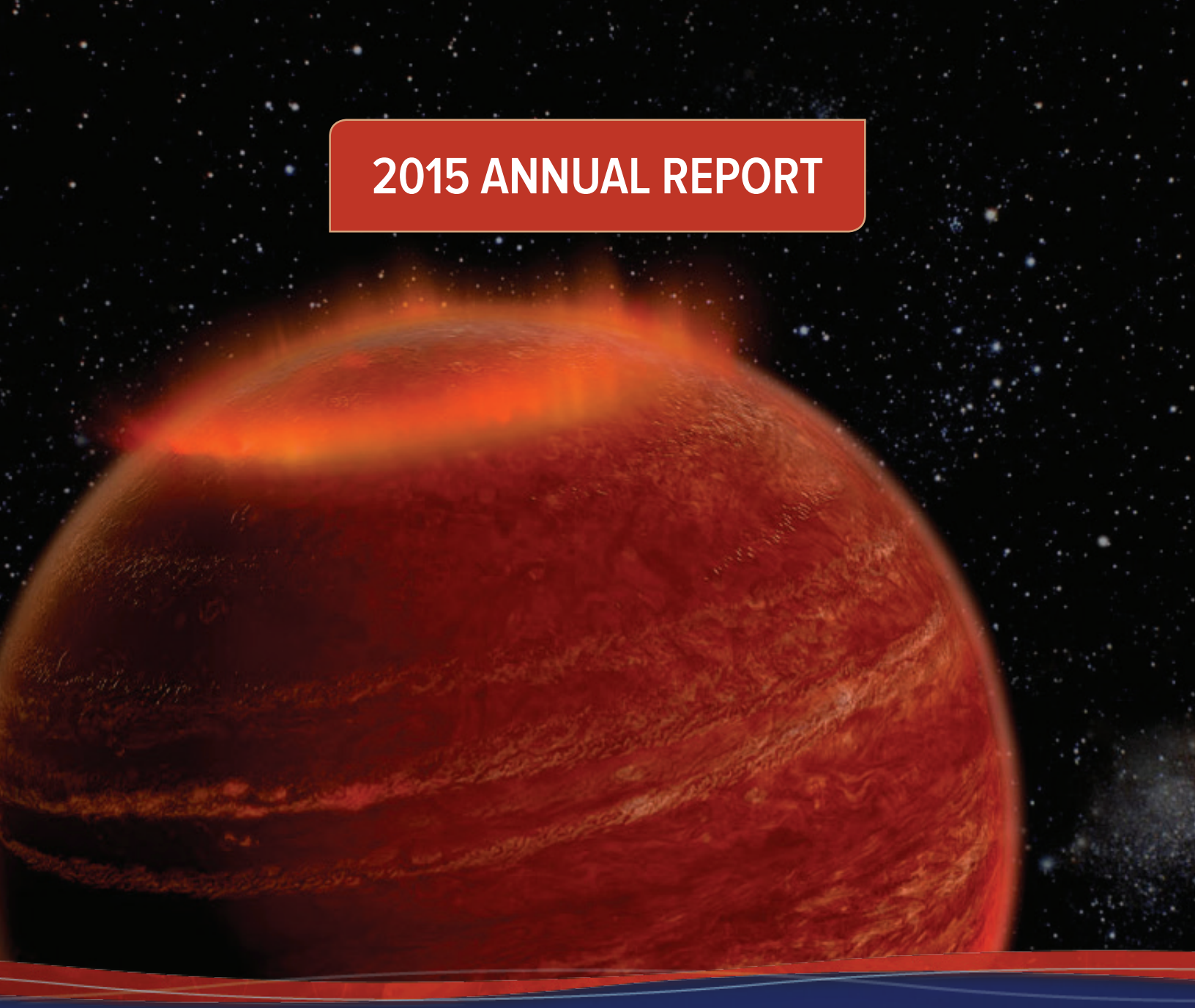
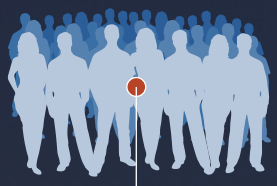
2015 ANNUAL REPORT



