National Radio Astronomy Observatory

2006 Annual Progress Report

November 2, 2006

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Annual Progress Report

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1. Summary

This report describes the major accomplishments of the NRAO during the fiscal year FY 2006 (2005 October 1 through 2006 September 30).

Science

Science discoveries included the identification of short-duration gamma-ray bursts (GRBs), constraining changes in fundamental constants, measuring the size of the black hole in the center of our Galaxy, discovery of the fastest-spinning millisecond pulsar (1.397 ms period), the most accurate measurement of the distance to the Perseus spiral arm (previously known only to within a factor of two), the discovery of a cold, extended dust disk suffused with centimeter-sized pebbles around a nearby star tracing the earliest stages of planet formation, detection of a huge hydrogen superbubble rising out of the plane of the Milky Way, and the detection of complex pre-biotic molecules in interstellar space.

ALMA Construction

The ALMA project team successfully concluded a comprehensive and intense round of reviews of scope and cost leading to a new baseline. In early February the NSF convened a panel of experts for a comprehensive management and cost review of the North American portion of the ALMA Project. The NSF panel report validated the technical readiness, the current project management, the cost estimates (except for a concern that the contingency may be too small), and endorsed the viability of the rebaselined ALMA project. In May, the National Science Board accepted the recommendation of NSF Director Bement to proceed with a 50-antenna version of ALMA (with an increased contingency). Congressional action on the NSB recommendation is pending. The Array Operations Site (AOS) Technical Building was completed. The antenna contract was initiated. Local labor plans and procedures were developed and implemented.

EVLA Construction

Six antennas were outfitted with EVLA electronics and released for use by observers. Progress on the WIDAR correlator by our Canadian collaborators is proceeding. Successful prototypes have been completed for nearly all electronics modules, allowing full construction to proceed. The EVLA Advisory Committee and an NSF mid–project review panel met in May 2006 and expressed confidence and general satisfaction with the projects.

Telescope Science Operations

The North American Alma Science Center (NAASC) held a science workshop in Charlottesville and Town Meetings at both AAS meetings. A spectral-line catalog was initiated and integrated into the ALMA archive.

The Green Bank Telescope (GBT) operation matured significantly during FY 2006. Downtime from faults diminished to 1–2%, and time available for scheduled observations approached 70% of total time in the year (24/7/365 basis). The telescope was made significantly easier to use by the introduction of the Astrid scheduling-block user interface. First light was received by the $\lambda = 3$ mm Penn Array bolometer. The first six EVLA antennas were returned to the VLA. The VLA Low-frequency Sky Survey and a large program to study gamma-ray burst afterglows were completed at the VLA. The eight-day Synthesis Imaging Summer School served 170 students. The pilot project to image data in the VLA archive was completed, and responsibility was transferred to the e2e Operations Division. Operational dynamic scheduling began.

Mark 5A disk–based recording systems have been installed at all 10 VLBA stations plus the GBT, which often participates in VLBA projects. The Mark 5 systems have reduced operations and maintenance costs by replacing the tape recording systems, and they have also improved sensitivity through higher-bandwidth recording.

Technical Capability Development

New cryogenic HFET amplifiers were developed for the EVLA, and 50 production amplifiers were built. New MMIC amplifiers were developed for ALMA and for the 11–34 GHz SKA band. The Green Bank Solar Radio Burst Spectrometer (GB/SRBS) was completed and routine operations began. An eight-element imaging array with baselines up to 300 m was deployed in Green Bank for the Precision Array to Probe the Epoch of Reionization (PAPER).

Community Support Programs

Following the recommendations of the NSF Software Review panel (September 2005), the NRAO appointed a dedicated team to manage the Observatory's e2e Operations initiative, which will make the NRAO telescopes and data products easier to use by non-experts and experts alike. The Assistant Director for e2e Operations (Radziwill) and Principal Scientist (Fomalont) have already developed an organization and detailed plans for the initiative and work is underway. NRAO programs for undergraduate and graduate summer students, support for students doing thesis research on the GBT, the Jansky postdoctoral fellowships, and the co-op student program helped to develop the next generation of astronomers and engineers.

Management and Administration

One of the major management accomplishments last year was the completion of the senior management team hiring and reorganization. Over the past 18 months, appointments have been made for Deputy Director (Jewell), Associate Director for Administration (Clark), NRAO ALMA Project Director (Russell), Assistant Director for Green Bank Operations (Prestage), the new EVLA Project Manager (McKinnon), the new Head of Division of Scientific and Academic Affairs (Frail), the Assistant Director for e2e Operations (Radziwill), and the Head of the North American ALMA Science Center (Carilli), and Observatory Technical Leader (Fisher). The new administration team has introduced monthly "flash reports" which provide status snapshots of all Observatory accounts. The flash reports provide an early warning system for potential overruns or underruns so that corrective action can be taken promptly. A new budget development cycle provides a rational process for building and justifying budget expenditures.

2. Science Highlights in FY 2006

Measurements of the Zeeman Effect: Robishaw and Heiles have used the GBT to observe the $\lambda = 21$ cm hydrogen line along two strips crossing the major axis of a molecular filament in the Orion molecular cloud. They detected significant Zeeman splitting at almost every position and find that the line-of-sight magnetic field reverses direction across the axis of the molecular cloud. These observations are consistent with lower-resolution detections made using the Hat Creek 85-foot telescope. Stellar polarization data show that the plane-of-sky field is nearly perpendicular to the cloud's major axis. This, in addition to the opposite directions of the line-of-sight fields above and below the cloud, suggests a helical magnetic field structure. MHD simulations of filamentary molecular clouds have been able to reproduce just such a helical magnetic field structure. The line-of-sight field strengths in this region are at least 10 microGauss, corresponding to a pressure of at least 30,000 K cm^{-3}; this is comparable to the pressure from the hot gas that permeates the Eridanus loop. A long-standing theoretical construct maintains that high-mass star formation is moderated by magnetic fields: regions of massive-star formation should possess low fields for gravitational instabilities to dominate. However, observations, including these GBT results, have shown just the opposite. The Taurus molecular clouds are devoid of high-mass star formation yet exhibit upper limits on magnetic field strengths of less than 8 microGauss. In Orion, a site of high-mass star formation, line-of-sight fields larger than 10 microGauss in emission were found throughout the region.

Investigators: T. Robishaw, C. Heiles (UC Berkeley).

Closest Pair of Supermassive Binary Black Holes: Astronomers using the VLBA have discovered a black-hole binary in the radio galaxy 0402+379 ($z = 0.055$) with a combined mass of 1.5×10^8 solar masses and a separation of only 7.3 pc. This is closer by more than two orders of magnitude than any other known supermassive black-hole pair. It has implications for how galaxies form and evolve, and it provides constraints for the success rates of experiments designed to detect gravitational waves from black-hole mergers.

Investigators: C. Rodriguez (UNM), G. B. Taylor (UNM), R. Zavala (USNO), A. Peck (CfA), L. Pollack (UCSC), R. Romani (Stanford).

Constraints on Changes in Fundamental Constants from a Cosmologically Distant OH Absorber or Emitter: Kanekar et al. have used the GBT to detect the four $\lambda = 18$ cm OH lines from the $z \sim 0.765$ gravitational lens toward PMN J0134–0931. The 1612 and 1720 MHz lines are in conjugate absorption and emission, providing a laboratory to test the evolution of fundamental constants over a large lookback time. Kanekar et al. compared the HI and OH main-line absorption redshifts of the different components in the $z \sim 0.765$ absorber and also the $z \sim 0.685$ lens toward B0218+357 to place stringent constraints on changes in the quantity $F \equiv g_p[\alpha^2/\mu]^{1.57}$, where α is the fine-structure constant and μ is the electron-proton mass ratio. They obtain $[\Delta F/F] = (0.44\pm0.36^{stat}\pm1.0^{syst}) \times 10^{-5}$, consistent with no evolution over the redshift range $0 < z < 0.7$. The measurements have a 2σ sensitivity of $[\Delta\alpha/\alpha] < 6.7\times10^{-6}$ or $[\Delta\mu/\mu] < 1.4\times10^{-5}$ to fractional changes in α and μ over a period of ~ 6.5 Gyr, half the age of the Universe. These are among the most sensitive constraints on changes in μ.

