently broad-band in both RF and IF, require no mechanical tuners, and achieve record-low noise temperatures. These devices are used for the λ = 3 mm (84–116 GHz) and λ = 1.3 mm (211–275 GHz) bands on ALMA. The CDL is now developing NbTiN mixers for use at $\lambda < 0.4$ mm ($\nu > 700$ GHz).

Digital auto- and cross-correlators are the heart of digital data processing for all radio telescopes. The CDL has been a world leader in the development and construction of such systems, including the ALMA correlator which performs 1.7×10^{16} multiply-and-add operations per second using a custom chip designed at the CDL.

Many aspects of research, development, and production are not suitable for commercial development. For example, there is little industrial experience with cryogenic receiver systems, which are required for the lowest possible noise, because the market is very small. Developments at the CDL benefit the radio-astronomy instrumentation community worldwide because the NRAO regularly shares designs, collaborates on development projects, and builds components for other radio telescopes on a cost-reimbursement basis.

5.6 Frequency Agile Solar Radio Telescope (FASR)

The Frequency Agile Solar Radiotelescope (FASR) will be a dedicated ground-based, interferometric array optimized to perform broadband imaging spectroscopy of the Sun from $\lambda < 1$ cm to $\lambda = 3$ m (0.1 to beyond 30 GHz). It will do so with the angular, spectral, and temporal resolution required to exploit radio emission from the Sun as a diagnostic of the wide variety of astrophysical processes that occur there. A development proposal by a consortium of university groups, with NRAO participation, has been submitted to the Atmospheric Sciences Division of the NSF. One of the two candidate sites for hosting FASR is the VLA site in Socorro. See the FASR web site http://www.ovsa.njit.edu/fasr/ for details.

5.7 Astrometry and Geodesy

The common calibration and continuous operation of the VLBA have made it the leading astrometric instrument in the world. Local astrometry with accuracies nearing 10 microarcseconds is achieved with the VLBA, an accuracy which will remain unmatched until the launch of SIM PlanetQuest (formerly called the Space Interferometry Mission), now scheduled for 2011. VLBA global astrometry with 100 microarcsecond accuracy forms the backbone of the International

Celestial Reference Frame (ICRF), the fundamental inertial frame used for a myriad of astrophysical and geodetic applications.

The Gravity Probe B (GP-B) mission (http://einstein.stanford.edu/) is currently measuring two phenomena predicted by Einstein's General Theory of Relativity (GR): the geodetic effect and frame dragging. The axes of gyroscopes in a polar orbit are referenced to the radio star IM Peg, whose position is tied to the inertial frame defined by distant quasars via multi-epoch VLBA observations. Without that tie-in, the accuracy of this half-billion-dollar physics mission would be degraded by more than a factor of two.

Geodetic observations are carried out using antennas all over the world, so the VLBA is not the only contributor. But the VLBA, with ten 25 m antennas and electronics designed for high stability, provides much of the best available data. For example, the results from major geodetic observations involving the VLBA give Earth orientation results a factor of two to three more precise than those acquired without using the VLBA. Plate tectonic motions are clearly observed in VLBA data, demonstrating that these motions are on-going rather than episodic.

5.8 Transportation Safety

The Global Positioning System (GPS) is being designed into the next-generation aircraft landing system which supports precision approach, landing, and terminal navigation systems including automatic takeoff and landing (http://gps.faa.gov/programs/index.htm). Critical verification measurements of GPS signals are required for this Local Area Augmentation System (LAAS) to be implemented with the designed levels of safety and integrity. Only the GBT is able to track all 27 GPS satellites with enough sensitivity to detect the relevant signals (1 MHz square-wave modulation on 1227.6 and 1574.2 MHz carriers) well above the thermal noise floor and characterize them. The GBT is being used to study "evil waveforms" that may produce hazardous differential ranging errors at the aircraft. This effort will ultimately benefit the entire transportation sector, not just aviation. This research is being conducted by personnel at the Stanford University GPS Research Laboratory for the U.S. Wide Area Augmentation System recently approved by the Federal Aviation Administration.

6. SCIENCE AND COST METRICS

6.1 Introduction

In this section we summarize a few metrics describing the publication rates, user communities, and operating costs of NRAO telescopes. Appendix A presents a far more detailed set of metrics, including those specifically requested by Dr. Eileen Friel of the NSF Astronomy Division in an e-mail dated July 5, 2005.

Refereed Publications

Figure 6.1.1 shows the numbers of refereed publications per year based on data from the VLA, the VLBA, and the GBT from 1977 through 2004. The VLA and VLBA publication rates both rose over the first eight years and then stabilized. Comparison with metrics from Grothkopf et al. (2005, ESO Messenger, 119, 45) indicates that the publication rate of the VLA is equivalent to two new 10-m-class optical/infrared telescopes. Remarkably, the VLA publication rate of 160–180 papers per year has been maintained for the last 20 years, making the VLA the most productive ground-based telescope in the world for many years. The number of refereed publications based on VLBA data is now leveling out at 60–70 papers per year, a factor of 2.6 lower than the VLA. This factor matches the smaller number of elements of the VLBA (10 instead of 27) and its slower mapping speed. For the newer GBT, the refereed publication rate is just starting a rapid rise expected to continue until at least 2007 or 2008. Experience at other single-dish observatories (e.g., the JCMT) shows that the number of publications also rises sharply upon the introduction of multi-pixel cameras. The first GBT camera, the λ = 3 mm Penn Array, will begin testing in 2006.

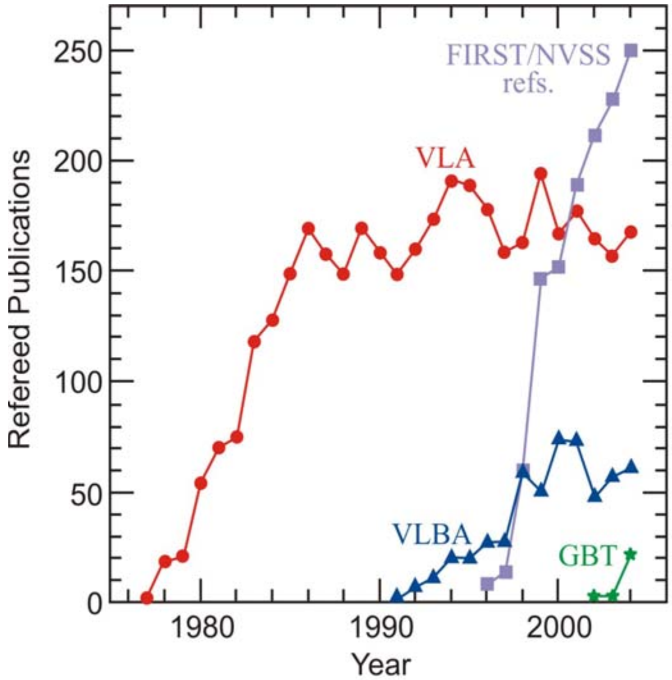


Figure 6.1.1 Refereed publication rates for the VLA, VLBA, and GBT. The numbers of published papers that reference the primary data sources for the two large VLA legacy surveys, FIRST and NVSS, are shown as well.

Figure 6.1.1 also indicates the rapidly growing number of published papers using results from the two large “legacy” continuum surveys made with the VLA—the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey. Both are freely available via public web sites (see http://www.cv.nrao.edu/NVSS/ and http://sundog.stsci.edu/top.html) which provide “virtual observatory” data products and services including calibrated images, postage-stamp image servers, source catalogs, and catalog browsers. The NVSS is also accessible from the U.S. National Virtual Observatory (http://www.us-vo.org/) funded by the National Science Foundation under its Information Technology Research program.

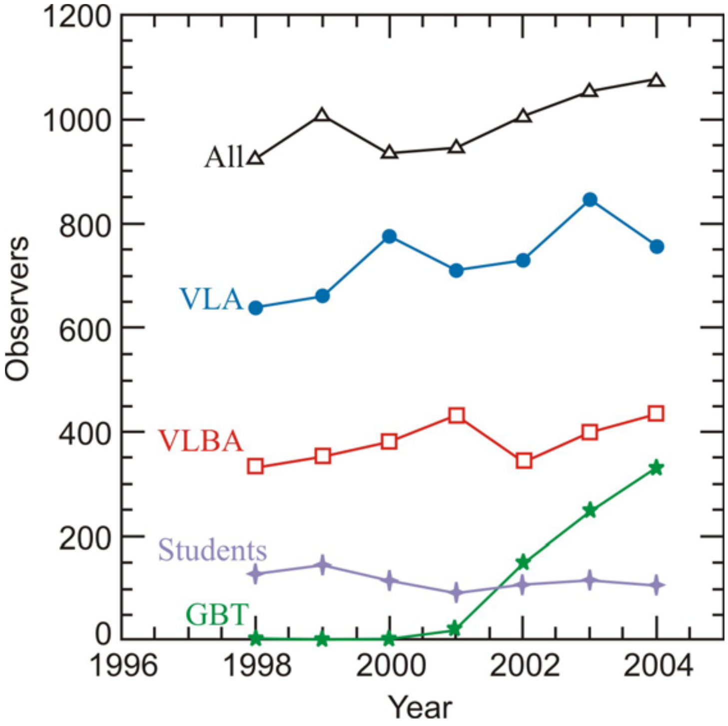
During the last few years approximately 20 refereed papers per year have been published based directly on raw data from NRAO archives. These data are available after the expiration of their proprietary periods, and the NRAO Data Archive has been on-line since 15 October 2003. It allows astronomers access to all VLA data, and some VLBA and GBT data. To date, over 640 users from 240 institutions have downloaded over 1.5 TBytes of non-proprietary telescope data from this new service. The download rate is over 100 GBytes per month for non-proprietary data and is steadily increasing. (Comparable download rates exist for proprietary data, which are downloaded conveniently from the archive by recent observers.) We expect that the rate of publications based on these data will rise sharply in the next few years. These survey- and archive-based publications confirm the enduring value of the data products of NRAO instruments to the astronomy community.

6.2 The NRAO User Community

Astronomers around the world recognize the unique capabilities of NRAO facilities. Principal Investigators at non-US institutions account for ~45% of VLA proposals, ~55% of VLBA proposals, and ~25% of GBT proposals, the last number being lower because most GBT observers must still travel to the telescope. In 2004, 758 individual astronomers from 211 institutions used the VLA for scientific programs, 435 astronomers from 144 institutions used the VLBA, and 332 astronomers from 105 institutions used the GBT (see Figure 6.2.1).

In 2004 the VLA received ~400 new proposals requesting a total of 12,882 observing hours; the VLBA, ~200 proposals for 6,804 hours; the GBT, ~150 proposals for 6,476 hours. Observer demand for the relatively new GBT is still rising rapidly (Figure 6.2.1). Approximately 50% of all VLA and GBT proposals obtained at least some time on those respective telescopes, while 60% of proposals obtained time on the VLBA. This high success rate is possible because radio telescopes can observe 24 hours a day, not just 10 hours per night, and can be scheduled dynamically to observe at long wavelengths even during poor weather.

Figure 6.2.1 The total numbers of individuals using the VLA, VLBA, and GBT during each calendar year from 1998 through 2004. The open triangles marked "All" indicate the total number of different observers using one or more NRAO telescopes. More than 100 students per year were identified among these users.



An important task of the NRAO is training future astronomers. Figure 6.2.1 shows that ~100 students use NRAO telescopes each year. The GBT has a highly successful student-support program (http://wiki.gb.nrao.edu/bin/view/Observing/GbtStudentSupportProgram) which provides financial support for graduate students at U.S. institutions who use the GBT, and a similar program is now being introduced for the VLBA. The NRAO also holds one summer school for graduate students and PhD astronomers every year, alternating between focusing on interferometry and single-dish radio astronomy. Attending the Ninth Synthesis Imaging Summer School in 2004 were about 150 students. See (http://www.aoc.nrao.edu/events/synthesis/2004/) The joint NAIC-NRAO School on Single-Dish Radio Astronomy (http://www2.naic.edu/~astro/School/) has an attendance of about 45 students, and the third session was held in 2005. Many of these students will be future users of NRAO and other radio facilities.