Investigators: N. Kanekar, C. L. Carilli, and G. I. Langston (NRAO), G. Rocha (Cavendish Laboratory), F. Combes (Observatoire de Paris), R. Subrahmanyan (Australia Telescope National Facility), J. T. Stocke (University of Colorado), K. M. Menten (Max‐Planck‐Institut für Radioastronomie), F. H. Briggs (Australia Telescope National Facility and Australian National University), and T. Wiklind (Space Telescope Science Institute).

VLA Identifies Afterglow of Short Gamma Ray Burst in an Elliptical Galaxy: Using the rapid-response observing mode put in place in 2005, the VLA was used to unambiguously identify the afterglow of the short "hard" gamma-ray burst GRB050724 detected by the Swift satellite. The identification of the radio afterglow of this burst showed its association with an elliptical galaxy at redshift z = 0.257. The association with a galaxy that is dominated by an old stellar population provides key support for the model in which two compact stellar remnants in a binary system coalesce, giving rise to the gamma-ray burst and the relativistic fireball.

Investigators: E. Berger (Carnegie Observatories) and 23 collaborators.

VLA Low-frequency Sky Survey Observations Completed: The VLA Low-frequency Sky Survey (VLSS) is a 74 MHz survey of the entire sky above –30 degrees declination, or about 75% of the celestial sphere. An allocation of 700 hours of observing time has enabled this survey to cover more than 500 fields with a combination of 80" resolution and 0.1 Jy noise level. This combination of resolution and sensitivity is unparalleled in any other low-frequency survey, due in large part to the excellent VLA imaging capabilities that reduce the impact of confusing sources. About 95% of the fields have now been imaged and may be seen in the second major data release, (see http://lwa.nrl.navy.mil/VLSS). About 67,000 sources have been identified to date. All sky maps and the source catalog are available via interfaces similar to those used by the NRAO VLA Sky Survey. The VLSS is expected to be a resource for all astronomers for many years to come, with potential discoveries of fossil radio sources and very distant galaxies still lurking in the data.

Investigators: R. A. Perley, J. J. Condon, W. D. Cotton (NRAO); A. S. Cohen, W. M. Lane Peters, N. E. Kassim, T. J. W. Lazio (NRL); and W. C. Erickson (University of Maryland).

VIVA, a New HI Survey of the Virgo Cluster: VLA Imaging of Virgo in Atomic gas (VIVA) is a VLA Large Project that has been observing during the past two C configurations. This survey has now imaged the neutral hydrogen (HI) emission from 50 galaxies in the Virgo cluster with sensitivity, angular resolution, and velocity resolution that are factors of 3–5 better than a similar VLA survey carried out nearly 20 years ago. A wealth of galaxy morphologies has been found. In several galaxies, there is strong evidence for ram-pressure stripping of the HI caused by galaxy motion through the intracluster medium (ICM). There is at least one case in which a cluster-subcluster merger may have driven large bulk motions in the ICM, increasing the ram pressure by an order of magnitude. Finally, a number of galaxies have HI tails pointing away from the cluster center and appear to be falling into the cluster center for the first time. Clearly, in this nearest cluster of galaxies, we are seeing evolutionary processes that continue even to the present date, and are not just restricted to the distant early Universe.

Investigators: A. Chung (Columbia University), H. Crowl (Yale University), J. Kenney (Yale University), J. van Gorkom (Columbia University), and B. Vollmer (Strasbourg University).

Measuring the Size of the Black Hole at the Center of Our Galaxy: The VLBA has been used at its highest frequency of 86 GHz (λ = 3.5 mm) to image Sgr A*, the compact radio source at the center of our Galaxy. Observations at such a high frequency are necessary to reduce the interstellar scattering that smears images at lower frequencies. The intrinsic size of Sgr A* measured by the VLBA is only 1 AU, showing that the radio emission originates at less than 13 Schwarzschild radii from the event horizon of the black hole. When this size is combined with a lower limit on the mass, the resulting mass density of 6.5×10^{21} solar masses pc^{-3} provides the most stringent evidence to date that Sgr A* is a supermassive black hole.

Investigators: Z. Q. Shen, (Shanghai Observatory), K. Y. Lo (NRAO), M. –C. Liang (Caltech), P. T. P. Ho (ASIAA), J. –H. Zhao (CfA).

The Fastest-Spinning Neutron Star: Astronomers using the GBT have discovered a binary pulsar (PSR J1748−2446ad) in the globular cluster Terzan 5 that is rotating about its axis 716 times per second (P = 1.4 msec). The GBT now holds the record for the fastest-spinning pulsar known, breaking the nearly 25-year record held by the 642 Hz pulsar B1937+21. Studying maximally rotating neutron stars is important for a range of astrophysical problems that include constraining the equation-of-state of matter at supra-nuclear densities and estimating the importance of neutron stars as gravitational-wave sources.

Investigators: J. Hessels (McGill), S. Ransom (NRAO), Stairs (UBC), P. Freire (NAIC), V. Kaspi (McGill), F. Camillo (Columbia).

Detection of Biologically-Significant Molecules in the Interstellar Medium: **In** just over two years, an international research team has detected eight new complex, biologically significant molecules in the interstellar medium using the GBT. The discoveries are revealing the mechanisms by which complex molecules are formed in the ISM. Two mechanisms appear to account for these molecules: simple chemical reactions that add an atom to a molecular structure residing on the surface of a dust grain, and neutral-radical reactions that occur in the interstellar gas. The molecules acetamide (CH_3CONH_2), cyclopropenone (H_2C_3O), propenal (CH_2CHCHO), propanal (CH_3CH_2CHO), and ketenimine (CH_2CNH) were detected in the Sagittarius B2(N) cloud, and the molecules methyl-cyano-diacetylene (CH_3C_5N), methyl-triacetylene (CH_3C_6H), and cyanoallene (CH_2CCHCN) were found in the Taurus Molecular Cloud (TMC-1). Acetamide is of particular interest since it contains a peptide bond in which an NH_2 group is bound to a CO group. Such bonds provide the means for linking amino acids together to form proteins. The presence of such complex, biologically-significant interstellar species makes it increasingly plausible that interstellar chemistry played some role in the formation of the complex chemistry of the early Earth.

Investigators: J. Hollis (NASA-GSFC), P. Jewell and A. Remijan (NRAO), F. Lovas (NIST), L. Snyder (University of Illinois), H. Mollendal (University of Oslo, Norway), V. Ilyushin (Inst. of Radio Astronomy of the National Academy of Sciences of the Ukraine), I. Kleiner (University of Paris).

VLBA Measures the Distance to the Perseus Spiral Arm: Using the VLBA, a team of researchers has measured a precise distance to the Milky Way's Perseus spiral arm by determining the trigonomic parallax to several strong methanol masers in the W3OH star-forming region. Their direct measurement of 1.95 ± 0.04 kpc resolves a previous factor-of-two discrepancy in the kinematic distance to the Perseus spiral arm that arose because of anomalous motions in that part of the Perseus arm. The new result shows that the VLBA can measure distances out to 10 kpc with an accuracy 100 times better than that of the Hipparcos satellite and can lead the way to mapping the spiral structure and full kinematics of massive star-forming regions in the Milky Way.

Investigators: Y. Xu (Nanjing), M.J. Reid (CfA), X.W. Zheng (Nanjing), and K.M. Menten (MPIfR, Bonn).

A Gigantic Eruption from the Inner Disk of the Milky Way: Pidopryhora, Lockman, and Shields have used the GBT to discover a coherent structure that seems to be a huge superbubble extending more than 3 kpc from the Galactic plane. It has been detected in both Hα and HI, and a detailed HI map of it has been produced with the Green Bank Telescope. The total hydrogen mass within the outflow is $\approx 10^6$ solar masses and its energy content is of order 10^{53} ergs. At the top of the structure there is a peculiar "plume" consisting of more than 10^4 solar masses of hydrogen, likely the cap of the superbubble which is now stalled in its expansion and undergoing instabilities.

Investigators: Y. Pidopryhora and F. J. Lockman (NRAO), J. C. Shields (Ohio University).

Magnetic Collimation of Jets from an Evolved Star: VLBA polarization measurements of the AGB star W43A, which is rapidly undergoing evolution into a planetary nebula, have produced the first direct evidence for magnetic collimation of an astrophysical jet. The VLBA observations measured the polarization of 22 GHz emission from water masers at opposing tips of the jets. The magnetic field direction was shown to be almost perfectly perpendicular to the jet, consistent with a toroidal magnetic field. The magnetic pressure in these regions is seen to dominate the gas pressure by a factor of 2–200. This result supports recent theoretical models that use magnetically collimated jets to explain the shape of asymmetric planetary nebulae.