6.3 Cost of Operations

The cost per observing hour of operating each major NRAO facility in 2005, derived by taking its burdened operations cost and dividing by the successful hours of observing (down time has been subtracted out), is given in Table 6.3.1. The hours observed by the VLBA and VLA are assumed to remain the same in 2005 as in 2004, while the GBT observing hours are assumed to increase from its 2004 value of 4,700 hours to 5,500 hours. The table also gives comparable hours for some other telescope facilities on the ground and in space; these numbers have some uncertainty, but were derived from publicly accessible data available from the NSF, from NASA, or from the relevant observatory web sites. In this table, the Arecibo operations cost is the sum of the contributions from the NSF Astronomy Division and the NSF Atmospheric Sciences Division, with the observing time also summed for the two disciplines. The available Gemini observing time is the sum of the U.S. time for both Gemini-North and South (about 200 nights per year at 11 hours per night, times 80% data delivery from mechanical and weather downtime). The operations costs for Spitzer, Chandra, and Hubble Space Telescope do not include their grants programs and are probably lower limits owing to uncertain additional costs for spacecraft operations outside the science centers. The cost for SOFIA is a prospective annual cost, although it now appears that science operations will not begin in Fiscal Year 2005.

Table 6.3.1 Annual Operations Costs of Selected Observatories in FY 2005

Telescope	Hours Observed	Operations Cost	Cost/Hr
NRAO-GBT	~5,500	$15.2M	$2,800
NRAO-VLA	6,728	$14.4M	$2,100
NRAO-VLBA	4,494	$10.2M	$2,300
Arecibo	~7,000	$12.3M	$1,800
Gemini- US time	~1,800	$14.8M	$8,200
Spitzer	~6,000	~$43M	~$7,000
Chandra	~6,000	~$53M	~$9,000
HST	~4,300	~$82M	~$19,000
SOFIA (planned)	~960	~$55M	~$57,000

The average cost per refereed scientific publication for each facility is its annual operations cost divided by its publication rate. In 2004 this was a very economical $80k for the VLA, $160k for the VLBA, and $600k for the GBT. The per-publication cost for the VLA and VLBA are expected to remain approximately constant for the next few years, while it should decrease by a large factor for the GBT as it comes into full operation.

7. NRAO OPERATIONS AND BUDGET[1]

7.1 NRAO Operations Model

The NRAO operates and develops three telescopes—the GBT, the VLA/EVLA, and the VLBA—as an integrated facility. ALMA will join this group over the next few years. The VLA and VLBA jointly comprise New Mexico Operations, sharing management, scientific, and technical staff.

Scientific operations and the support and maintenance of telescope equipment and control software are provided most responsively and efficiently at the individual telescope sites. Table 7.1.1 summarizes the management and operations groups and their key functions at the telescope facilities.

Table 7.1.1 Telescope Management Groups and Their Key Functions

Group	Key Functions
Assistant Director's (Site Director's) Office	Local scientific direction and facility supervision Proposal handling and scheduling Participation in Observatory-wide senior management
Support & Development Divisions	
Scientific Services	Observer support and documentation Project scientists
Telescope Operations	Telescope and correlator operators
Engineering Services / Mechanical Eng.	Mechanical design Telescope mechanical support
Electronics	Electronics and cryogenic support and development
Software Development	Control and analysis software support and development
Computing Infrastructure	Computing hardware & network support
Business Administration and Physical Plant Maintenance	Local business operations Observer logistical support (local food, lodging, and transportation) Facility and grounds maintenance
Visitor Center Operations	Visitor center day-to-day operations (tours, gift shop, café, etc.)

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[1] Additional budget details were provided in this chapter of the document that was submitted to the NSF on July 31, 2005.

The Assistant Director's office is responsible for overall site management and for participation in the Observatory-wide senior management team. Site scientific management is also responsible for proposal handling and telescope scheduling. Observer scientific support provided by the Scientific Services group includes proposal technical advice, documentation of observing systems and capabilities, training for observing-run setup and execution, assistance and consultation during runs, and data-reduction support.

The engineering, mechanical, and operational staff support the complex systems associated with each facility, including the telescopes and their mechanical subsystems, cryogenic receivers, frequency-conversion systems, and backends (correlators, VLBI systems, continuum total-power detectors, pulsar detectors, and radar detection systems). Software systems including real-time telescope control and data-analysis packages are largely developed and maintained at the telescope sites, although there is considerable Observatory-wide participation in this area. The telescope facilities must also maintain radio-frequency interference (RFI) mitigation groups and computing-infrastructure support groups (for networks, computing hardware, etc.).

The business group at each site provides logistical support of observers including local lodging and transportation arrangements. They are also responsible for local business operations, physical plant infrastructure and maintenance, interaction with the local community and general public, and on-site visitor and science-center operations.

The scientists, engineers, and technicians who support the sites also work in a matrix-management system for development projects. This makes very effective use of personnel, ensuring that a highly trained staff is available for both support and development work.

In addition to the telescopes, the NRAO operates the Central Development Laboratory (CDL). The CDL provides the detector devices, including SIS mixers for ALMA and HEMT low noise amplifiers for all the NRAO centimeter-wave telescopes as well as for a great many external groups. The CDL also provides the backbone of digital signal processing engineering for the Observatory. In addition to specific device manufacture, the CDL is the long-range research and development arm of the NRAO.

As part of ALMA Operations, the NRAO will run the North American ALMA Science Center (NAASC) from its Charlottesville office. The NAASC is responsible for supporting the science use of ALMA by the North American astronomical community (US astronomers via the NRAO, and Canadian astronomers via the National Research Council of Canada). The NAASC is also responsible for the core functions in support of ALMA operation in Chile and the research and development activities in support of future upgrades of ALMA.

Management and services that are common to all telescopes and facilities are provided most efficiently by the central organization. NRAO's central management and services groups and their key functions are summarized in Table 7.1.2.

Table 7.1.2 NRAO Central Management and Service Groups and Their Key Functions

Management or Operating Group	Key Functions
Observatory Director's Office	Overall scientific direction of the Observatory Budget and priority determination
Division of Science and Academic Affairs	Scientific-staff research programs and functional support, Visitor's program, Postdoctoral and student programs, conferences, colloquia, etc. Proposal referee and selection committee appointments Libraries and observer publication support
Business Administration	Budget planning and Fiscal control Contracts & procurement Human Resources Environmental Safety & Security
Program Management Office	Observatory program management Management Information Services
Computing and Information Services	Networks, major computing hardware Software licenses Telecommunications
Education and Public Outreach	Public Information Office Educational programs Visitor Center programs and exhibits

The Director's Office is responsible for overall operation of the Observatory, setting scientific direction, future planning, establishing external and international collaborations, determining budget priorities and distribution among the various activities and initiatives, administrative practices, and for analyzing feedback of performance metrics from projects and operational initiatives.

The Division of Science and Academic Affairs (DSAA) oversees and supports individual research activities and provides scientific motivation for Observatory initiatives. In addition, this group supports many of the Observatory functional activities such as the telescope-proposal refereeing and selection process. The DSAA administers the Jansky Fellowship program, coordinates the Pre-Doctoral and Co-op Engineering Programs, and oversees the REU (Research Experiences for Undergraduates) Program at the Observatory. The DSAA also oversees the NRAO libraries and the NRAO historical archive (distinct from data archives), including the library-administered program of page-charge support for publications by U.S.-based observers. In addition, the DSAA is responsible for coordinating the functional duties of the tenured scientific staff, such as their assignment to support operating telescopes or observatory-wide activities such as international spectrum management.

The Observatory has three oversight groups which advise the Director, help set priorities, and ensure sharing and uniformity of approach across all Observatory activities. These are the Observatory Science Council (OSC), the Observatory Technical Council (OTC), and the Observatory Computing Council (OCC). Engineering and software designs are often used in multiple applications and at different sites.

The Administration and Business Services group provides the Observatory-wide support and oversees a central system for budget planning and fiscal control, payroll, contracts and procurement, human resources, etc. Safety policies and practices are established and followed uniformly throughout the Observatory.

The Program Management Office (PMO) provides Observatory-wide program-management support to all aspects of Observatory projects including telescope construction, hardware and software development, and telescope operations. The PMO is responsible for providing program-management support to ensure on-time, on-schedule delivery for each project in the Observatory, applying mitigation strategies as necessary to maintain project critical paths.

Computer infrastructure, including networks and software licensing, is provided centrally, while site computing (IT service) is provided at each site. The public information office and the programmatic direction of education and public outreach are directed from the central EPO office.

7.2 Baseline Budget for 2005–2011

As described in previous chapters, the NRAO operates a highly integrated set of telescopes which provide non-overlapping coverage of the sensitivity and angular-resolution parameter space of observational radio astronomy. Each NRAO facility is the best in its class in the world, and an uncompromised combination of these facilities is necessary to address the astrophysical problems of today and to cover the discovery space for future research. The baseline budget for NRAO operations from 2005 through 2011 provides for continued operation of the existing facilities. Consistent with NSF's assumption that its budget will grow no faster than inflation through the remainder of the decade, NRAO budget figures assume inflation at 3.5% per year along with several other year-to-year changes. In the future, should the rate of inflation be different than 3.5%, NRAO budgets will be adjusted accordingly. The baseline budget for existing NRAO Operations is essentially a constant-dollar budget.

This constrained budget does not maximize scientific return from the NSF's capital investment in NRAO facilities (see section 7.3). Nonetheless, it does provide for:

- Completion of EVLA Phase I construction.
- EVLA, VLBA, and GBT scientific operations at approximately the current level.
- Initial (but not optimal) GBT operations at $\lambda = 3$ mm and the completion of first-generation $\lambda = 3$ mm instrumentation including the Penn Array bolometer camera.
- CDL basic operations (e.g., continued HEMT amplifier manufacture).
- Completion of ongoing PMO and Business Services initiatives.
- Continuation of central administrative services, EPO activities, etc.

This budget assumes that EVLA construction will continue along the funding profile originally authorized by the National Science Board (NSB). GBT azimuth-track repairs were largely funded by a special allocation in FY2004 that will be fully expended in FY2006 and FY2007. Services that benefit all Observatory activities jointly and cannot be clearly attributed to an individual facility are considered common costs and are distributed to the operating facilities in proportion to the facility's fraction of the direct-cost (unburdened) budget. NRAO achieves considerable economy of scale by using shared, central staff to provide these services.

By 2011, construction projects managed by NRAO decline nearly to zero. The ALMA construction budget is part of the NSF Major Research Equipment and Facilities Construction (MREFC) line. EVLA Phase I construction is, in contrast, a component of the NSF Astronomical Sciences (AST) Division operating budget.

7.3 Maximizing Scientific Output in 2011

The NRAO operations baseline budget described in the previous section will provide for stable astronomical operation of existing facilities through 2011 but falls well short of maximizing their scientific potential. There are a number of initiatives that, at incremental cost to the baseline budget, would provide very significant scientific returns to the astronomical community. These include:

- A comprehensive end-to-end system of observer support and data archiving at the EVLA, VLBA, and GBT.

- Second-generation GBT instrumentation including large-format cameras and optimized λ = 3 mm performance.
- New research and development activities at the CDL for next-generation detector devices and digital signal-processing systems.
- Significant bandwidth expansion on the VLBA
- Expansion of the user-support stipend program.

7.3.1 End-to-End Support

The NRAO strives to make its facilities available to all professional astronomers, not only experts in radio astronomy. Progress has already been made in this direction, and the baseline budget will allow continued efforts in observation control and some pipeline analysis of data obtained using specific observing modes. A comprehensive end-to-end system that allows non-specialists to specify their observations easily and have them taken, processed, and archived automatically requires a substantial project effort that is not within the scope of the baseline budget. NRAO believes that such an effort would be of major benefit, as it would greatly facilitate the use of its facilities by astronomers not having specific experience in radio observing. Improved access would facilitate multi-wavelength observing programs that comprise the majority of present-day research projects. The creation of a fully-retrievable and value-added data archive, and substantially more active participation in the National Virtual Observatory, would allow the full integration of radio images and results with those of other disciplines of astronomy, and facilitate the type of multi-wavelength science and statistical astronomy that is becoming the expectation in the community.

7.3.2 GBT Instrumentation

The technology for large-format focal-plane arrays—bolometers and monolithic microwave integrated circuits (MMICs)—suitable for use on single-dish radio telescopes has advanced at an extremely rapid pace in recent years. It is now possible to construct bolometer cameras having up to 10,000 pixels and MMIC arrays for spectroscopy having 100–1000 elements. Wide-field observing speed increases in direct proportion to these numbers. The GBT is completing its first generation of instrumentation that includes pathfinder instruments such as the Penn Array 64-pixel bolometer camera for λ = 3 mm. Enhanced funding would allow initiation of a next generation of cameras including:

- An ~6400 pixel, λ = 3 mm bolometer camera.
- A 100+ pixel, λ = 3 mm heterodyne array for spectroscopy.
- An ~50 pixel beam-forming array for λ = 21 cm HI and pulsar observations.