Investigators: W. Vlemmings and P. Diamond (Jodrell Bank), H. Imai (Kagoshima).

3. FY 2006 Technical Highlights

- Substantially reduced elevation dependence of GBT gain at 40 GHz through "out of focus" holography
- Completed a 16-channel digital back-end from Caltech for the pseudo-correlation GBT continuum receiver for 26–40 GHz
- Full release of the Astronomer's Integrated Desktop (ASTRID) for the GBT
- The Ka-band (26–40 GHz) and Q-band (40–50 GHz) GBT receivers were released as planned
- Developed new amplifier designs covering 4–8, 4–12, and 12–18 GHz for the EVLA
- Redesigned the 35–46 GHz amplifier developed originally for WMAP in order to achieve flat noise and gain over the 40–50 GHz EVLA frequency band
- Developed a new GaAs MMIC power amplifier (PA), fabricated at BAE Systems, which meets the requirements for ALMA Bands 4, 8, and 9, with a longer lifetime than previous PAs
- Continued a joint R&D project between the NRAO and UVa for a new 385–500 GHz beam-lead SIS mixer, supported mainly by an NSF grant to the UVa
- Fabricated the first NbTiN trilayer structure (NbTiN/AlN/Nb) at the UVML
- Designed and tested a superconducting 180-degree IF hybrid covering 4–12 GHz that is small enough to be mounted inside a balanced SIS mixer block
- Designed and tested a scaled prototype of the holography feed for measuring ALMA antennas at 79 and 104 GHz.
- Designed and tested a half-size prototype of the EVLA 2–4 GHz feed
- Studied the beam pattern properties of a prime-focus array receiver for the GBT at 1.4 GHz and 2.5 GHz
- Brought 20–70 MHz and 250–1000 MHz solar monitor systems into routine operation at Green Bank
- A new VLA Proposal Submission Tool (common with GBT) made its debut
- Four EVLA antennas are now functioning with four complete IFs and receivers for L, C, X, K, and Q-bands
- The RFI-shielded room for the new EVLA correlator was completed in December 2005, and its shielding effectiveness was tested and verified
- The formatter and 8-bit digitizer boards in the EVLA digital transmission system module was redesigned, fabricated and successfully tested

- The three frequency converters that up- or down-convert the RF signals from the EVLA receivers to the 8–12 GHz IF of the EVLA were designed, prototyped, and placed into production
- The new EVLA correlator chip design was released for production and 10 packaged chip prototypes were delivered to Penticton
- All 10 VLBA antennas were equipped with Mark 5 data recorders, and the VLBA correlator has 11 Mark 5 playback units

ALMA FY 2006 technical highlights are described in the section on ALMA Construction.

4. ALMA Construction

FY 2006 was dominated by the rebaselining exercise and the subsequent reviews. The ALMA Cost Review of the rebaselined project was held in Garmisch-Partenkirchen on 13–15 October 2005. In the final days before the Cost Review it became clear that the project would procure antennas from two different vendors and that a Delta Review would be required to examine the cost implications of this. In addition, the NSF requested a North American Cost/Management Review to review the NSF component of the ALMA budget and on a similar timescale to the Delta Review.

Shortly after the ALMA Cost Review, a high-level delegation from the NSF/NRAO/AUI visited Taiwan to discuss the prospect of Taiwan joining the North American ALMA partnership.

The Delta Review concluded that the project had both made good progress and correctly assimilated the costs of having two antenna vendors. The North American ALMA Cost/Management Review was a success and concluded that the costs were both understood and under control; it further concluded that the North American (NA) ALMA Management was capable of delivering its part of the project. NSF called for a fourth review in April, this time of the contingency associated with ALMA. This review concluded that we had come close to achieving the 25% target through parametric cuts but that we should increase the contingency somewhat by adding additional cash as well.

The NSB approved the new ALMA baseline at their May 2006 meeting.

In early 2006 agreement was reached between NSF and ESO that AUI would hire the local staff in Chile. Since then work has largely concluded to allow AUI to hire the ALMA Local Staff in Chile and the first staff member has been hired. The AUI Implementation Plan was approved by ALMA Board on March 24. The amendment to the ALMA Agreement designating AUI as the employer of Local Staff for the Bilateral Project was approved by ESO Council on June 6, signed by the ESO Director General June 14. NSF approved in early July and then the AUI/ESO Management Agreement was signed. This, inter alia, designates the NRAO Director as responsible for Local Staff matters; formally establishes the "Director's Council" consisting of NRAO Director, ESO Director General and ALMA Director, and enables sharing of procurement information between AUI and ESO.

During FY 2006 the Site IPT (Integrated Product Team) made very significant progress with the construction of the Array Operations Site (AOS) Technical Building (TB) foundation, superstructure, and envelope all completed. The contract for the AOS TB completion, which includes all architectural interior furnishings, was signed. In addition, the NRAO completed the Contractors' Camp at the Operations Support Facility (OSF) level, at an altitude of approximately 9,600 ft. Finally the preparation of the Vertex lay-down area at the OSF for antenna assembly was completed, together with the necessary antenna foundations and underground utilities.

The Antenna IPT completed the Vertex Antenna Preliminary Pre-Production Design Review and the Pre-Production Design Review. The assembly of the pedestal and yoke-arm structure began at Vertex's dedicated ALMA Antenna integration facility in Kilgore, Texas. In addition to the antenna, ancillary ALMA antenna-equipment activities completed were the Production Nutator technical specification and Statement of Work, the competitive bidding process and evaluation of proposals, and the Production Optical Pointing Telescope technical specification. Finally, the key positions of Quality Assurance engineer and Antenna engineer were filled.

The Front-End IPT (FE IPT) made steady progress toward delivery of the first Front End. All cold-cartridge groups have built and tested their first receivers, and the first deliveries to the North American Front End Integration Center (NA FEIC) took place. The sensitivity of these cold cartridges substantially exceeds the performance of any other mm-wave receivers ever built. The test facilities at the NA FEIC were essentially completed, and assembly and initial test of the first FE began in July 2006. Agreement was reached on the design of the amplitude-calibration device and serious design work began. Many FE subassemblies and components are now in full production mode. Agreements on FE local-oscillator (LO) requirements and configurations were reached with ALMA-J (ALMA Japan) in order not to delay Band 4 and Band 8 work.

The Back-End IPT (BE IPT) completed delivery of prototype modules to Prototype System Integration and resolved successfully most of the deficiencies noted so far in system testing. Successful cross-correlation tests were performed from front end to correlator using the BE digital data system and LO references. The BE IPT also delivered sixteen Digital Transmission System (DTS) deformatter/receiver boards for testing on the correlator first quadrant and BE deliverables to the FE IPT for holography testing of antennas in Chile. Construction of modules and performance of environmental and other tests are currently on schedule for delivery of pre-production racks for the first antenna in early CY 2007, delivery of a limited Central LO (125 MHz and TE references only) to the OSF for single-antenna testing in October 2006, and delivery of Central LO equipment to the AOS in CY 2008.

The Correlator IPT substantially completed the first quadrant and began construction of the second quadrant. A full complement of optical receiver boards (DRX) from the Back End IPT and two new low-power Tunable Filter Bank (TFB) cards permitted verification of all card slots, interfaces, and cables in the first quadrant. A plan was implemented for volume production of the TFB cards. All printed-circuit boards (except TFB) have been completed and almost all have been tested. Upgrades of the two-antenna prototype correlator firmware were made to support Prototype System Integration.

The Computing IPT performed the first end-to-end test of the whole ALMA computing system with a real observing mode (optical pointing, needed first for antenna acceptance) and with real hardware at the Antenna Test Facility (ATF). Good progress has been made on the off-line processing system with the creation of an execution framework for CASA (Common Astronomy Software Applications) to enable the use of the popular Python scripting interface. Other achievements include the implementation of TFB (Tunable Filter Bank) support in the correlator software to enable hardware testing, finishing the definition of the raw data ALMA Science Data Model (ASDM), and implementation of a manual scheduling mode in the dynamic-scheduling subsystem to support initial observatory operations. In addition the IPT performed six external user tests.