Such cameras are revolutionary and would dramatically improve the scientific throughput of all NRAO facilities. For example, a large-format bolometer camera would image entire galaxy clusters exhibiting the Sunyaev-Zeldovich effect with 8 arcsecond resolution, and identify protogalaxies and protosolar nebulae for follow-up imaging by ALMA and the EVLA with high angular resolution. The heterodyne array would allow rapid identification of star-formation sites and rapid imaging of the ambient cloud morphology. The λ = 21 cm beam-forming array would make rapid surveys for pulsar detections and imaging of large-scale Galactic HI structure which would complement EVLA observations, including the required extended structure (short-spacing) data for accurate imaging. Incremental funding increases would also provide the necessary optimization of λ = 3 mm performance of the GBT so that the high-frequency instrumentation can be used with best efficiency.

7.3.3 Engineering Research and Development

Before advanced observing instruments such as those described above can be built, extensive research and development (R&D) programs are required. The NRAO's principal R&D arm is the Central Development Laboratory (CDL). The CDL has an impressive history of development that includes cryogenic mixers, low-noise amplifiers, superconductor-insulator-superconductor (SIS) devices, electromagnetic devices such as feeds and polarizers, and digital signal processing. In recent years, declining budgets have significantly squeezed R&D efforts at the CDL. As this activity provides tomorrow's technological breakthroughs for radio astronomy, a reinvigoration of the R&D program is badly needed. Incremental increases in the baseline budget would allow research into:

- New superconducting materials for high frequency and higher-T_c SIS mixers for application to sub-mm receivers (applicable to ALMA). Current Nb-based SIS mixers achieve quantum-limited performance up to the band-gap energy corresponding to ν = 700 GHz, and noise temperatures climb rapidly above that frequency. New materials have the potential to greatly improve receiver performance in the THz (λ = 0.3 mm) regime.
- MMIC technology for best performance of focal-plane array systems (applicable to GBT). Compact, multi-element spectroscopic arrays have the potential to make possible wide-field spectral-line mapping observations which at present require impractical amounts of observing time, particularly at high frequencies.
- Ultra-wideband feed and receiver components (applicable to EVLA and GBT). Observing at multiple low frequencies with current receivers, of particular interest to pulsar observers, requires swapping feeds, with consequent loss of observing time. New systems would enhance observing efficiency.

- Continuum radiometer development (applicable to ALMA and GBT total power modes). The objective is to be limited only by the sky, not the instrument.
- Highly integrated receivers, with key passive and active elements combined into unified structures (applicable to EVLA, VLBA, and GBT). At present, feeds, couplers, polarizers, isolators, and amplifiers are built separately and bolted together, resulting in systems with multiple pathways for subtle interactions and reflections which lead to unrepeatable spectroscopic baselines. In the past, higher noise temperatures, narrower bandwidths, and smaller antennas than are now common masked these effects, but the full productivity which should be associated with noise and bandwidth improvements are difficult to realize without improvements in receiver integration.

7.3.4 Bandwidth Expansion on the VLBA

Section 4.3 discussed the fact that the VLBA scientific return is limited by the fact that the instrument is "sensitivity starved", as is the current VLA. This section presented a goal of achieving 4 Gbit/s recording rate on the VLBA by 2011, which would provide 500 MHz bandwidth at each of two polarizations. In the same era, both EVLA and ALMA will have 8 GHz bandwidth at each polarization, and GBT will have a capability of up to 14 GHz bandwidth at once with the Zpectrometer. Thus, the VLBA would be behind the rest of the NRAO telescope suite in its ability to study faint sources. The issue is particularly acute for the VLBA, whose high resolution restricts it to studies of high-brightness sources.

Expansion of the VLBA bandwidth to 8 GHz in each polarization would provide a match to the EVLA for ultimate combination into the North American Array. Immediate scientific goals would include the following:

- Study of the luminosity functions of supernovae in starburst galaxies, down to luminosities near that of Cas A.
- Imaging of faint jets in radio quiet quasars, and comparison of their properties (e.g., morphology and expansion speed) to the jets in radio-loud quasars.
- Searches for direct emission from the accretion disks in low-luminosity active galactic nuclei, and for the compact radio jets predicted by models of radiatively inefficient accretion flows.
- Measurement of the structure of the Milky Way galaxy by means of pulsar astrometry at higher radio frequencies (e.g., 8 GHz instead of 1.4 GHz), where the pulsars are much weaker, in order to reduce the limiting effects of dispersion caused by the Galaxy and the Earth's ionosphere.

VLBA bandwidth expansion will require an enhancement of the VLBA intermediate frequency system to EVLA standards, improved recording capabilities, and ultimately a mechanism for real-time data transmission from the VLBA stations to a more capable correlator. Although we expect that these enhancements cannot be achieved by 2011, they should be under way in order to continue the production of forefront science by the VLBA.

7.3.5 User Stipend Program

Astronomers wishing to make extensive use of NRAO facilities are often hampered by lack of funds. Without reliable funding avenues, faculty members are often reluctant to assign their Ph.D. students to radio projects. As a trial program to help mitigate this obstacle, the NRAO has for the past three years offered support stipends to students with approved GBT observing programs. This modest program has allocated a total of about $200k in each of the past three years, distributed among about 10 students annually (the maximum stipend amount is $35k). The program has been very successful and will be extended to the VLBA at approximately $100k annually in 2006. The NRAO would like to expand this program significantly to include students using the VLA/EVLA, and eventually extend eligibility to professionals as well as students. A program of ~$800k/year would provide a reasonable start, with funds distributed among the EVLA (~$500k/yr), GBT (~$200k/yr), and VLBA (~$100k/yr). A full user-grants program, similar in scope to the Hubble Space Telescope grants program, is envisioned for ALMA.

7.3.6 Summary: Maximizing Scientific Output

In summary, for modest incremental funding, NRAO could initiate programs that would:

- Make the EVLA, VLBA, and GBT more accessible to <u>all</u> astronomers.
- Multiply the imaging speed of the GBT in key wavebands by factors of up to 1,000.
- Undertake R&D for a new generation of devices, including low-noise SIS mixers that would be effective to down to λ = 0.3 mm (up to 1 THz) for ALMA.
- Expand the bandwidth of the VLBA, improving sensitivity to faint sources by more than a factor of 10.
- Enable financial support for professional astronomers and doctoral students using the EVLA, as well as the GBT and VLBA.

7.4 Cost-Saving Options

Given the complexity and support demands of the telescope facilities it operates, the NRAO has operated under constrained budgets for many years. Several rounds of staff layoffs were required in the 1990s, and the problem once again became acute in FY2005, requiring NRAO to issue a call for volunteers for early retirement and part-time status. Thirteen staff members accepted the early retirement offer and another five moved to part-time status. This has resulted in reduced services and capabilities in a number of areas and strain on the remaining staff.

In view of the financial circumstances at the NSF, the NRAO is firmly committed to further cost savings, efficiency measures, and reductions through rigorous priority-setting. In addition, the full annual construction budget for EVLA Phase I will become available to the NSF by 2011 for competitive redistribution. This alone returns $5.5M of freed funds to the NSF beginning in FY2011.

The NRAO has examined a number of other cost savings options that include reductions in the hours of telescope operations, reduction in support and call-out services, reducing available observing bands and equipment, etc. Careful analysis of these options has shown that such measures are quite severe in their impact on science but produce relatively small annual savings. Most of the operating costs of NRAO facilities are in infrastructure maintenance and technical support of equipment and systems, so that the incremental hourly cost of scientific operations is quite small. Specific analysis of GBT, EVLA, and VLBA scenarios has shown that cutting the observing time by 50% for any telescope will save less than 10% of telescope's operating costs, since most of the savings come from items such as slightly reduced power consumption and telescope operator staffing requirements. Consequently, it is the NRAO's position that such measures offer a very poor return and should not be considered.

7.5 Closure Options

The NRAO has demonstrated in this report that each of its observing facilities is unique, state-of-the-art, and the best in its class in the world. The facilities form an integral combination that is necessary to cover the parameter space of observational astronomy. Furthermore, the existing instruments could form an extremely cost-effective backbone for a North American Array concept for the Square Kilometer Array. Closure of any of the NRAO facilities would inflict grievous harm on present-day and future astronomical research. Finally, the NRAO notes that it has already been very responsible in closing (or transferring to private parties) facilities that were no longer at the cutting edge, even if they were still producing significant scientific results. Specific facilities closed since 1999 include the:

- Green Bank Interferometer
- Green Bank 140 Foot (43 m) Telescope
- 12 Meter millimeter-wave telescope on Kitt Peak

Nevertheless, this report will respond to the request of the NSF by providing closure savings for all NRAO telescopes and laboratory facilities, including the GBT, VLA/EVLA, VLBA, and CDL.

Termination of the EVLA-I construction project was also considered, but that would likely lead to closure of the VLA as well. The VLA to EVLA conversion is already well underway; halting EVLA construction would leave mismatched systems that would make efficient operations and maintenance very difficult. Furthermore, the aging electronics technology on the VLA cannot be maintained effectively much beyond 2011. For example, the supply of spare correlator chips, which can no longer be produced, is likely to be exhausted soon after 2011. Thus, cessation of the EVLA-I project, along with wasting the EVLA investment of approximately $42M that NSF will have made by the end of FY 2006, also will most likely result in closing the VLA. In addition, it would abrogate the signed agreements between NRAO and the Canadian National Research Council, as well as between the NRAO and the Mexican CONACYT (National Council of Science and Technology), regarding joint activities on EVLA and ALMA. Closure of the VLA or termination of EVLA construction would thus have international ramifications.

Because of the economies of scale that are achieved through the unified NRAO business model, the full operating budget of a facility cannot be recouped by the closure of the facility. About 30% of the total budget of New Mexico Operations is for staff and services shared between VLA and VLBA operations. As a specific example, many of the same individuals who repaired significant rust damage at the St. Croix VLBA antenna in April 2005 then returned to New Mexico where they prepared for and executed the replacement of an azimuth bearing on a VLA antenna. If either telescope were closed, many of the shared personnel would still have to be retained in order to perform critical duties for the remaining telescope. Consequently, closure savings for either the VLA or VLBA considered singly are about 30% below direct operating costs.

Similar economies of scale exist in Observatory common services. For example, the Human Resources group has one visa specialist who, among a number of other duties, provides those services to the entire observatory. One person negotiates and maintains most of the software licenses and network services for the entire Observatory. Such staff members provide only a fraction of a full-time-equivalent (FTE) of effort to a given telescope or laboratory facility, and closure of that single facility will not eliminate the need for their services for the remaining groups. Tenured scientists often contribute to more than one facility and are in any case afforded some job protection by their employment status. In general, only a small fraction of common costs are eliminated with the closure of a single facility.

Closure of a facility must be done in an orderly way, and staff members whose positions are terminated must be paid severance costs. In the cases of long-serving employees, this can amount to nearly a year's salary. To satisfy safety and environmental requirements, the telescopes must be demolished and the sites returned to original condition. A number of staff would have to be retained to manage and carry out these requirements. The time required to effect a closure of an NRAO facility ranges from 2 to 5 years, depending on the specific facility and circumstances.

While the closure of a single NRAO facility may save annual operational funding, it is important to recognize the scientific implications of shutting down the VLBA or a new facility such as the GBT. Without the VLBA, the astronomy community would lose the unique capability of a dedicated sub-milliarcsecond imaging telescope that operates at wavelengths as short as λ = 3 mm. VLBI observations between λ = 13 mm and λ = 3 mm are required to overcome opacity effects that obscure the cores of AGN and to provide the angular resolution to image Sgr A* to within tens of Schwarzshild radii of the black hole. The distance determination using water megamasers as independent checks of the distance scale and the expansion rate of the Universe would be very difficult without the VLBA. The ability to make high-frequency images at intervals of days to weeks will be lost in practice, significantly limiting the physical understanding of the thousands of gamma-ray blazars which will be detected by GLAST. Further, the forefront science possible with astrometry at the ~10 microarcsecond accuracy level will be completely lost. The closure of VLBA also will mean giving up a $100M capital investment after just 10 years and losing the leadership in a field initiated and developed in North America.

Giving up the GBT represents the loss of an extremely sensitive and versatile 100 m radio telescope which can access 85% of the celestial sphere at frequencies from 290 MHz up to (in 2011) 115 GHz. The GBT's location in the National Radio Quiet Zone allows it to operate in portions of the spectrum which might not otherwise be available; without the GBT, the Quiet Zone, an irreplaceable scientific resource, would be lost. The astronomy community would lose the capability for sensitive studies of pulsars in the inner Galaxy and in globular clusters, and timing observations of pulsars outside the Arecibo declination range. The community would lose a sensitive instrument for the study of weak emission from interstellar bio-molecules and giant molecular clouds at all redshifts, performing Zeeman measurements of interstellar magnetic fields, or measuring extended HI clouds in the Milky Way. Closure would abandon wide-field imaging cameras which could image diffuse emission such as the SZ effect in galaxy clusters with great sensitivity and at an angular resolution of ~8". Also lost would be the clean point spread function afforded by its off-axis optics which enables high-fidelity imaging. The community would lose an instrument whose sensitivity and location make it a cornerstone of the High Sensitivity VLBI Array. Closing this facility would remove a unique opportunity for university groups developing and exploiting innovative new instruments and techniques. Lost would be an essential pathfinder for discovery of individual objects and fields for detailed follow-up with ALMA, EVLA and VLBA. Finally, similar to the VLBA, closure of the GBT would mean giving up the ~$100M capital investment in this world-class facility.