The main Systems Engineering and Integration (SE&I) effort at the NRAO remains the Prototype System Integration (PSI) taking place at the Array Operations Center in Socorro, NM. In December 2005 the complete set of racks and modules for a two-antenna interferometer was available to PSI for system-level testing. The first task was to achieve full system connectivity among all hardware with reliable computer monitor and control. Numerous timing problems were discovered as well as phase stability and phase-lock problems in the LO system. While the discovery and resolution of problems can be time consuming,

it demonstrates that PSI is doing what it should be—finding problems before we move to Chile. Some hardware changes were initiated. In July 2006 full connectivity was achieved with a 100 GHz signal injected into the Front-End Simulator and a cross-correlation spectrum displayed at the correlator output.

The Science IPT led studies of ALMA's ability to address level-one science goals as it builds to its final complement of antennas. An array configuration was developed that can provide excellent imaging with an antenna complement ranging from 50 to 64 elements; fewer stations are a cost-saving feature of this array design. During the course of the year, antenna contracts were placed. The science IPT considered whether ALMA science goals could be met with an array of differing antenna designs and concluded that, as long as ALMA antennas meet their specifications, an ALMA constituted of antennas of different designs is fully capable of delivering top-level science as planned. The ALMA Calibration Plan was refined to encompass particular examples for the various sorts of calibration. The Front End IPT installed the prototype water-vapor radiometers on elements of the Smithsonian Submillimeter Array on Mauna Kea; Science IPT members began evaluating results. The Science IPT led a System Requirements Review in order to detail the flowdown of science requirements through system requirements to an assessment of detailed system performance. The Science Specifications and Requirements document was approved by the ALMA Board. ALMA was represented at a number of regional and international meetings through the year. The meeting "From ZMachines to ALMA" was held in Charlottesville in early January 2006, just after the Town Meeting at the AAS in Washington.

5. EVLA Construction

Project Management

The EVLA Advisory Committee met on May 8–9, 2006 to review progress on the project. An NSF Mid-Project Review was held on May 11–12, 2006.

In early 2005 the Mexican CONACyT issued a contract to the NRAO for constructing equipment including complete sets of electronics for two antennas plus K- and Q-band receivers. The equipment was built and presented to Mexican UNAM representatives, who visited the VLA site in November 2005.

Systems Integration

A total of six VLA antennas are in various stages of retrofit to the EVLA design. Four EVLA antennas are now functioning with four complete IFs. These antennas are equipped with receivers for L, C, X, K, and Q bands. The scientific and technical staff used them to evaluate the performance of the EVLA hardware and software. These antennas were returned to operations for scientific observations by both NRAO and external users. The fifth and sixth antennas were outfitted with EVLA electronics and are operating with four IFs at X band.

Civil Construction

The installation of the RFI-shielded room for the new correlator was completed in December 2005. The shielding effectiveness of the room was tested and verified, and the tightness of the room was checked as part of a fire-suppression contract. The installation of the room's fire-suppression system, HVAC system, electrical power distribution, lighting, and computer flooring were completed in August 2006.

Antennas

Two EVLA antennas were overhauled mechanically. The fabrication of mechanical components, such as platforms and feed towers, for the next three EVLA antennas began.

The fiberglass lamination of 13 L-band feed horns was completed. Storage fixtures for the L-band feed horns were designed, and the first of four fixtures was built and utilized. All but three of the C-band feed horns were assembled and stored in the warehouse.

Front End

The critical design review (CDR) for Front-End Systems was held on April 24–25, 2006. Overall, the CDR panel felt that the definition of the front-end requirements was comprehensive and realistic, and that for the most part the designs selected appear to meet the Project Book requirements, thus allowing hardware production to proceed in most areas.

The L-band receivers currently in use on the EVLA antennas are the old narrowband VLA receivers modified for use with the new EVLA feed horns. The new prototype L-band receiver was assembled and is undergoing vacuum, thermal, and RF performance tests.

Prototype feed horns for the other receiver bands are being developed. A half-sized S-band prototype feed was tested on an outdoor antenna-test range located on the New Mexico Tech campus. The measured beam patterns and VSWRs agreed well with theoretical projections. Two prototype horns for the production X-band receiver were built and tested in Green Bank.

Local Oscillator (LO) Systems

All LO modules are in or moving into full production.

Fiber Optics Systems

Thirty five of the 72 stations on the array were completely cabled with optical fibers for LO, IF, and Ethernet connections. Fiber-optic pad boxes were set at the 35 antenna pads, and fiber splices were made to the boxes. The fiber to each pad has been tested, and its losses have been documented.

The formatter and 8-bit digitizer boards in the Digital Transmission System (DTS) module were redesigned. The new design was fabricated and successfully tested, allowing the full production of the DTS modules to proceed. Construction of the DTS modules, the formatter, and the de-formatter continue to meet the antenna outfitting schedule. Procurement of the half transponders for all DTS modules was completed. The prototype design of the 3-bit, 4 GHz sampler was completed, and a circuit card for the sampler was been designed, built, and received.

Intermediate Frequency (IF) Systems

The three frequency converters that up- or down-convert RF signals from the antenna receivers to the 8–12 GHz IF of the EVLA were designed, prototyped, and placed into production

Correlator

The design of the new correlator chip was released for production in December 2005. Ten packaged correlator-chip prototypes were delivered to Penticton in June 2006. A manufacturer was selected for the

fabrication of all printed-circuit boards for the correlator. The order for the first station-board prototype was placed, with an expected delivery of September 2006.

Monitor and Control (M&C)

An interim Observation Executor is now used more widely and supports even more capabilities than can be specified in a VLA Observe file. VLA operators, some astronomers, and some engineers now use a web-based interface to the Observation Executor to submit jobs for EVLA antennas. EVLA antennas have been included in some of the standard observing sessions, such as the pointing runs used to determine the coefficients in the antenna-pointing models. Requirements for the final version of the Observation Executor were developed in May 2006.

Another area of significant progress has been the development of software to enable the EVLA antennas to participate in transition-mode observing with the VLA antennas and correlator. Software is now available to allow the observer and array operator to include EVLA antennas in most standard-observing-mode experiments. A production version of an interim program that makes complex antenna gains and on-the-fly pointing offsets available to the EVLA M&C system was completed in March 2006. Test and verification plans were produced to specify the software needed to support the testing of the prototype station and baseline boards for the new WIDAR correlator. Development work began on Interim Data Capture and Format (IDCAF), the software that will format and write VLA-format archive records from the M&C system. The final version of the Module Interface Board (MIB) that allows communications between electronics modules and the M&C system was designed, tested, and released for production.

Data Management

Two software engineers were hired to work on the High Level Architecture (HLA) for EVLA Science Support Systems (SSS) software. The HLA effort continues to concentrate on the development of models for its various components. The first application to use these models was the Observation Preparation Tool (OPT). The first release of the OPT was made. A second release of the VLA Proposal Tool took place in May 2006, when 120 proposals were received. The scientific requirements for all SSS subsystems for the EVLA were examined in detail and re-prioritized.

The Interferometry Software Division (ISD) continued work toward the development of common EVLA and ALMA models in order to facilitate the EVLA's reuse of ALMA software. Work is under way to use the ESO/ALMA storage technology for the VLA/VLBA archive.

EVLA Milestones

The table below lists the FY 2006 milestones for the EVLA given in the 2006 NRAO Program Plan, updated with the performance on those milestones.

EVLA Milestones from the 2006 Program Plan

Item	Planned	Current Plan
Use EVLA antennas for routine VLA operation	6/2006	8/2006
New correlator shielded room complete	9/2006	8/2006
Complete top-level design of e2e software	5/2006	10/2006
Retrofit a total of 7 antennas to the EVLA design	9/2006	11/2006
Complete installation of array fiber infrastructure	9/2006	7/2007
Continue design/construction of EVLA corrrelator		ongoing

6. Telescope Science Operations

6.1. North American ALMA Science Center

The first NAASC Science Workshop was held in Charlottesville in January 2006 to a capacity crowd. The initial NAASC Staffing plan was developed and presented to the NSF in April 2006. Presentations and Town Meetings were given at each AAS meeting (January 2006 in Washington D.C.; June 2006 in Calgary) and to NRAO Committees and the NSF. The NAASC staff together with interested parties from NRAO Operations and ALMA Construction participated in software tests of all the major user software systems (offline, pipeline and observing tool). Work started on developing a spectral-line catalogue, and this prototype system was successfully interfaced to the ALMA Archive. More formal discussions with our Canadian partners were held to fully integrate them into the NA ALMA operations planning. The ANASAC was reconstituted to provide more focus and constructive input into the NAASC operations planning. Finally, the NAASC staff were instrumental in revising and updating the overall ALMA Operations plan and budget.