8. CONCLUSION

In 2011 the NRAO will be the premier radio observatory providing the astronomy community a remarkable suite of extremely powerful and complementary telescopes to address key astrophysical questions. The open- skies policy it has championed has promoted the best possible science over the years, has led to many important discoveries, and has been in accordance with the strong sentiment of the user community. The exceptional breadth and depth of the facilities, and the expertise and experience in radio-astronomical science and technology have taken 50 years to build up, resulting in an NRAO that is recognized by many as an essential resource for astronomy in the US, and indeed in the world.

A Senior Review of the portfolio of NSF/AST-supported facilities is a necessary process to evaluate the costs and benefits of these facilities and to prioritize spending, especially at this time of budget pressure when many worthwhile new projects are awaiting funding. However, care must be taken to avoid irreparable damage to existing US astronomy infrastructure in this process. The balance between supporting those existing facilities which give U.S. astronomy a competitive advantage and initiating new projects which will maintain that competitive position is a very delicate one.

APPENDIX A: OBSERVATORY METRICS FOR USE IN THE SENIOR REVIEW

A1. NSF Request

Appendix A provides the common set of “Observatory metrics for use in the Senior Review” requested by Dr. Eileen Friel of the NSF in her email dated 2005 July 5. The material below is extracted from her request; the primary segments of this letter correspond to the subsections of the Appendix.

Telescope Subscription Rates

These should be normalized for comparison, say by 6-month semesters. Should be presented for the last 6 to 10 years. Should be broken out by telescope within a facility.

- Number of proposals received;
  - separated by staff and non-staff PIs
  - domestic and foreign (for Gemini US and partners)
- Amount of time (by night or hours) requested;
  - separated by staff and non-staff PIs
  - domestic and foreign (for Gemini US and partners)
- Total time requested/total time available for science.

Users/Programs Supported

These should be normalized for comparison, say by 6-month semesters. Should be presented for the last 6 to 10 years. Should be broken out by telescope within a facility.

- Number of programs allocated time;
  - number of programs with non-staff PI’s
  - number of programs with observatory staff as PI’s
  - number of thesis programs
  - number with U.S. PI’s
  - number with foreign PI’s
  - Information on geographic distribution – number of states, number institutions, characterization of institution (R1, PUI, etc), if known
- Number of PI’s and PI’s + co-PI’s (sum on proposals and by individual);
- Number of students - graduate, PhD, undergraduate;
- Collaborative programs, e.g., coordinated with other observatories or space-based;
- Fraction of community served (e.g., number of users/number of AAS members associated with discipline).

Publications/Citations

Normalized by available science time with consideration that some facilities were not under full science operations during this period.

- Number of publications in peer-reviewed journals (if numbers for conferences provided, should be given separately);
    - by observatory, and by telescope
    - both staff and non-staff - led publications
      (Need to describe how papers that acknowledge more than one telescope used are counted.)
- Citations of papers using observatory data;
    - by observatory and by telescope
    - both staff and non-staff - led publications
- Other publications or citations.

Data Archive and Access

- Description of digital library and archival products and services provided to the community;
- Amount of data ingested to archive;
- Amount of data retrieved from archive;
    - If possible, characterize downloads by site
- Number of papers based on archival data, if not included in publications above.

Nature of Facility

- Are telescopes, instruments, or capability provided unique?
- Does the facility offer capabilities that are otherwise unavailable to U.S. astronomical community?

Partnerships and Service to the Community

- Software provided, and characterizations of its distribution or use
- Partnerships with universities, instrument design or fabrication
- Added value infrastructure provides to the community (e.g. tenant support)

Education and Outreach

- Number of visitors, participants in sponsored programs, tours, etc.;
- Programs sponsored, e.g., teacher enhancement, community engagement, curriculum development;
- Press releases, media events, media products or resources provided;

- Other publications, web presence and use;
- REU program – number and demographics of student participants;
- RET program – number and demographics of teacher participants;
- Other possible metrics, if available and at the discretion of the observatory;
- Cost effectiveness – normalized to operating costs, staff FTE, observing time, etc.;
- Scientific highlights;
- Development of future projects and instruments.

A2. Telescope subscription rates

A2.1 VLA Scientific Demand

Table A2.1 lists the numbers of domestic and foreign VLA proposals received annually from 1998 through 2004. The NRAO makes three calls for proposals every year. The number of proposals received and the amount of time requested each year are measures of scientific demand. Some variability arises because only three of the four VLA configurations are scheduled in any given year and "Large Proposal" deadlines do not occur annually. Proposals requesting the VLA as part of a VLBI array are not included in these totals; typically about 10%–15% of the VLBA proposals at a given deadline request the phased VLA, and another 10% request a single VLA antenna to help with imaging of extended emission. Domestic and foreign Principal Investigators (PIs) have been tracked separately only since 2002. More detailed data distinguishing between staff and non-staff PIs or tracking the countries/institutions of PIs have not generally been kept. However, such data were derived from all NRAO telescope proposals for the trimester whose deadline was February 1, 2005, and they are reported in Section A2.4 below.

The columns in Table A2.1 list:

1. Calendar year.
2. Total number of "normal" VLA proposals (excluding VLBI proposals, "large" proposals, Exploratory proposals, or target-of-opportunity [ToO] proposals) received.
3. Number of normal proposals from domestic PIs.
4. Number of normal proposals with foreign-based PIs.
5. Number of hours requested by "normal" proposals. Large time requests by the FIRST legacy survey in 1998 and 1999 are not included.
6. Number of Exploratory and ToO proposals (new categories starting in late 2003, not applicable [NA] before 2004).

Table A2.1. VLA Scientific Demand by Observing Year, 1998-2004

(1)	(2)	(3)	(4)	(5)	(6)
Year	**# Normal Proposals**	**# Prop- US PI**	**# Prop- Foreign PI**	**# Hrs Requested**	**Exploratory/ToO Proposals**
2004	414	209	205	12,900	36
2003	426	227	199	15,600	NA
2002	380	213	167	13,100	NA
2001	345	NA	NA	15,000	NA
2000	449	NA	NA	11,100	NA
1999	413	NA	NA	11,000+FIRST	NA
1998	368	NA	NA	10,100+FIRST	NA

A2.2 VLBA Scientific Demand

Table A2.2 lists comparable data for the VLBA. The numbers include all proposals requesting the VLBA alone or combined with other ground-based telescopes such as the GBT, the phased VLA, Effelsberg, the High Sensitivity Array (2004 only), and the European VLBI Network. From 1997 through 2000, the VLBA was the key ground facility in the VLBI Space Observatory Program (VSOP) whose proposals were submitted separately to the Japanese Institute of Space and Astronautical Science. The numbers of proposals and hours cited below do not include those requested through VSOP calls for proposals, which typically resulted in about 50 proposals requesting more than 1,000 hours per year of VLBA time annually.

Table A2.2 VLBA Scientific Demand by Observing Year, 1998-2004

(1)	(2)	(3)	(4)	(5)	(6)
Year	**# Normal Proposals**	**# Prop- US PI**	**# Prop- Foreign PI**	**# Hrs Requested**	**Exploratory/ToO Proposals**
2004	219	82	137	6,800	14
2003	182	79	103	6,900	NA
2002	179	81	98	8,200	NA
2001	191	NA	NA	9,200	NA
2000	210+VSOP	NA	NA	8,100+VSOP	NA
1999	195+VSOP	NA	NA	6,900+VSOP	NA
1998	202+VSOP	NA	NA	8,200+VSOP	NA

A2.3 GBT Scientific Demand

Table A2.3 gives proposal statistics for the GBT from 2001 through 2004. The proposal count for 2001 is from a single call for “first science” proposals. Proposal calls prior to 2005 were restricted to allow time for commissioning the new telescope and receivers, especially in 2003, and steady-state demand will probably not be reached until 2006 or 2007. We anticipate that the percentage of foreign PIs will rise as remote observing becomes routine. Proposals requesting the GBT as part of a VLBI array are not included in these totals. About 15% to 20% of the VLBI proposals at a given deadline request use of the GBT.

Table A2.3 GBT Scientific Demand by Observing Year, 2001-2004

(1)	(2)	(3)	(4)	(5)	(6)
Year	**# Normal Proposals**	**# Prop-US PI**	**# Prop-Foreign PI**	**# Hrs Requested**	**Exploratory/ToO Proposals**
2004	150	114	36	6,500	12
2003	113	86	27	3,300	NA
2002	161	123	38	9,500	NA
2001 (1st call)	79	61	18	6,300	NA

A2.4 Detailed Proposer Statistics from the February 1, 2005 Proposal Deadline

Detailed statistics describing affiliations and nationalities of PIs and their co-investigators (CoIs) submitting proposals for the trimester following the February 1, 2005 deadline were developed for the VLA, VLBA, and GBT. They are representative except that the VLA deadline was for the “C” configuration, which is more lightly subscribed than the higher-resolution “A” and “B” configurations and is therefore allocated proportionally less observing time.

Individual nationalities were defined by primary institutional affiliations. Investigators listing joint affiliations on their proposals were counted as 50% at each institution. The numbers of PhD students could not be determined reliably from the proposals. About 10% of the observers on NRAO telescopes are students at various levels.

Table A2.4 gives the detailed statistics for the February 1, 2005 deadline. Definitions of the rows are:

1. Total number of proposals received. VLBI proposals include all varieties of proposals including the VLBA, while VLA and GBT proposals do not include the VLBI proposals that also request use of those telescopes.
2. Number of US Principal Investigators (PIs), and percentage of total.
3. Number of US PIs based at universities, and percentage of total.
4. Number of US PIs based at the NRAO (including postdocs), and percentage of total.
5. Number of US PIs based at government labs or at other observatories (e.g., NRL, JPL, STScI, NASA/Goddard), and percentage of tota.l
6. Number of PIs based in Canada, and percentage of total.
7. Number of PIs based in Mexico, and percentage of total.
8. Number of PIs based in Europe, and percentage of total.
9. Number of PIs based in Japan, and percentage of total.
10. Number of PIs based in Asia outside Japan (e.g., China, Korea), and percentage of total.
11. Number of PIs in other countries (e.g., Australia, South Africa, Chile), and percentage of total.
12. Number of proposals with a US-based investigator either as PI or Co-Investigator (CoI), and percentage of the total number of proposals including a US investigator.
13. Total number of CoIs.
14. Total number of US-based CoIs, and percentage of the total number of CoIs.
15. Total number of US university CoIs, and percentage of the total.
16. Total number of NRAO CoIs, and percentage of the total.
17. Total number of US lab/other observatory CoIs, and percentage of the total.
18. Total number of Canadian CoIs, and percentage of the total.
19. Total number of Mexican CoIs, and percentage of the total.
20. Total number of European CoIs, and percentage of the total.
21. Total number of Japanese CoIs, and percentage of the total.
22. Total number of other Asian CoIs, and percentage of the total.
23. Total number of other CoIs, and percentage of the total.
24. Average number of investigators per proposal.