6.2. Green Bank Telescope (GBT)

Observing Software

ASTRID (the ASTRonomer's Integrated Desktop) is a unified workspace that incorporates the GBT's new scheduling-block-based observing system with the real-time quick-look display. ASTRID allows observers to build observing scripts as part of their scheduling blocks well in advance of their observations. The full release of ASTRID, including source catalogs, support for non-sidereal sources, and control of the pulsar spigot, was completed as planned in early FY 2006. All observations are now performed using Scheduling Blocks and ASTRID, and this new interface has proved extremely successful and very popular with astronomers.

Data Analysis Software

GBTIDL is the interactive package for reduction and analysis of spectral-line data taken with the GBT. GBTIDL development continued during FY 2006, and GBTIDL is now at release 2.0.1 and considered mature. As planned, the IDL algorithms have been made available to the quick-look data display, so that GBT data for all continuum and spectral-line observing modes are now displayed in real time by a single software application. A generic flagging solution was developed and was released with GBTIDL Version 2.0.

Heterodyne Instrument Program

High-Frequency Receivers: The Ka-band (26–40 GHz) and Q-band (40–50 GHz) receivers were released as planned for Winter 2005/2006. Early science and commissioning observations at the start of FY 2006 revealed intermittently poor spectral-baseline performance with both receivers. The baseline problems may result from intrinsic properties of the low-noise amplifiers. If this is the case, faster switching with the existing receiver can ameliorate the effects at Ka band, but the Q-band receiver may require a major hardware redesign. Retrofits to the Q-band receiver to restore the full 40–50 GHz bandwidth and to the Ka-band receiver to accommodate the Zpectrometer were performed as scheduled during summer 2006.

Caltech Continuum Backend (CCB): The CCB is a collaborative project between Caltech and the NRAO to develop a fast-switching high-sensitivity continuum backend for use with the Ka-band and future W-band (λ = 3 mm) receivers. This backend is capable of analyzing essentially the full bandwidth of each

receiver, with the bands broken into three or four sub-bands to allow some spectral analysis. CCB development was funded as part of the Observatory's University-built Instrumentation Program. The first CCB unit, for use with the Ka-band receiver, was completed and commissioned as planned in FY 2006. Extremely successful science observations were performed. The second and third units (for the W-band receiver and a spare) were completed, completing the project.

Zpectrometer: The Zpectrometer is a wide-band analog spectrometer under construction by Prof. Andy Harris at the University of Maryland. Green Bank staff will provide software development, interfacing, and other support. The Zpectrometer covers the full 14 GHz-wide Ka band with a set of analog lag correlation spectrometers in a multichannel correlation-radiometer architecture. The Zpectrometer's bandwidth and stability, combined with the GBT's collecting area, enable sensitive and efficient spectral searches for molecules in high-redshift galaxies. The instrument is optimized for observations of low-excitation spectral lines from the carbon monoxide (CO) molecule at redshifts of $1.88 < z < 3.43$ and $4.76 < z < 7.87$. These ranges of redshifts are of intense current interest because they may correspond to the eras when most of the stars in the universe formed and when galaxies were assembled, respectively. Development work for the Zpectrometer began as planned in FY 2006, and the preliminary instrument commissioning should commence in early FY 2007.

Penn Array Camera

The Penn Array is a 64-pixel bolometer camera for the $\lambda = 3$ mm band that is being developed by a consortium of the University of Pennsylvania, NASA-Goddard, NIST, Cardiff University, and the NRAO, and funded largely through the NRAO University-built Instrumentation Program. The camera has an 8×8-pixel array with full spatial sampling; the field of view is approximately 30" × 30" and the angular resolution is about 8" per pixel. The detector array is made up of state-of-the-art Transition Edge Sensors (TESs) with SQUID multiplexers, all cooled to a cryogenic temperature of 0.25 K. The sensitivity of the array should be better than 500 μJy/$\sqrt{}$sec per pixel.

Engineering commissioning began near the end of FY 2006, and the GBT detected Saturn at 3 mm wavelength.

Precision Telescope Control System

The "out-of-focus" holography campaign designed to correct the elevation-dependent surface deformations was extremely successful and resulted in a new model for the surface, now in routine use, which flattens the gain-elevation curve at all observing frequencies.

Azimuth Track Refurbishment

All contracts for the azimuth track were placed in FY 2006. This work remains on schedule for completion in summer 2007.

RFI Mitigation

The National Radio Quiet Zone (NRQZ) remains a unique National resource, and we have renewed our commitment to preserve our relatively RFI-free environment to the greatest extent possible. Recent outstanding pulsar discoveries resulted directly from the low RFI in Green Bank and provide a compelling argument as to why this work remains vital. Recent progress includes development of five zones around the GBT within which clear RFI policies have been defined and documented, installation of an abbreviated version of the GBT RFI monitoring station, hiring of a new NRQZ administrator, and the start of a public-relations campaign to raise awareness of RFI issues in the local community via

newspaper, radio, and direct mailing. In addition, material is being developed and distributed to communicate on-site RFI policy (signs, leaflets, web-based material, presentations), and mitigation efforts are underway for all on-site telescopes and projects. The RFI group is also facilitating a collaborative propagation-model study with Virginia Tech and the Naval Surface Warfare Center.

Externally Funded Projects

In FY 2005, the NRAO and Lincoln Laboratories entered into a collaborative agreement to measure the properties of the Earth's ionosphere using bi-static radar techniques. The project consists of two phases: (I) System Development and Implementation, and (II) Operations. Phase I was completed to budget and schedule in March 2006. Phase II is proceeding and we currently expect this to continue at least through FY 2007.

We supported a number of other externally funded projects on the Green Bank site, providing infrastructure support and, in some cases, a modest level of staffing funded by the relevant project. These include the Solar Radio Burst Spectrometer (SRBS) and the Precision Array to Probe the Epoch of Reionization (PAPER).

A summary of performance against milestones in FY 2006 for all GBT Projects is provided in the table below.

GBT Milestones from 2006 Program Plan

Item	Planned	Accomplished
Initiate 43m MIT/LL test observations	10/2005	10/2005
Q-band production science begins	10/2005	10/2005
Initiate Zpectrometer instrument construction	11/2005	11/2005
Ka-band spectral line commissioning complete	11/2005	11/2005 (see note)
Begin CCB commissioning	12/2005	11/2005
Integrate pulsar spigot control into std observing	12/2005	10/2005
AZ track refurbishment contracts let	12/2005	4/2006
Initiate Penn Array /3mm engineering tests	02/2006	09/2006
Agree on dynamic scheduling policies and processes	05/2006	06/2006
Full Q-band bandwidth restored	09/2006	09/2006

6.3. Very Large Array (VLA)

Observing and User Programs

Two VLA Large Programs were completed in FY 2006: the VLA Low-frequency Sky Survey and a study of radio afterglows from gamma-ray bursts discovered by the Swift satellite. A special proposal call was made for extragalactic "blank field" observations associated with deep surveys by other telescopes; four such programs, ranging from 60 to 90 hours of total observing time, were allocated time and observed during the past year.

The 10th Synthesis Imaging Summer School was held in June 2006 at the University of New Mexico and at the NRAO. It was the largest yet, with approximately 170 attendees at the 8-day school.

A new VLA Proposal Submission Tool debuted for the February 2006 proposal deadline and was required at the June 2006 proposal deadline. This tool is in common with the GBT and is ultimately expected to include VLBA capability as well.

EVLA Transition

Transition observing using EVLA antennas together with VLA antennas and the old correlator was debugged. Six EVLA antennas were returned to the operational VLA for all users. The NRAO began preparing a forecast of short-, medium-, and long-term predictions of VLA capabilities during the transition to EVLA. This forecast is e-mailed to a large list of individuals who have written VLA proposals in the past, approximately two weeks prior to each proposal deadline.
A first draft of a comprehensive EVLA Operations Plan for 2012 was completed and distributed for review. This plan provides the scientific and budget requirements for baseline EVLA Operations and for a new Array Science Center for the EVLA and VLBA. The draft plan also is the basis for generating a staffing plan for EVLA/VLBA Operations between 2007 and 2012.