Table A2.4 Affiliations of Proposers for the February 1, 2005 Deadline

		VLA	VLBI	GBT
(1)	Total Proposals	106	71	42
(2)	US PIs	57.5 (54.2%)	33 (46.5%)	32 (76.2%)
(3)	US University PIs	36 (34.0%)	10 (14.1%)	20 (47.6%)
(4)	NRAO PIs	6 (5.7%)	12 (16.9%)	6 (14.3%)
(5)	US Lab/Observatory PIs	15.5 (14.6%)	11 (15.5%)	6 (14.3%)
(6)	Canadian PIs	0 (0%)	1 (1.4%)	4 (9.5%)
(7)	Mexican PIs	2.5 (2.4%)	2 (2.8%)	0 (0%)
(8)	European PIs	37 (34.9%)	18 (25.4%)	5 (11.9%)
(9)	Japanese PIs	1 (0.9%)	9 (12.7%)	0 (0%)
(10)	Other Asian PIs	8 (7.5%)	6 (8.5%)	1 (2.4%)
(11)	Other PIs	0 (0%)	2 (2.8%)	0 (0%)
(12)	# prop. w/ US PI/CoI	80 (75.5%)	49 (69.0%)	41 (97.6%)
(13)	Total Co-Investigators	316	224	152
(14)	Total US CoI	142.5 (45.1%)	110.5 (49.3%)	82 (53.9%)
(15)	US University CoI	65 (20.6%)	46 (20.5%)	40 (26.3%)
(16)	NRAO CoI	30 (9.5%)	37 (16.5%)	17 (11.2%)
(17)	US Lab/Observatory CoI	47.5 (15.0%)	27.5 (12.3%)	25 (16.4%)
(18)	Canadian CoI	6 (1.9%)	1 (0.4%)	17 (11.2%)
(19)	Mexican CoI	5 (1.6%)	8 (3.6%)	1 (0.7%)
(20)	European CoI	146 (46.2%)	74 (33.0%)	43 (28.3%)
(21)	Japanese CoI	0 (0%)	12 (5.4%)	1 (0.7%)
(22)	Other Asian CoI	10 (3.2%)	13.5 (6.0%)	4 (2.6%)
(23)	Other CoI	7 (2.2%)	5 (2.2%)	4 (2.6%)
(24)	Investigators/Proposal	3.98	4.15	4.62

A2.5 Total Science Time Available

All NRAO telescopes observe day and night and in almost all weather conditions, with shutdowns only for the Thanksgiving, Christmas, and New Year's holidays (typically 24–36 hours each) and for scheduled maintenance. Peer-reviewed scientific programs typically receive about 4,500 successful observing hours per year on the VLBA and almost 7000 on the VLA. As the GBT has moved from commissioning to routine observing, the annual science time has increased from 400 hours in 2001 to 4,700 hours in 2004. The VLBA is dynamically scheduled so that it makes optimum use of the best weather, while the VLA and GBT have forms of contingency scheduling, selecting between paired high- and low-frequency programs to match current weather conditions. The total numbers of hours available are comparable with those of Spitzer and Chandra (about 6,000 hours per year), higher than the HST (about 4,000 hours per year) and much higher than all ground-based optical telescopes. For example, an optical telescope that observes for 10 hours per night on 365 days per year, with a hardware plus weather reliability of 75%, would have 2,555 hours of scientific observing available each year.

Table A2.5 shows the amount of successful scientific observing time, after subtracting down time, for each NRAO telescope over the last several years. For interferometers, these numbers are scaled by fractional antenna availability. For example, a 1 hour VLA observation with 2 of the 27 antennas missing is counted as 0.926 hours of successful observing.

Table A2.5 Hours of Successful Observing per Year for NRAO Telescopes

Year	VLA	VLBA	GBT
2004	6,728	4,494	4,671
2003	6,508	4,588	3,496
2002	6,546	4,485	2,237
2001	6,620	4,626	408
2000	5,789	4,172 (with VSOP)	NA
1999	5,622	4,854 (with VSOP)	NA
1998	6,272	5,352 (with VSOP)	NA

A2.6 Ratio of Time Requested to Total Science Time Available

The ratio of time requested to time available for science is not well defined for an individual year since, for example, a VLBA observation made in 2004 may result from a multi-epoch observing proposal submitted in 2001. Averaging over a number of years, the ratio for the VLA is typically 2:1 and rises to well above 4:1 at popular right ascensions in some configurations. The typical VLBA ratio is in the range of 1.5:1 to 2:1. The GBT ratio is very high but has not yet reached a steady state. In any case, the ratio of time requested to time available for science is a poor measure of scientific demand. Dividing scientific demand (time requested) by operational efficiency (time available for science) inappropriately downgrades any facility having high operational efficiency (reliable instrumentation, good sites, and efficient dynamic scheduling).

A3. Users/Programs Supported

This section gives the numbers of programs actually observed with the VLA, VLBA, and GBT annually since 1998. The total number of programs observed in a given year with the VLA or VLBA typically is about 33% higher than the total number of proposals accepted in a given year because multi-epoch VLBA programs and multi-configuration VLA programs often stretch across more than one calendar year. We can show fairly complete statistics for PIs but only a few representative numbers for all investigators (Principal Investigators plus co-Investigators). However, the percentage distributions of co-investigators by institutional and national origins are roughly the same as those of principal investigators. We note that about 85% to 90% of the U.S. universities are major research universities (e.g., Caltech, Cornell, University of Illinois) and about 10% are smaller institutions stressing undergraduate education (e.g., Agnes Scott College, Haverford, Bucknell). The numbers of student observers probably are uncertain at the 10%–20% level each year since the NRAO cannot reliably track their graduation dates.

A3.1 VLA Observing Programs

Table A3.1 summarizes all scheduled VLA observing programs for the calendar years 1998 through 2004. The total number of programs with observing time in any year is about 33% higher than the number of proposals accepted for that year because some programs stretch across multiple years. Rows (1) through (11) of Table A3.1 give statistics for the PI-led programs proposed directly to the VLA. Rows (12) through (18) give total statistics that include all programs in rows (1) through (11) plus programs that use the VLA as a phased array. Programs that include only a single VLA antenna in a VLBI observation are not listed Table A3.1. The total number of institutions for 2002 is anomalously low, apparently owing to the accidental omission of some institutions from the annual observing statistics.

The columns for Table A3.1 are defined as follows:

1. Total number of different programs having observing time during a calendar year, with all observing tracks coming from a single proposal counted as a single program.
2. Number of different Principal Investigators (PIs) who observed during a calendar year.
3. Number of different institutions that had a PI observe during a calendar year.
4. Number of different countries that had a PI observe during a calendar year.
5. Number of different PIs associated with U.S. institutions.
6. Number of different PIs affiliated with the NRAO.
7. Number of different “states” (including the 50 states, Puerto Rico, and the District of Columbia) with PIs who observed during the calendar year.
8. Number of different US universities with PIs observing during the calendar year.
9. Number of different US institutions (includes universities, the NRAO, and other institutions) with PIs observing during the year.
10. Number of different PIs affiliated with foreign institutions.

11. Number of different foreign institutions with at least one PI.
12. Number of additional programs in which the VLA is used as a phased-array VLBI telescope.
13. Total number of different observers, counting all PIs and co-investigators.
14. Total number of different institutions, counting all PIs and co-investigators.
15. Total number of different US states with at least one PI or co-investigator who observed during a calendar year.
16. Number of different US universities with at least one PI or co-investigator during a calendar year.
17. Number of different US institutions with at least one PI or co-investigator during a calendar year.
18. Number of different students who observed during a calendar year.

Table A3.1 VLA Observing Programs, 1998-2004

	Item	**2004**	**2003**	**2002**	**2001**	**2000**	**1999**	**1998**
(1)	# Stand-alone Programs	330	312	336	312	327	319	342
(2)	# Different PIs	228	228	232	221	246	231	253
(3)	# Different Institutions w/ PIs	108	115	112	105	109	101	113
(4)	# Different Countries w/ PIs	18	21	21	23	21	20	22
(5)	# Different US PIs	122	121	124	117	135	120	130
(6)	# Different NRAO PIs	19	20	18	21	26	21	22
(7)	# Different US States w/ PIs	23	24	22	21	26	19	22
(8)	# Different US Univ. w/ PIs	40	38	41	34	43	43	38
(9)	# Different US Inst. w/ PIs	51	54	53	48	57	49	50
(10)	# Different Foreign PIs	106	107	108	104	111	111	123
(11)	# Different Foreign Inst. w/ PIs	57	61	59	57	52	52	63
(12)	# Additional VLBI Programs	14	17	11	25	35	53	56
(13)	Total # Different Observers	758	847	731	711	777	662	640
(14)	Total # Different Institutions	211	205	>150	176	187	179	170
(15)	Total # Different US States	31	33	29	29	31	27	26
(16)	Total # Different US Univ.	57	63	54	58	66	59	53
(17)	Total # Different US Inst.	78	93	70	74	86	81	73
(18)	Total # Different Students	63	86	79	69	82	96	74

A3.2 VLBA Observing Programs

Table A3.2 gives the total numbers of VLBA observers for the calendar years 1998 through 2004, broken down as for the VLA. It includes all VLBI observations using the VLBA, either by itself or in combination with a wide variety of other telescopes, including the VSOP Space VLBI satellite (1998–2002). As for the VLA, the total number of institutions (row 14) is anomalously low in 2002, probably because of omissions in the annual observing statistics. The rows for Table A3.2 have the same definition as the rows for Table A3.1.

Table A3.2 VLBA Observing Programs, 1998-2004

	Item	**2004**	**2003**	**2002**	**2001**	**2000**	**1999**	**1998**
(1)	# Stand-alone Programs	177	185	186	195	189	200	213
(2)	# Different PIs	120	113	129	139	126	132	139
(3)	# Different Institutions w/ PIs	77	65	62	65	61	60	61
(4)	# Different Countries w/ PIs	16	18	19	19	14	13	20
(5)	# Different US PIs	53	56	67	62	55	68	66
(6)	# Different NRAO PIs	11	14	21	17	10	23	18
(7)	# Different US States w/ PIs	17	12	16	15	14	16	14
(8)	# Different US Univ. w/ PIs	24	18	22	19	20	23	16
(9)	# Different US Inst. w/ PIs	34	28	31	30	22	26	29
(10)	# Different Foreign PIs	67	57	62	77	71	64	73
(11)	# Different Foreign Inst. w/ PIs	43	37	31	35	39	34	32
(12)	# Additional VLBI Programs	NA	NA	NA	NA	NA	NA	NA
(13)	Total # Different Observers	435	400	342	432	381	352	332
(14)	Total # Different Institutions	144	122	>82	114	112	96	91
(15)	Total # Different US States	26	23	20	20	19	17	21
(16)	Total # Different US Univ.	45	38	32	32	29	33	31
(17)	Total # Different US Inst.	65	51	45	50	43	48	47
(18)	Total # Different Students	36	45	47	39	45	50	44

A3.3 GBT Observing Programs

Table A3.3 gives the total number of GBT observers for calendar years from 2001 through 2004. Rows (1) through (11) are counts of PI-led programs submitted directly to the GBT, whereas rows (12) through (18) add the additional programs that incorporated the GBT as an element of a VLBI array. Note the substantial increases in numbers of programs and observers through 2004, as the GBT has been moving from commissioning to routine scientific observing.

Table A3.3 GBT Observing Programs, 2001-2004

	Item	2004	2003	2002	2001
(1)	# Stand-alone Programs	136	88	42	9
(2)	# Different PIs	95	55	29	7
(3)	# Different Institutions w/ PIs	48	32	17	6
(4)	# Different Countries w/ PIs	9	6	3	1
(5)	# Different US PIs	76	45	26	7
(6)	# Different NRAO PIs	12	12	9	2
(7)	# Different US States w/ PIs	17	16	11	6
(8)	# Different US Univ. w/ PIs	19	16	10	3
(9)	# Different US Inst. w/ PIs	30	24	15	6
(10)	# Different Foreign PIs	19	10	3	0
(11)	# Different Foreign Inst. w/ PIs	18	8	2	0
(12)	# Additional VLBI Programs	22	16	16	0
(13)	Total # Different Observers	332	247	148	20
(14)	Total # Different Institutions	105	88	55	13
(15)	Total # Different US States	21	25	16	8
(16)	Total # Different US Univ.	37	35	20	5
(17)	Total # Different US Inst.	55	51	29	10
(18)	Total # Different Students	29	25	12	2

A3.4 Collaborative Programs

Many programs use the NRAO jointly with other major observatories. For example, several Spitzer Legacy programs have been granted large amounts of observing time on the VLA and the GBT. Most of these programs went through the NRAO Large Proposal process or were refereed as individual “normal” proposals, as the NRAO generally has responded to PI proposal pressure rather than favoring particular science areas. Recent large VLA programs include radio imaging of the HST COSMOS survey area, follow-ups to gamma-ray bursts detected with Swift, and the Spitzer First Look Survey.

There are currently two institutional collaborations through which a fraction of NRAO telescope time may be allocated either to Chandra or to Spitzer for proposals submitted to those space missions. The Chandra program has been in operation for several years; Chandra typically receives 25–30 joint VLA proposals (more than for joint observations with HST or any other facility) and several VLBA proposals. In the future, we expect a major VLBA collaborative program with the Gamma-ray Large Area Space Telescope (GLAST).

A3.5 Fraction of Community Served

The NRAO strives to be an observatory for all astronomers, not just expert radio astronomers. Many NRAO users are primarily optical, infrared, or X-ray astronomers, or do not identify themselves with any specific wavelength regime. The AAS has about 7,000 members, about half of whom are active researchers (defined as publishing at least one refereed paper per year). If 10%–15% of U.S. astronomers are “radio astronomers,” there are about 400–600 active radio astronomers in the U.S. From the numbers in Tables A2.1, A2.2, and A2.3, we estimate that there are about 400 U.S. VLA observers per year, 200 U.S. VLBA observers per year, and 200 U.S. GBT observers per year. Based on these very rough numbers, it appears that the VLA serves 50% or more of the U.S. radio astronomers in any year (after accounting for the non-radio astronomers), while the VLBA and the GBT each serve 30% or more of the U.S. radio astronomers annually.