VLA + Pie Town Link

The fiber-optic link between the Pie Town VLBA antenna and the VLA was offered to observers once again in FY 2006. This link doubles the longest baseline of the VLA, improving the angular resolution by a factor of two for complete syntheses of northern sources and somewhat less for shorter observations or sources at low declinations. During the A-configuration period from February 2006 through May 2006, a total of 23 observing programs used the Pie Town link in 31 sessions for a total of 240 hours of observing, nearly 15 percent of the total A-configuration scientific observing time.

Dynamic Scheduling

During the antenna reconfigurations in fall 2005 and winter 2006, the VLA was primarily scheduled dynamically, with progressively more refined combinations of VLA and EVLA software. Beginning in May 2006, all "filler" VLA time was scheduled dynamically.

Infrastructure

The degenerated azimuth bearing on antenna 26 was replaced by a new bearing in FY 2006, the 11th such bearing replacement done on the VLA.

The standard Astronomical Image Processing System (AIPS) used for both the VLA and VLBA continued to be supported by the NRAO for export to its entire user community: a frozen 31DEC05 version of AIPS and a daily-updated 31DEC06 version were produced.

The VLA was the last remaining NRAO VLBI telescope recording data with the old longitudinal tape transports; a new Mark 5 disk-based recorder was installed at the end of FY 2006 to replace the tape recorder.

VLA Data Archive

A pilot project to produce images of all 5 GHz and 8.4 GHz archive data from a single VLA B configuration was completed in late FY 2006, and responsibility for the project was transferred to the NRAO e2e Operations Division.

VLA Milestones from the 2006 Program Plan

Item	Planned	Accomplished
Freeze AIPS version 31DEC05, begin 31DEC06	12/2005	12/2005
Release the new VLA proposal tool	12/2005	01/2006
Initiate the next Pie Town link observations	02/2006	02/2006
Return the first EVLA antennas to the VLA	01/2006	03/2006 (on request) 08/2006 (default)
Replace one azimuth bearing	09/2006	05/2006
Initiate operational dynamic scheduling	12/2007	05/2006 (filler time)
Complete the archive imaging pilot project	01/2006	Early FY 2007
Replace 3,500 railroad ties	09/2006	Only ~3,000 done
Decommission the Modcomp computers	07/2006	Moved to FY 2007

6.4. Very Long Baseline Array (VLBA)

Observing and User Programs

The VLBA continued to perform scientific observing for about 50% of the wall-clock hours in FY 2006, or 65% if scaled to the sustainable data rate of 128 Mbps.

The observations for three large VLBA programs began in late FY 2005 and early FY 2006 and continued throughout the fiscal year: long-term monitoring of the structures of active galaxies at 15 GHz, 5 GHz VLBA Imaging Polarimetry Survey (VIPS) of 1000 blazars that are likely to be gamma-ray sources detected by GLAST after its launch in late 2007, and an astrometric investigation of the spiral structure and kinematics of the Milky Way galaxy. Observations for the VIPS program were completed late in FY 2006.

Mark 5 Recording System

The VLBA was completely converted to Mark 5 except for global observations that required more than 11 inputs to the correlator. At the end of FY 2006, the VLA was converted to Mark 5 recording, and the number of correlator inputs was raised to 14 Mark 5 units in order to input the High Sensitivity Array (HAS = VLBA, VLA, GBT, Arecibo, and Effelsberg) on disk.

International VLBI

The VLBA took part in three global runs of the worldwide centimeter-wavelength VLBI network and two global $\lambda = 3$ mm VLBI sessions. These fixed sessions defeat the advantages of dynamic scheduling on the VLBA alone but provide additional scientific capabilities by providing significantly more collecting area and improved imaging capabilities. Since many of the users of the VLBA (and the VLA) are from non-U.S. institutions, we have begun discussions with our international partners about how we might increase the international participation in funding and governance of the VLBA in order to maintain and enhance its scientific capabilities.

Astrometry

The VLBA continued its bimonthly participation in geodetic/astrometric observations to improve the accuracy of the fundamental astronomical reference frame and to determine the Earth-orientation parameters. The VLBA often is used with other non-NRAO telescopes to place all VLBI antennas on a

common geodetic frame, and it provides the strongest data in the long-running studies of such fundamental issues such as continental drift and nutation of the Earth.

The relative position accuracy of radio sources reached the 10 microarcsecond level in a number of VLBA experiments. This precision is obtained thanks to the high stability of the VLBA system, the improved signal-to-noise resulting from increased bandwidth, and the availability of thousands of position calibration sources well distributed over the sky. Comparable astrometric precision will not be reached in the optical domain until the space-based astrometric observatory GAIA is launched in about 2012. The further increased sensitivity of the VLBA, discussed in the long range plan, will more than triple the number of detected radio stars and enable more studies of galactic dynamics with the VLBA.

Phase referencing, which is needed for astrometric observations and for detecting weak radio sources, is now used for more than half of all VLBA experiments. New phase-referencing observing strategies were developed to decrease the systematic phase errors that are often the main limitation to astrometric accuracy and image quality. In order to provide the VLBA astrometric capabilities to the larger astronomical community, the AIPS software system was updated to include astrometric corrections, pipeline and semiautomatic data-reduction processes, and a variety of astrometric programs for correcting ionospheric and tropospheric refraction.

Infrastructure

A program was started in the first quarter of FY 2004 to replace the expensive high-maintenance analog tachometers with low-noise digital tachometers. This was completed in July 2006 with installation of digital tachometers on the Mauna Kea VLBA station.

Standard VLBA tiger-team visits were made to the Kitt Peak, Mauna Kea, and Hancock VLBA antennas during FY 2006. These visits typically involve teams of 6–8 individuals who spend 1–2 weeks on intensive maintenance overhauls of the antenna systems. The three stations generally were found to be in good shape, although the antenna in Hancock, NH also shows signs of long-term deterioration due to the weather and needs repainting.

Since its inception, cooling of the VLBA correlator has relied on air-conditioning units that were original equipment at the VLA site in the late 1970s. These units have reached the end of their operational lives and can no longer be maintained. New air conditioning units were installed in FY 2006 in order to keep the correlator operational.

VLBA Data Archive

All VLBA archive data from late 1998 through the most recent data correlations were loaded into the on-line VLBA archive.

Performance on VLBA Milestones from the FY 2006 Program Plan

The VLBA milestones from the FY 2006 Program Plan and the performance on those milestones are listed below.

VLBA Milestones from the FY 2006 Program Plan

Item	Predicted	Accomplished
Eight full-time Mark 5 stations	10/2005	12/2005
Ten full-time Mark 5 stations	6/2006	6/2006
Completion of the digital-tachometer conversion	6/2006	7/2006
Paint the St. Croix antenna	6/2006	Deferred to 2007
Observing increase to 58% of hours in year	9/2006	Data rate increased instead
Maintenance visits to HN, MK, and SC	9/2006	Visited KP, MK, and HN; evaluation visit to SC

7. Technical Capability Development (Central Development Laboratory)

Cryogenic HFET Development

Amplifier Development: New amplifier designs for 4–8, 4–12, 12–18 and 40–50 GHz for the EVLA were completed. A collaborative effort with the Center for Astrophysics (CfA) on mm-wave SIS mixers with extremely wide IF bandwidths required development of yet another version of this amplifier covering 5–20 GHz. A redesign of the 35–46 GHz amplifier developed originally for WMAP to achieve flat noise and gain over the 40–50 GHz EVLA frequency band was successfully completed.

Production amplifiers were built for receiver systems on the GBT and EVLA. The total number of new amplifiers produced in the last year was 50, of which 32 were delivered to the EVLA. In addition, work was carried out to repair and perform Cryo-3 upgrades to 25 additional LNAs.

Amplifier Research: Progress in SiGe and InP heterostructure bipolar transistors (HBTs) has made their application in radio-astronomy receivers feasible at frequencies up to 115 GHz. Although these devices are not expected to offer the noise performance of InP HFETs, especially at cryogenic temperatures, they could in principle offer an order-of-magnitude lower 1/*f*-like gain fluctuations, which currently set the minimum switching frequency of broadband continuum receivers, thus improving radiometer sensitivity and perhaps lowering cost. Research into noise models of HBTs applicable at cryogenic temperatures has started, and a paper study of their noise properties was published.

MMIC Development

The CDL continued development of a wide variety of custom centimeter- and millimeter-wave Monolithic Millimeter-Wave Integrated Circuit (MMIC) components. A MMIC-based approach for the front ends holds the promise of more compact, lightweight receivers and possible cost savings for large array receivers. This will have a positive impact on many fronts from cryogenics and power distribution to antenna structure and maintenance operations, as well as improved impedance match, gain slopes, and even optical parameters such as beam spacing and field of view.