The executive summary of “Astronomy and Astrophysics in the New Millennium” (AANM 2001) noted that the NRAO serves as an “effective” national organization for radio astronomy. The 2001 Panel on Radio and Submillimeter-wave Astronomy reported:

> The radio astronomy community is proud of the national radio astronomy centers. At centimeter wavelengths, the National Radio Astronomy Observatory (NRAO) and the National Astronomy and Ionosphere Center (NAIC) lead the world, and U.S. astronomers rely almost entirely on them for telescope access. (AANM 2001)

A4. Publications/Citations

This section summarizes the annual numbers of refereed publications and citations involving data from NRAO telescopes during the years 1998–2004. The national and institutional affiliations of first authors and co-authors are similar to those for observing programs (Section A3), so similar statistics are not provided here. We do list the numbers of refereed publications by journal. All publications that make use of original data from the VLA, VLBA, and GBT are included, regardless of whether or not the papers also include data from other telescopes. In particular, papers that use the VLA as part of a VLBI array including the VLBA appear in both the VLA paper counts and the VLBA paper counts. NRAO postdoctoral fellows are counted as NRAO first authors, while pre-doctoral fellows are counted as non-NRAO authors from their home institutions.

Note that the GBT has been coming into full science operation during the last several years. Based on the time lags observed for the VLA and VLBA, we expect the GBT to reach a steady state in publication rate in about 2007.

A4.1 Refereed VLA Publications

Table A4.1 summarizes the refereed VLA publication rate from 1998 through 2004. The rows list:

1. Total number of refereed publications.
2. Number of publications with NRAO staff (including postdocs) as first author.
3. Number of papers in the Astrophysical Journal.
4. Number of papers in the Astrophysical Journal Letters.
5. Number of papers in the Astrophysical Journal Supplements.
6. Number of papers in the Astronomical Journal.
7. Number of papers in the Monthly Notices of the Royal Astronomical Society.
8. Number of papers in Astronomy and Astrophysics.
9. Number of Papers in Icarus.
10. Number of papers in Nature.
11. Number of papers in Science.
12. Number of papers in other professional journals (e.g., PASP, PASJ, IEEE, Radio Science, Phys. Rev.).

Table A4.1 Refereed VLA Publications by year: 1998-2004

	Item	2004	2003	2002	2001	2000	1999	1998
(1)	# Refereed Papers	176	157	165	177	167	194	163
(2)	# Papers w/ NRAO 1st authors	8	7	13	20	16	18	12
(3)	# ApJ papers	50	55	65	56	51	63	35
(4)	# ApJL papers	12	12	11	22	16	17	18
(5)	# ApJS papers	9	3	4	3	5	8	7
(6)	# AJ papers	24	22	24	33	27	33	27
(7)	# MNRAS papers	31	23	21	24	23	27	27
(8)	# A&A papers	33	26	34	24	32	25	33
(9)	# Icarus papers	2	5	2	3	0	2	2
(10)	# Nature papers	2	3	2	4	1	4	2
(11)	# Science papers	1	1	0	1	1	0	0
(12)	# Other journal papers	12	7	2	7	11	15	12

A4.2 Refereed VLBA Publications

Table A4.2 lists the numbers of VLBA publications in each year from 1998 through 2004. The breakdown of the papers and the definition of the rows are identical to those for the VLA in Table A4.1

Table A4.2 Refereed VLBA Publications by year: 1998-2004

	Item	**2004**	**2003**	**2002**	**2001**	**2000**	**1999**	**1998**
(1)	# Refereed Papers	62	57	48	73	74	50	58
(2)	# Papers w/ NRAO 1st authors	8	11	5	11	10	9	9
(3)	# ApJ papers	22	28	18	23	24	15	18
(4)	# ApJL papers	3	7	3	11	4	7	10
(5)	# ApJS papers	1	0	2	3	3	2	1
(6)	# AJ papers	11	3	7	8	3	7	5
(7)	# MNRAS papers	7	7	3	10	4	4	7
(8)	# A&A papers	14	9	9	10	24	9	13
(9)	# Icarus papers	0	0	0	0	0	0	0
(10)	# Nature papers	0	0	2	2	0	2	2
(11)	# Science papers	2	1	0	2	1	0	1
(12)	# Other papers	2	2	4	4	11	4	1

A4.3 Refereed GBT Publications

Since the GBT is just coming on-line, the first GBT publications appeared in 2002, as indicated in Table A4.3. The number of publications is rising sharply and should reach a steady state around 2007.

Table A4.3 Refereed GBT Publications by year: 2002-2004

	Item	**2004**	**2003**	**2002**
(1)	# Refereed Papers	24	3	2
(2)	# Papers w/ NRAO 1st authors	3	2	1
(3)	# ApJ papers	7	0	0
(4)	# ApJL papers	13	1	2
(5)	# ApJS papers	1	1	0
(6)	# AJ papers	0	0	0
(7)	# MNRAS papers	1	0	0
(8)	# A&A papers	0	0	0
(9)	# Icarus papers	0	0	0
(10)	# Nature papers	0	0	0
(11)	# Science papers	1	1	0
(12)	# Other papers	1	0	0
(13)	# Unrefereed papers	7	5	1

A4.4 Citations

Papers published in 2003 and 2004 are too new to have meaningful citation rates. Since almost all GBT papers have been published since the beginning of 2004, there is not yet a useful citation statistic for the GBT. The NRAO does not track citations to its papers, so we have used the Astrophysical Data System (ADS) to determine the numbers of citations, as of mid-July 2005, of refereed papers using the VLA and VLBA in 1998 and 1999. The results are given in Table A4.4.

Table A4.4 Citations to Refereed VLA and VLBA Papers

	VLA-1999	VLA-1998	VLBA-1999	VLBA-1998
# Papers	194	163	50	58
# with at least 100 citations	2	3	1	3
# with 80-99 citations	1	4	2	1
# with 60-79 citations	5	7	0	2
# with 50-59 citations	7	5	1	4
# with 40-49 citations	10	8	2	4
# with 35-39 citations	8	6	0	5
# with 30-34 citations	13	11	4	5
# with 25-29 citations	11	6	3	2
# with 20-24 citations	19	15	7	9
# with 15-19 citations	21	15	8	6
# with 10-14 citations	32	25	5	9
# with 5-9 citations	34	35	10	3
# with 0-4 citations	31	23	7	5
Total # citations	4,082	4,553	1,085	1,818
Mean # citations/paper	21.0	27.9	21.7	31.3
# Papers with NRAO PI	18	12	9	9
# citations for NRAO PIs	417	1,250	328	400
Mean citations, NRAO PIs	23.1	104.2	36.4	44.4
# Papers, non-NRAO PI	176	151	41	49
# Citations, non-NRAO PI	3,665	3,303	757	1,418
Mean citations, non-NRAO	20.8	21.9	18.5	28.9

Table A4.5 Most-cited Papers from the VLA, 1998–1999

No. Citations	Reference
892	Condon et al. “The NRAO VLA Sky Survey.” 1998, AJ, 115, 1693
259	Kulkarni et al. “The Afterglow, Redshift, and Extreme Energetics of the Gamma-ray Burst of 23 January 1999.” 1999, Nature, 398, 389
152	Mirabel et al. “Accretion Instabilities and Jet Formation in GRS 1915+105.” 1998, A&A, 330, L9
139	Smail et al. “The Discovery of ERO Counterparts to Faint Submillimetre Galaxies.” 1999, MNRAS, 308, 1061
119	Richards et al. “Radio Emission from Galaxies in the Hubble Deep Field.” 1998, AJ, 116, 1039
92	Best et al. “HST, Radio and Infrared Observations of 28 3CR Radio Galaxies at Redshift z~1—II. Old Stellar Populations in Central Cluster Galaxies.” 1998, MNRAS, 295, 549
90	Junor et al. “Formation of the Radio Jet in M87 at 100 Schwarzschild Radii from the Central Black Hole.” 1999, Nature, 401, 891
89	Owsianik & Conway. “First Detection of Hotspot Advance in a Compact Symmetric Object. Evidence for a Class of Very Young Extragalactic Radio Sources.” 1998, A&A, 337, 69
83	Van Zee et al. “Neutral Gas Distributions and Kinematics of Five Blue Compact Dwarf Galaxies.” 1999, AJ, 116, 1186
76	Biggs et al. “Time Delay for the Gravitational Lens System B0218+357.” 1999, MNRAS, 304, 349

Table A4.5 gives the references to the ten most-cited papers from the VLA in 1998 and 1999, while Table A4.6 gives similar information for the VLBA. Note that two papers appear in both lists, an indication of the synergy between the VLA and the VLBA. (In these two cases, the phased VLA was used as part of a VLBI array with the VLBA.)

Table A4.6 Most-cited Papers from the VLBA, 1998–1999

No. Citations	Reference
135	Kellermann et al. "Sub-Milliarcsecond Imaging of Quasars and Active Galactic Nuclei." 1998, AJ, 115, 1295
115	Herrnstein et al. "A Geometric Distance to the Galaxy NGC 4258 from Orbital Motions in a Nuclear Gas Disk." 1999, Nature, 400, 539
107	Wardle et al. "Electron-Positron Jets Associated with the Quasar 3C279." 1998, Nature, 395, 457
100	Smith et al. "A Starburst Revealed – Luminous Radio Supernovae in the Nuclei of Arp 220." 1998, ApJL, 493, L17
98	Reid et al. "The Proper Motion of Sagittarius A*. I. First VLBA Results." 1999, ApJ, 524, 816
90	Junor et al. "Formation of the Radio Jet in M87 at 100 Schwarzschild Radii from the Central Black Hole." 1999, Nature, 401, 891
89	Owsianik & Conway. "First Detection of Hotspot Advance in a Compact Symmetric Object. Evidence for a Class of Very Young Extragalactic Radio Sources." 1998, A&A, 337, 69
72	Smith et al. "The Starburst-AGN Connection. II. The Nature of Luminous Infrared Galaxies as Revealed by VLBI, VLA, Infrared, and Optical Observations." 1998, ApJ, 492, 137
71	Hirabayashi et al. "Overview and Initial Results of the Very Long Baseline Space Observatory Programme." 1998, Science, 281, 1825
59	Owsianik et al. "Renewed Radio Activity of Age 370 Years in the Extragalactic Source 0108+388." 1998, A&A, 336, L37

A5. Data Archive and Access

For a number of years, the NRAO has maintained complete VLA and VLBA data archives on tape. However, accessing them required finding the data via an on-line search engine, then requesting that the data be downloaded manually and sent from the NRAO.

In mid-October 2003 a fully on-line VLA data archive was opened for general use, with the data resident on a hard-disk array for fast access. Archive users can transfer unlimited amounts of non-proprietary archive data to an ftp site and download the data by anonymous ftp. Proprietary data (with the proprietary period changed from 18 months to 12 months beginning at the October 2003 proposal deadline) may be accessed similarly only by members of proposal teams, who must use a specially created password "key" to transfer the data to the ftp site and to download it. To date, slightly more than half of the download volume (and well over half of the files) from the archives have been of non-proprietary data, while the remaining downloads have been proprietary data being accessed by the observing teams. The total size of the VLA archive is about 4 Terabytes, and an amount of data roughly equal to the total VLA archive size has been downloaded in the 21 months since the on-line archive was released. A mirror of the on-line archive for VLA now is available at the National Center for Supercomputing Applications (NCSA), with VLBA and GBT data gradually being filled in to the NCSA.

At present, the on-line archive contains all raw VLA data going back to 1976, raw VLBA data going back to September 1999, some calibrated VLBA data, and some GBT data from July 2002 through October 2004. A pilot project is under way to calibrate and image a small subset of data from the VLA archive, and to make these images available via the National Virtual Observatory along with the uncalibrated data. Completion of this pilot project is expected in late 2005 or early 2006, and we will use the results to assess the possibilities for generating images from and making available a much larger subset of the invaluable VLA archive.

Statistics of archive use are given below in Table A5.1; more than 90% of the downloads are of VLA archive data.