In FY 2006, new MMIC designs included:

1. A revised version of the wideband MMIC LNA for the 11–34 GHz SKA band.
2. A new GaAs MMIC power amplifier (PA), fabricated at BAE Systems, that meets the requirements for ALMA Bands 4, 8, and 9 with better lifetime than previously existing Pas.

In addition to these MMIC designs, a wide-bandwidth Voltage Controlled Oscillator (VCO) MMIC development effort was carried out by a post-doctoral visiting researcher from the Institute of Astronomy and Astrophysics, Academia Sinica (ASIAA) under the guidance of CDL staff. Four different MMIC VCOs were designed and are being fabricated at a Taiwanese foundry.

Millimeter- and Submillimeter-Wave Receiver Development

In addition to ALMA 211–275 GHz receiver work, there are three millimeter and sub-millimeter technical development efforts being carried out at the CDL (only one of which is funded by the NRAO): development of a new SIS mixer design for 385–500 GHz, development of a Hot Electron Bolometer (HEB) mixer for 600–720 GHz, and a new technology development effort for 350 μm (780–950 GHz) heterodyne receivers.

385–500 GHz SIS mixer: The joint R&D project between the NRAO and the UVa for a new 385–500 GHz beam-lead SIS mixer, supported mainly by an NSF grant to the UVa, continued. The NRAO is providing mixer designs and the UVA foundry is fabricating devices. This work will explore the use of both Nb and NbTiN materials for sub-mm SIS mixers. Mixer design using beam-lead connections of the mixer chip to the external circuit is complete. Development of the junction fabrication process was carried out.

HEB mixers: This work began as a Small Grant for Exploratory Research from the NSF under the Approaches to Combat Terrorism program. Although the grant has ended, collaboration with the University of Virginia continued, supported partly through UVa's NSF grant. The goal of this work in FY 2006 was to verify that the performance of the ultra-thin Silicon on Insulator (SOI) substrate beam-lead HEB mixers matches that of the existing state-of-the-art waveguide HEB mixers. Design and optimization of the next phase of 1.5 THz pHEB mixers on SOI can then proceed. Phonon-cooled (pHEB) mixers designed and built at the Uva have been successfully cryogenically tested at the CDL. An NSF REU summer student upgraded the test receiver to include a 3–13 GHz cryogenic LNA; the pHEB mixer was measured to have an IF bandwidth greater than 7 GHz, which is the widest IF bandwidth ever reported for this type of mixer.

350 μm (780–950 GHz) Heterodyne Receiver Technology Development: At present, no heterodyne receivers for the 350 μm atmospheric window can achieve the nearly quantum-limited sensitivity that niobium SIS receivers provide below ~600 GHz. Success in this work would enable the NRAO to provide the best possible receivers for ALMA Band 10 and provide bridging funds to continue mm-wave receiver development at the NRAO and the Uva until the start of ALMA operations. The goal is to produce reliable, repeatable, inexpensive, quantum-limited receivers using recently developed SIS mixer fabrication technology.

Our collaborators, the University of Virginia Microfabrication Laboratory (UVML), have successfully developed a process for producing high quality NbTiN films, a major step towards NbTiN SIS junctions. In addition, the first NbTiN trilayer structure (NbTiN/AlN/Nb) has now been made at the UVML. .

Balanced SIS Mixer Development: Our work on balanced mixers is funded primarily by the Arizona Radio Observatory of the University of Arizona.

Balanced mixers have three desirable characteristics for radio astronomy receivers: (i) immunity to LO sideband noise, (ii) 50 times lower LO power requirement, and (iii) 3 dB greater dynamic range. A critical component of a balanced mixer is a 180-degree IF hybrid which separates the downconverted signal and downconverted LO sideband noise. We designed and tested a superconducting 180-degree IF

hybrid covering 4–12 GHz that is small enough to be mounted inside the mixer block. The hybrid was fabricated at the University of Virginia Microfabrication Laboratory and tested at the CDL.

Electromagnetics

Thanks to recent advances in wide-band amplifiers and mixers, the bandwidths of many receiving systems are no longer limited by these active components, but by passive components such as feed, phase shifter, and orthomode transducer. We designed and tested several new components with the goal of having receiver performance limited only by the bandwidths of single-mode waveguide at high frequencies and by feed dimensions at low frequencies.

The holography receiver for measuring ALMA antennas will be used at 79 and 104 GHz. A scaled prototype of the holography feed was designed with a center frequency of 4.28 GHz. This feed was designed to provide flatter amplitude and phase patterns than an earlier feed. The measured illumination taper at 62° is -5.5 dB and the 10 dB beamwidth is 156°.

A scaled version of the EVLA 4–8 GHz feed for 2–4 GHz would result in an aperture diameter of 44 inches for the 2–4 GHz feed, which would not fit in the available space. A new design with an aperture diameter of 42 inches was completed. A half-size prototype of this feed was fabricated and successfully tested.

The GBT beam at 1.4 GHz was calculated using the NEC-Reflector code (SatCom Workbench) developed at the Ohio State University.

A study of the beam-pattern properties of a prime-focus array receiver for the GBT at 1.4 GHz and 2.5 GHz was completed. For a 2.4λ feed offset, the gain loss of the telescope is about 1 dB. A feed array with one feed on-axis and six feeds in an outer ring is a possible configuration for a gain loss under 1 dB for the outer feeds.

Green Bank Solar Radio Burst Spectrometer (GB/SRBS)

In June 2003 the NRAO received a three-year NSF MRI grant to develop the Green Bank Solar Radio Burst Spectrometer (GB/SRBS), an instrument to receive solar radio emissions with adequate temporal and spectral resolution to probe a wide variety of active solar phenomena from the base of the corona. It consists of radio spectrometers to provide contiguous frequency coverage from 10 to 2500 MHz. It provides a basic research tool in solar radiophysics for use by the wider community, remedies the lack of an important component of the U.S. Space Weather effort, and provides a platform for research and development work on broadband antennas, feeds, and receivers needed for the upcoming Frequency Agile Solar Radiotelescope (FASR) project.

Two systems covering the bands 20–70 MHz and 250–1000 MHz continued to operate on a daily basis with excellent reliability, and the data were archived for public access. All of the instrument development tasks were completed. A dual-polarization wide-bandwidth antenna that covers 70–300 MHz was designed and fabricated; a prototype digital spectrometer for 30–350 MHz was completed. Work to install and upgrade all systems, including telescope and infrastructure improvements, was completed in August 2006.

Graduate students continue to be an integral part of the instrument program. One student from the University of Virginia developed a high-speed data-acquisition and analysis system that will use the GB/SRBS receiver on the 45-foot telescope to search for the very short duration (<10 nS) pulses of Cherenkov radiation emitted when a high-energy particle interacts with the lunar regolith. This work was

partially supported by a grant from Sigma Xi. Another graduate student from the University of Virginia is developing an improved wide-bandwidth sinuous feed that is highly integrated with a low-noise amplifier. This work will also have direct application to the proposed FASR array. A cryogenic version of the integrated front-end system is also being studied.

Precision Array to Probe the Epoch of Reionization (PAPER)

At the end of the "Dark Ages" the first stars formed from the gravitational collapse of the densest regions of the primordial cosmic structure. Ultraviolet photons from these stars excited the hyperfine (spin-flip) transition in hydrogen and led to emission from the intergalactic medium in this spectral line, now greatly redshifted. The NRAO is assisting in the development of an instrument designed to search for this hydrogen signature of reionization. A team of researchers from U. C. Berkeley, the University of Virginia, and the NRAO is pursuing the design, fabrication, deployment, calibration, and operation of this unique imaging instrument. A prototype array is being developed for deployment in Green Bank, while a larger version is being planned for Western Australia.

Three graduate students are actively involved in this work. The U.C. Berkeley researchers in conjunction with the Berkeley Wireless Research Center and the Center for Astronomical Signal Processing and Engineering Research developed an 8-channel full-Stokes correlator. The NRAO and University of Virginia researchers designed, fabricated, and characterized eight 120–200 MHz RF sub-systems. An effective, inexpensive shielded enclosure was developed for RFI prevention. In June 2006 the group successfully deployed an 8-element full-Stokes imaging array in Green Bank with a maximum baseline length of 300 meters.