Table A5.1 NRAO On-Line Archive Characteristics

Total On-Line Archive Size	19 Tbytes
VLA On-Line Archive Size	4 Tbytes
VLBA On-Line Archive Size	13 Tbytes
GBT On-Line Archive Size	1 Tbyte
Other Data (e.g., Large Surveys)	1 Tbyte
Files Downloaded since October 2003 (mostly VLA)	25,000 files
Data Amount Downloaded since October 2003	4 Tbytes (50%-60% public data)
Archive Users since October 2003	700+ users from 250+ institutions
Current File Download Rate	1,600 data files per month
Current Data Download Rate	> 200 Gbytes per month

The NRAO has attempted since 2000 to monitor publications that are based on archival data. We expect the numbers of archival publications to climb in the future as users “digest” more of the archive data and as we become better at identifying publications. Table A5.2 gives the numbers of refereed papers that we have identified in the past several years that make use of archival (non-proprietary) data from the VLA and VLBA. These numbers are very much lower limits since there is not yet a foolproof system for identifying the use of archival data in papers.

Table A5.2 Refereed Publications from VLA and VLBA Archives, 2000-2004

Telescope	2000	2001	2002	2003	2004
VLA	4	17	25	13	23
VLBA	0	0	1	1	2

The large VLA "legacy" sky surveys FIRST (Faint Images of the Radio Sky at Twenty cm) and the NVSS (NRAO VLA Sky Survey) were made as a service to the astronomical community. All of their final images and source catalogs are available via web sites which provide postage-stamp servers, catalog browsers, and other fully reduced data in convenient form. These "virtual radio observatories" are linked to the U.S. National Virtual Observatory (NVO), the NASA/IPAC Extragalactic Database (NED), and similar multiwavelength data services. Because of the use of the FIRST and NVSS data, the two primary FIRST papers and the primary NVSS paper have been cited 651 and 892 times, respectively.

A6. Nature of Facilities

The GBT, VLA/EVLA, and VLBA all are unique facilities, each the world leader of its type. Their unique observational characteristics are summarized in Sections A6.1 through A6.3 below.

A6.1 Unique GBT Characteristics

- Largest fully-steerable single-dish telescope in the world.
- The only large telescope having an unblocked aperture.
- Large sky coverage and low elevation limit makes 87% of the entire celestial sphere accessible and allows long observations for monitoring transient events, pulsar timing, and VLBI.
- Low-RFI environment owing to terrain shielding and the National Radio Quiet Zone, allowing unique HI and pulsar observations. This offers access to frequencies which might not otherwise be observable, greater sensitivity for continuum and pulsar observations, and greater opportunity to observe spectral lines both at rest and redshifted throughout the spectrum.
- Highest pulsar sensitivity of any fully-steerable telescope.
- Continuous frequency coverage from 290 MHz–52 GHz (current), to 115 GHz (target).

- Largest effective collecting area (~$2,000 m^2$) and focal plane capable of accepting array cameras having thousands of pixels at $\lambda = 3$ mm.
- Possibly the best imaging capability of any single-dish radio facility owing to the offset optics; high-fidelity wide-field HI imaging capability.
- The large diameter (in wavelengths) of the 100 m filled aperture results in a unique combination of high point-source sensitivity, high angular resolution, and high sensitivity to extended, low-surface-brightness emission.

A6.2 Unique VLA/EVLA Characteristics

- Only connected-element interferometer with 27 antennas (the next in number is Westerbork with 14, and the number of baselines sampled is proportional to N^2) and excellent instantaneous two-dimensional aperture-plane coverage enabling good snapshot imaging.
- Well-sampled frequency coverage from 1 to 50 GHz, evolving to complete frequency coverage by 2010.
- Sampling of angular scales from 50 milliarcseconds through many arcminutes by means of the wide wavelength span and the use of four different “normal” configurations plus three “hybrid” configurations having long north arms that enable circular aperture-plane sampling for southern sources.
- Sky coverage ranging from the North Pole (90 degrees declination) to –47 degrees declination, including 85% of the sky.
- Scientific observing day and night, year-round on a high (2,100 meters or 7,000 feet) dry site.

A6.3 Unique VLBA Characteristics

- Only full-time astronomical imaging instrument capable of imaging faint, complex sources with sub-milliarcsecond resolution.
- Only VLBI instrument with antenna locations designed for optimal imaging capability over a wide variety of scales, rather than a haphazard sampling distribution based on pre-existing antennas.
- Only VLBI instrument that can repeat identical observations on time scales from days to years, which enables sampling of the evolution of many varieties of radio sources over a wide range of linear and temporal scales.
- Only VLBI instrument with identical, commonly calibrated antenna and telescope systems, facilitating the production of images with high dynamic range.
- Time sampling and common calibration permit both global and local astrometry, with accuracies better than 10 microarcseconds for well-designed local astrometric programs.

- Only VLBI instrument with excellent sensitivity and imaging characteristics at high frequencies of 22 GHz and 43 GHz (water and SiO masers, plus continuum imaging at 200–400 microarcsecond resolution), with some imaging capabilities at $\lambda \approx 3$ mm ($\nu = 86$ GHz).
- Only VLBI instrument with full-time dynamic scheduling, enabling access to the high radio frequencies (mentioned above) under the best conditions.
- Sky coverage ranging from the North Pole (90 degrees declination) to about –50 degrees declination (not possible for all telescopes), including 85% of the sky.

A7. Partnerships and Service to the Community

A7.1 Software

The NRAO continues to provide the Astronomical Image Processing System (AIPS) software to the entire astronomical community. AIPS was the first general-purpose data-reduction software in the U.S. to be produced for export to all external users of a particular facility. It presently is used for all VLBA observations and virtually all VLA observations, as well as at a wide variety of other radio interferometers around the world. The NRAO maintains ports to Linux, Unix, and Mac OS/X systems with easy installation procedures, a simple "midnight job" procedure that permits daily updates of software fixes and enhancements, as well as binary versions of the software that incorporate the fastest compilers available. A helpdesk supports users with bug reports or questions, which include both data-analysis subtleties and installation problems. In 2004 the daily updated 31DEC04 version of AIPS was downloaded by 808 unique IP addresses, of which 231 ran the midnight job at least occasionally. The frozen 31DEC03 version was downloaded by 196 sites, and a total of 1276 unique IP addresses downloaded a copy of AIPS or accessed the main site that houses the AIPS software.

A future software system including AIPS++ code, with a graphical user interface and easy scripting, is under development for ALMA and the EVLA. It is not currently available as a user package, owing to the present effort to increase robustness and scientific completeness. ALMA design reviews and tests of the next-generation data-analysis software, with real and simulated data sets of increasing complexity, all have been passed for the last two years. The new software is expected to be available as a user package well in advance of ALMA and EVLA completion around 2010, and to be available with somewhat more limited capabilities for first science in 2007 and 2008.

The NRAO also supports the SCHED software which has been exported and used to schedule VLBI observations at many facilities worldwide, specifically including the VLBA and the European VLBI Network. It also maintains and exports the JOBSERVE software that is used exclusively to schedule VLA observations, but which will be replaced for the EVLA.

Historically, the NRAO has provided algorithm development for radio astronomy that is used in many software packages for radio telescopes worldwide. Some areas in which the NRAO has contributed algorithms include deconvolution of interferometric data, self-calibration and hybrid mapping, global fringe-fitting for VLBI, wide-field imaging, and mosaicing. For example, the short paper entitled "An efficient implementation of the algorithm 'CLEAN'."(Clark 1980, A&A, 89, 377) has been cited 381 times, and the cited implementation has been incorporated into software packages around the world.

A7.2 Partnerships with Universities, Instrument Design or Fabrication

During completion of the GBT, the NRAO initiated a university instrumentation program which provided funding to universities and NRAO support for the design, construction, and operation of new instrumentation to be placed on the GBT. The first two instruments approved for this program were the Penn Array, a $\lambda \approx 3$ mm ($v \approx 90$ GHz) multi-pixel bolometer camera, and the Caltech continuum backend for the $\lambda \approx 1$ cm (26–40 GHz) and $\lambda \approx 3$ mm (68–92 GHz) bands. Recently, the NSF Advanced Technologies and Instrumentation (ATI) program awarded a university grant for the University of Maryland "Zpectrometer," a wideband (14 GHz bandwidth) spectrometer to be used as a "redshift machine" to search for redshifted CO line emission from distant galaxies.

The VLA has participated in significant partnerships with the Naval Research Laboratory (NRL), NASA, Germany, and Mexico for produce $\lambda = 4$ m ($\nu = 74$ MHz), $\lambda = 3.6$ cm (8 GHz) and $\lambda = 7$ mm (43 GHz) receiving systems which have enhanced the VLA since its dedication in 1980. Significant Canadian and Mexican contributions to the EVLA now are taking place, with advanced receiving systems funded by Mexico through a grant to the Universidad Nacional Autonoma de Mexico (UNAM) and a new state-of-the-art correlator from the Dominion Radio Astrophysical Observatory (DRAO) in Canada. The NRAO is cooperating with the Smithsonian Astrophysical Observatory (SAO) in their efforts to build a $\lambda \approx 2$ m ($\nu \approx 200$ MHz) receiving system to search for redshifted HI during the Epoch of Reionization. For the VLBA, a partnership with Germany has resulted in development of a $\lambda \approx 3$ mm (86 GHz) receiving system, while partnership with the MIT-Haystack Observatory resulted in the VLBA recording system. The NRAO also has contributed to MIT-Haystack for their development of Mark 5 disk-based recording systems. The NRAO currently participates as a partner in the U.S. Square Kilometer Array (SKA) consortium, facilitating university leadership in the design of a next-generation centimeter-wavelength interferometer.

The Central Development Laboratory (CDL) has played the leading role in the design and fabrication of low-noise amplifiers and receivers for many radio telescopes around the world. In particular, the CDL supplied all of the low-noise amplifiers for the Wilkinson Microwave Anisotropy Probe (WMAP), and either amplifiers or designs for many general-purpose radio telescopes and cosmic microwave background radiation (CMBR) experiments around the world.

A7.3 Added-Value Infrastructure

NRAO infrastructure has been used to host a variety of user instrumentation for many different purposes related to radio astronomy. After they were removed from general-purpose observing funded by the NSF, the 85-foot (26 m) telescopes of the Green Bank Interferometer have been used for pulsar timing, monitoring of transient sources, and measurements of Earth Orientation. The Green Bank site hosts a 20 m radio telescope built by the U.S. Navy to monitor Earth orientation by VLBI techniques. The NRAO also developed and hosted at Green Bank one of the primary tracking stations for the VSOP space VLBI mission. The 140 Foot (43 m) Telescope in Green Bank was used for a short time in the Search for Extraterrestrial Intelligence (SETI). Although no longer used as an NSF scientific instrument, it is now is being refurbished by the U.S. Air Force for ionospheric research.

The VLA hosted NASA tracking equipment for the Voyager Neptune encounter. NASA funded $\lambda = 3.6$ cm (8.4 GHz) receivers on the VLA to enable a doubling of the data rate (and number of images) returned from Neptune in 1989. The VLA is hosting a development project of the Southwest Consortium (SWC, including the University of New Mexico, the University of Texas, the Los Alamos National Laboratory, and the Naval Research Laboratory). Their Long Wavelength Development Array (LWDA) is intended as a possible forerunner for the Long Wavelength Array (LWA), a $\lambda = 30$–3.4 m (10–88 MHz) interferometer that would be spread across New Mexico and west Texas for low-frequency radio astronomy and ionospheric studies. The VLA site also is one of two possible hosts for the future Frequency-Agile Solar Radiotelescope (FASR). FASR is a university consortium project recently proposed to the NSF Atmospheric Sciences Division for FASR development funding.

The VLBA is the backbone of the geodetic VLBI network, and it currently participates for 24 hours every two months in the observations that maintain and extend the Inertial Celestial Reference Frame (ICRF). These observations also are used to track plate-tectonic motions, with measures of the VLBA sites now recorded with accuracies of a few millimeters per year. Many of the VLBA stations also host GPS (Global Positioning System) receivers that are used for routine monitoring of the Earth's ionosphere and for continental-drift measurements.

Development of ALMA infrastructure on the Atacama Desert in Chile appears likely to lead to an entirely new site for high-altitude astronomy in Chile. Since the discovery of the site by NRAO in 1994, millimeter- and submillimeter-wavelength experimental facilities such as the CBI, ASTE, and APEX have proliferated; and new astronomical installations such as the Caltech-Cornell Atacama Telescope (CCAT), a large-aperture, far-infrared telescope for cosmology, are currently under development for the Atacama site. The site is now protected from RFI thanks to the creation of Quiet and Coordination zones by Chilean authorities following the Green Bank NRQZ model.

A8. Education and Outreach

The NRAO conducts a variety of programs of education and public outreach, many of which were discussed briefly in the "Broader Impact" chapter of this document. This section presents some of the metrics describing these programs.