We have also assisted our Australian colleagues in defining the infrastructure requirements for the Radio Astronomy Park currently being established at a site within Mileura Station, and we participated in discussions regarding the legislation of a Radio Quiet Zone in Western Australia.

8. Community Support Programs

8.1. End to End (e2e) Operations

The e2e operations division was created in FY 2006 to broaden access to NRAO facilities and increase their scientific impact. Its major activities were building the organization and defining its role. The major e2e milestones met in FY 2006 are listed below.

FY 2006 Milestones

Milestones	Delivery Date
Acquire and install ESO/NGAS Archive Software	01/2006
Initial planning for 3rd annual NVO Summer School	04/2006
Draft SSA 1.0 interface	05/2006
SIA 1.1 planning for May IVOA interop	05/2006
Initial draft spectral line list interface	05/2006
IVOA interoperability workshop (Victoria BC)	05/2006
NRAO/NVO archive/VO planning meeting held	06/2006
Scalable data analysis framework prototype	06/2006

Milestones	Delivery Date
NVO/Opticon data analysis frameworks workshop	06/2006
Install archive host prototype #2	07/2006
VOClient software for NVO summer school	07/2006
DAL service reference code in Java	07/2006

8.2. Scientific Community Outreach

The summer-student program allowed 25 undergraduate and graduate students to learn and work under the supervision of the NRAO staff members. The NRAO provided $200,000 in financial support to graduate students using the GBT, and this popular program is being expanded to cover all NRAO telescopes. The NRAO continued its successful Jansky Postdoctoral Fellowship program.

8.3. Spectrum Management

The International Telecommunications Union (ITU) adopted for study the subject of national radio-quiet zones, first formulated by the NRAO. The NRAO coordinated sharing of the 94.1 GHz between CloudSat radar and the world radio-astronomy community.

8.4. Education and Public Outreach (EPO)

A program for radio astronomy outreach to science museums and planetariums was inaugurated via collaboration with the Space Telescope Science Institute Office of Public Outreach and the multi-media program *ViewSpace*. The NRAO EPO delivered a *ViewSpace* program module that now distributes the NRAO science press releases to 100+ museums and planetariums.

EPO redesigned the NRAO exhibits that are deployed to professional astronomical meetings, such as the January (Washington D.C.) and June (Calgary) American Astronomical Society (AAS) meetings. Two exhibits were designed for the International Astronomical Union General Assembly (Prague, August): an NRAO exhibit, and an ALMA exhibit (a collaboration with JAO, ESO, and NAOJ).

EPO collaborated with the White Sands Missile Range and the New Mexico Institute of Mining and Technology to celebrate the 100th anniversary of Einstein's *annus mirabilis*. The Research Experiences for Teachers (RET) program continued, with participants presenting their research results at AAS meetings. The weeklong Education Research in Radio Astronomy (ERIRA) workshop continued as a cooperative effort of the NRAO, the University of Chicago, and the University of North Carolina, providing tours and observing projects for high school and undergraduate students. Three-day residential Chautauqua programs in Green Bank and Socorro continued a 20-year NRAO tradition of serving undergraduate science faculty. Green Bank hosted a NRAO / NASA *Living with a Star* workshop for 15 teachers and followed this with a *Hands-On Universe* teacher workshop. Teachers are being trained to use both the instruments and the curriculum developed through the NASA-funded *Quiet Skies* program for their classrooms. The NRAO and New Mexico Tech offered a two-week course, *Radio Astronomy for Teachers*, in the summer. The West Virginia Governor's School for Mathematics and Science returned to Green Bank in August, and the Virginia Governor's School visited the NRAO Technology Center and Green Bank in late July. GEAR-UP camp, a federally funded program that helps high school students reach and succeed in college, returned to Green Bank. EPO also collaborated with the Society of Amateur Radio Astronomers to define and seek funding for a pilot program that trains volunteers as the NRAO *Navigators*, bringing radio astronomy to venues across the U.S.

Fifteen press releases were distributed in FY 2006.

EPO initiated several new publications. Two high-quality color posters were produced and were widely distributed to the astronomical community and the general public. EPO Scientist Juan Uson continued to explore radio data visualization techniques and produced several excellent radio-optical composite images. EPO renewed the successful AUI/NRAO Radio Astronomy Image Contest.

The CY 2005 attendance at the Green Bank Science Center was 44,717 persons, an increase of 10.0% (4,077 persons) compared to CY 2004. The CY 2005 attendance at the VLA Visitors Center was 21,832 persons, a decrease of 6.3% (1,467 persons) from CY 2004. A $7.2M NRAO–University of New Mexico proposal was submitted to the NM State Legislature in January for the design and construction of a new 15,000 sq. ft. VLA Visitor and Education Center. A new Expanded Very Large Array exhibit was designed and installed at the VLA Visitors Center.

EPO staff participated in numerous community activities, including K–12 science activities in Green Bank, Socorro, and Charlottesville, providing speakers, judges, coaches, volunteers, prizes, and special tours. EPO staff also visited schools to lead science enrichment activities and gave invited talks to civic groups.

9. Management and Administration

9.1. Administration

Environment, Safety, and Security (ES&S)

ES&S formalized an Asbestos Management Program for use in facilities where asbestos has been identified. This program includes training specific employees in management and disposal procedures for asbestos materials and overseeing all asbestos-removal projects to ensure the health and safety of employees and visitors.

The NRAO completed an Observatory-wide environmental compliance audit in FY 2006. Thanks to our continued commitment to the protection and enhancement of the environment for research and administrative operations, no significant findings were noted. Within the NRAO, Observatory management establishes the standards that all employees have the responsibility to act consistently with environmental principles and objectives.

ES&S provided frequent safety education and awareness training to affected employees. Additionally, ES&S began a proactive program of inspection and training for the VLBA facilities. ES&S developed a VLBA-specific site inspection checklist designed to identify deficiencies and suggest corrective actions.

ES&S successfully developed the ALMA Safety Program. This program was reviewed by ESO, the NRAO, and the NAOJ to ensure compliance with international requirements. The ALMA Safety Manager is responsible for its implementation.

Fiscal Division

The NRAO completed an update of the Chart of Accounts to correlate with the implemented Work Breakdown Structure (WBS) system. Expansion of the WBS system provided more detailed geographical reporting capability and the addition of multiple WBS levels within each project.

As of January 1, 2006 the payroll function was converted to the central database of JD Edwards/Peoplesoft, effectively maintaining labor data in a central location to meet expected reporting requirements.

9.2. Computing and Information Services (CIS)

FY 2006 Milestones

Milestones	Delivery Date
1. 20 Mbps network service among the major NRAO sites	11/2005
2. New email quarantine service fully deployed	01/2006
3. Migration of Windows systems to AD domain complete	01/2006
4. Deployment of Google Mini for searching internal web pages	03/2006
5. Upgrade of the central disk filer in Charlottesville	04/2006
6. System administrators meeting in Socorro	04/2006
7. Begin new CCE coordination for Apple OS/X	04/2006
8. Deploy new central Ethernet hub in Green Bank	05/2006
9. Upgrade the main web server	05/2006
10.Upgrade capacity of the Google Mini search engine	05/2006
11. Draft data-security policy	07/2006
12. Migration to RedHat Enterprise Linux 4 complete at all sites	09/2006

9.3. Program Management Office (PMO)

While this is not a traditional PMO role, the NRAO PMO continued to lead the modernization of Observatory business services and systems by implementing the NRAO Web-Based Business Services (WBBS). The WBBS system improves the accuracy and timeliness of all business information, provides the foundation for project management controls, reduces administrative effort of the Observatory administration and operational business units, and generates early-warning triggers so NRAO project managers can launch mitigation strategies that will prevail in meeting the critical path of these projects.

During FY 2006 the PMO focused substantially on the implementation, prototype testing, training, deployment, and initial operation of the WBBS services.

FY 2006 WBBS Milestones

Service	Status	Completion Date
Architecture Upgrade	Operational	08/2005
Accounts Payable	Operational	10/2005
Job Cost	Operational	10/2005
General Ledger	Operational	10/2005
Human Resources	Operational	11/2005
Employee Self Services	Operational	12/2005

Service	Status	Completion Date
WBBS Help Desk	Operational	12/2005
Payroll	Operational	01/2006
Medical Change Order	Completed	01/2006
Firewall Installation	Completed	06/2006
AUI PeopleSoft Conversion	Completed	07/2006
Procurement	Completed	08/2006
WBBS CCB	Pending	09/2006