A8.1 Visitor Centers

The VLA operates a visitor center that is open year-round, providing self-guided tours and (since 2003) a small attached gift shop. The NRAO site at Green Bank has operated a visitor center for years and added a new education center, completed in 2001, in conjunction with the opening of the GBT. Table A8.1 gives the numbers of visitors at the two facilities since 1998. The VLA numbers are firm lower limits, taken only from guest-book signatures up until 2003, then from counts made by the gift-shop staff. Visitors who did not sign the guest book or came to the VLA when the gift shop was not open have not been counted. The VLA numbers went up significantly in 2004 after the gift shop was opened and staff members were available to count visitors, so the counts from earlier years should probably be increased by 25% to 50%.

Table A8.1 Visitor Counts at the Green Bank and VLA Visitor Centers

	Green Bank/GBT	VLA
2004	40,640	23,299
2003	32,830	16.268
2002	31,264	18,632
2001	31,680	18,120
2000	28,821	19,319
1999	24,981	NA
1998	22,001	NA

A8.2 Educational Group Tours

Along with the standard visitor tours, the NRAO hosts specific guided tours for school groups at both the Green Bank and VLA sites. The participants in these tours range from elementary-school and middle-school students to university classes and education professionals. Counts of educational-tour participants in the last four years are given for Green Bank and the VLA in Table A8.2.

Table A8.2 Educational Tour Participants at Green Bank and the VLA

	Green Bank/GBT	VLA
2004	3,550	2,017
2003	3,400	1,325
2002	3,615	2,541
2001	3,200	NA

A8.3 NSF-Funded Research Experience Programs

The NRAO has conducted successful programs for a number of years under funding from the NSF REU (Research Experiences for Undergraduates) and RET (Research Experiences for Teachers) programs. In a typical year, the NRAO has supported about 15 REU students plus another 5–8 graduate students or graduating seniors funded internally by the NRAO. We have found that the mix of more senior participants actually makes for a more beneficial experience for the undergraduates. Over the eight years from 1998 through 2005, the NRAO has supported 128 REU students, 76 females (59%) and 52 males. The RET program is necessarily more modest owing to its limited funding. Table A8.3 summarizes the statistics of the REU and RET programs, with the REU participation broken down among the Charlottesville (CV), Green Bank (GB), Socorro (SOC), and Tucson (TUC) sites. Typically, REU students in Socorro work on the VLA or VLBA, those in Green Bank work on the GBT or its predecessors, and those in Charlottesville work on any of the NRAO telescopes. In a representative year, 2 or 3 REU students work on theory, data from non-NRAO telescopes, or software projects. The last column of Table A8.3 summarizes the NRAO-wide numbers for the RET program.

Table A8.3 Participation in NRAO REU and RET Programs

Year	Students	CV	GB	SOC	TUC	Female	Male	RET
2005	18	5	6	7	0	9	9	3
2004	14	3	4	7	0	12	2	3
2003	15	1	5	8	1	11	4	3
2002	15	3	4	7	1	6	9	5
2001	17	3	3	9	2	9	8	1
2000	18	4	7	7	0	10	8	5
1999	14	3	4	6	1	8	6	NA
1998	17	3	5	6	3	11	6	NA
TOTAL	128	25	38	57	8	76	52	20

A8.4 Press Releases

The NSF does not have a full-time press officer assigned to the Astronomy Division, so the NRAO conducts its own vigorous program of press releases and AAS press conferences. Table A8.4 gives the total number of press releases each year since 1998, broken down by facility. The numbers for 2005 reflect only the first 7 months of the year. Note that some press releases report results involving more than one telescope, and the occasional release includes research by NRAO staff that did not use an NRAO telescope.

Table A8.4 NRAO Press Release Statistics, 1998–2005

Year	Total	Research News	Other News	VLA	VLBA	GBT	Other Telescopes
2005	16	12	4	6	5	2	0
2004	14	14	0	5	5	7	0
2003	18	15	3	5	6	2	0
2002	15	12	3	3	2	4	3
2001	21	16	5	6	5	1	3
2000	17	6	11	4	1	0	1
1999	10	7	3	4	5	0	0
1998	11	9	2	6	1	0	0

A9. Other Possible Metrics

A9.1 Cost Effectiveness

The cost effectiveness of the current suite of NRAO telescopes, compared with some other telescopes of the current era, is reported in the main part of this document in Section 6.3.

A9.2 Scientific Highlights

Tables A9.1 and A9.2 list the ten most-cited papers that we know of from both the VLA and the VLBA. We believe that the VLBA listing is fairly complete, but it is possible that we are missing one or two high-citation papers from the VLA.

Table A9.1 The Ten Most-Cited Papers from the VLA

No. Citations	Reference
892	Condon et al. “The NRAO VLA Sky Survey.” 1998, AJ, 115, 1693
473	Mirabel & Rodriguez “A Superluminal Source in the Galaxy.” 1994, Nature, 371, 46
431	Becker et al. “The FIRST Survey: Faint Images of the Radio Sky at Twenty Centimeters.” 1995, ApJ, 450, 559
405	Wood & Churchwell “The Morphologies and Physical Properties of Ultracompact HII Regions.” 1989, ApJS, 69, 831
394	Condon et al. “Strong Radio Sources in Bright Spiral Galaxies. II. Rapid Star Formation and Galaxy-Galaxy Interaction.” 1982, ApJ, 252, 102
379	Frail et al. “Beaming in Gamma-Ray Bursts: Evidence for a Standard Energy Reservoir.” 2001, ApJL, 562, L55
334	Thompson et al. “The Very Large Array.” 1980, ApJS, 44, 151
315	Kellermann et al. “VLA Observations of Objects in the Palomar Bright Quasar Survey.” 1989, AJ, 98, 1195
301	Perley “The Positions, Structures, and Polarizations of 404 Compact Radio Sources.” 1982, AJ, 87, 859
300	Chambers et al. “Alignment of Radio and Optical Orientations in High-Redshift Radio Galaxies.” 1987, Nature, 329, 604

Table A9.2 The Ten Most-Cited Papers from the VLBA

No. Citations	Reference
543	Miyoshi et al. "Evidence for a Black Hole from High Rotation Velocities in a Sub-Parsec Region of NGC 4258." 1995, Nature, 373, 127
135	Kellermann et al. "Sub-Milliarcsecond Imaging of Quasars and Active Galactic Nuclei." 1998, AJ, 115, 1295
131	Greenhill et al. "Detection of a Subparsec Diameter Disk in the Nucleus of NGC 4258." 1995, ApJ, 440, 619
127	Readhead et al. "Compact Symmetric Objects and the Evolution of Powerful Extragalactic Radio Sources." 1996, ApJ, 460, 634
120	Readhead et al. "The Statistics and Ages of Compact Symmetric Objects." 1996, ApJ, 460, 612
115	Herrnstein et al. "A Geometric Distance to the Galaxy NGC 4258 from Orbital Motions in a Nuclear Gas Disk." 1999, Nature, 400, 539
107	Wardle et al. "Electron-Positron Jets Associated with the Quasar 3C 279." 1998, Nature, 395, 457
100	Smith et al. "A Starburst Revealed – Luminous Radio Supernovae in the Nuclei of Arp 220." 1998, ApJL, 493, L17
98	Reid et al. "The Proper Motion of Sagittarius A*. I. First VLBA Results." 1999, ApJ, 524, 816
91	Jorstad et al. "Multiepoch Very Long Baseline Array Observations of EGRET-detected Quasars and BL Lacertae Objects: Superluminal Motion of Gamma-Ray Bright Blazars." 2001, ApJS, 134, 181

A9.3 Development of Future Projects and Instruments

Discussions of future projects and instruments appear throughout this document, including the ALMA and EVLA construction projects as well as the operational GBT and VLBA.

APPENDIX B: ACRONYMS AND ABBREVIATIONS

AANM	Astronomy and Astrophysics in the New Millenium
AAS	American Astronomical Society
AGN	Active Galactic Nucleus or Active Galactic Nuclei
AIPS	Astronomical Image Processing System
ALMA	Atacama Large Millimeter Array
APEX	Atacama Pathfinder Experiment
AST	Astronomical Sciences (Division of the NSF)
ASTE	Atacama Submillimeter Telescope Experiment
ATI	Advanced Technologies and Instrumentation
AUI	Associated Universities, Incorporated
BIMA	Berkeley Illinois Maryland Association
CBI	Cosmic Background Imager
CCAT	Caltech–Cornell Atacama Telescope
CDL	Central Development Laboratory
CGRO	Compton Gamma-Ray Observatory
CIS	Computing and Information Services
CMBR	Cosmic Microwave Background Radiation
CO	Carbon Monoxide
CoI	Co-Investigator
Con X	Constellation X-ray Observatory
CONACYT	National Council of Science and Technology
COSMOS	Cosmic Evolution Survey
DASI	Degree Angular Scale Interferometer
DOE	Department of Energy
DRAO	Dominion Radio Astrophysical Observatory
DSAA	Division of Science and Academic Affairs
EoR	Epoch of Reionization
EOS	Equation Of State
EPO	Education and Public Outreach
ESO	European Southern Observatory
ESS	Environmental Safety and Security
EVLA	Expanded Very Large Array
EVLA I	Phase I of the EVLA
EVLA II	Phase II of the EVLA
FASR	Frequency-Agile Solar Radiotelescope
FIRST	Faint Images of the Radio Sky at Twenty cm
FITS	Flexible Image Transport System
FY	Fiscal Year
GBT	Green Bank Telescope
GHz	Gigahertz
GLAST	Gamma-ray Large-Aperture Space Telescope
GP-B	Gravity Probe B
GPS	Global Positioning System
GR	General Relativity

GRB	Gamma-Ray Burst
GSFC	Goddard Space Flight Center
GSMS	Governor’s School for Mathematics and Science
GSMT	Giant Segmented-Mirror Telescope
HCN	Hydrogen Cyanide
HEMT	High Electron Mobility Transistor
HR	Human Resources
HSA	High Sensitivity Array
HST	Hubble Space Telescope
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
IGM	InterGalactic Medium
InP	Indium Phosphide
IR	InfraRed
IRAM	Institut de Radioastronomie Millimetrique
ISM	InterStellar Medium
JCMT	James Clerk Maxwell Telescope
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
LAAS	Local Area Augmentation System
ΛCDM	Lambda Cold Dark Matter
LIGO	Laser Interferometer Gravitational-wave Observatory
LSST	Large Synoptic Survey Telescope
LWA	Long-Wavelength Array
LWDA	Long-Wavelength Development Array
MAMBO	Max Planck Millimeter Bolometer
MHz	Megahertz
MIS	Management Information Services
MMIC	Monolithic Microwave Integrated Circuit
Mm	millimeter
MREFC	Major Research Equipment and Facilities Construction
MSP	MilliSecond Pulsar
NA	Not Applicable or Not Available
NAASC	North American ALMA Science Center
NAIC	National Astronomy and Ionosphere Center
NASA	National Aeronautics and Space Administration
Nb	Niobium
NCSA	National Center for Supercomputing Applications
NED	NASA/IPAC Extragalactic Database
NIST	National Institute of Standards and Technology
NRAO	National Radio Astronomy Observatory
NRL	Naval Research Laboratory
NRQZ	National Radio Quiet Zone
NSF	National Science Foundation
NVO	National Virtual Observatory

NVSS	NRAO VLA Sky Survey
OCC	Observatory Computing Council
OIR	Optical/InfraRed
OPM	Observatory Program Management
OSC	Observatory Science Council
OTC	Observatory Technical Council
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PI	Principal Investigator
PIO	Public Information Officer
PK	Post-Keplerian
PMO	Program Management Office
RET	Research Experiences for Teachers
REU	Research Experiences for Undergraduates
RFI	Radio-Frequency Interference
RHIC	Relativistic Heavy-Ion Collider
SAO	Smithsonian Astrophysical Observatory
SCOPE	Southwest Consortium of Universities for Public Education
SCUBA	Submillimeter Common-User Bolometer Array
SED	Spectral Energy Distribution
SHARC	Submillimeter High Angular Resolution Camera
SIM	SIM PlanetQuest (formerly Space Interferometry Mission)
SIS	Superconductor–Insulator–Superconductor
SKA	Square Kilometre Array
SMBH	SuperMassive Black Hole
SNAP	Supernova / Acceleration Probe
SOFIA	Stratospheric Observatory for Infrared Astronomy
STARTEC	State of the Art Telescope Educational Consortium
STScI	Space Telescope Science Institute
SWC	SouthWest Consortium
SZ	Sunyaev–Zeldovich
SZA	Sunyaev–Zeldovich Array
submm	submillimeter
ToO	Target of Opportunity
UNAM	Universidad Nacional Autonoma de Mexico
UV	UltraViolet
VHF	Very High Frequency
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VLSS	VLA Low-frequency Sky Survey
VSA	Very Small Array
VSOP	VLBI Space Observatory Programme
WMAP	Wilkinson Microwave Anisotropy Probe

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