NRAO

NATIONAL RADIO
ASTRONOMY OBSERVATORY

NRAO FACTS & FIGURES



496 EMPLOYEES

63 MEDIA RELEASES

666 REFEREED SCIENCE PUBLICATIONS

FISCAL YEAR 2015

NRAO / ALMA OPERATIONS
$86.3 M

EXTERNAL GRANTS
$3.7 M

ALMA CONSTRUCTION
$2.3 M

CALL FOR PROPOSALS

NRAO SEMESTER 2015B

	SUBMITTED	APPROVED
GBT	64	25
VLBA	40	24
VLA	173	56

NRAO SEMESTER 2016A

	SUBMITTED	APPROVED
GBT	49	16
VLBA	41	21
VLA	243	99

ALMA CYCLE 3

1578 proposals requesting 8854 hours

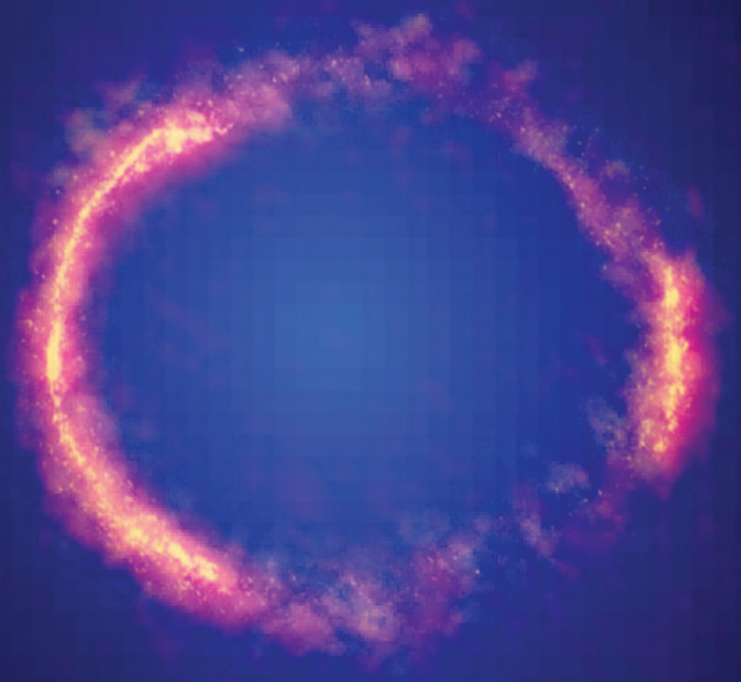
402 APPROVED PROJECTS REQUESTING 2133 HOURS

A SUITE OF **FOUR** WORLD-CLASS ASTRONOMICAL OBSERVATORIES

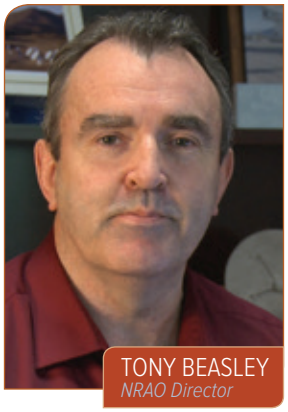
Contents

COVER: *An artists' concept of an aurora over the polar region of a brown dwarf. In their paper, "Magnetospherically Driven Optical and Radio Aurorae at the End of the Stellar Main Sequence" (2015, Nature, 523, 568), a science team led by Gregg Hallinan (Caltech) used the NRAO Very Large Array (VLA), the W. M. Keck Observatory, and the Palomar Observatory to discover auroral emission from the M8.5 brown dwarf J1835+3259. VLA dynamic spectra show circularly polarized cyclotron emission 10^4 times stronger than Jupiter's auroral emission, and the measured magnetic fields are very strong. The aurorae are powered by processes originating far out in the star's magnetosphere, implying large-scale currents with luminosities far greater than those in our Solar System. Brown dwarf systems are prime candidates of searches for life, hence, understanding their interplanetary environment is critical. Credit: Chuck Carter & Gregg Hallinan, Caltech.*

LEFT: *An international partnership between North America, Europe, East Asia, and the Republic of Chile, the Atacama Large Millimeter/submillimeter Array (ALMA) operates at an elevation of more than 5000m on the Chajnantor plateau in northern Chile, and is revolutionizing numerous fields of astrophysics. Credit: P. Carrillo, NRAO/AUI/NSF.*



ABOVE: ALMA/Hubble composite image of the gravitationally lensed galaxy SDP.81. The bright orange central region of the ring (ALMA's highest resolution observation ever) reveals the glowing dust in this distant galaxy. The surrounding lower-resolution portions of the ring trace the millimeter wavelength light emitted by carbon monoxide. The diffuse blue element at the center of the ring is from the intervening lensing galaxy, as seen with the Hubble Space Telescope. Credit: ALMA (NRAO/ESO/NAOJ); B. Saxton NRAO/AUI/NSF; NASA/ESA Hubble, T. Hunter (NRAO)



TONY BEASLEY
NRAO Director

In 2015, National Radio Astronomy Observatory (NRAO) research facilities enabled numerous ground-breaking scientific results. We also made excellent progress against several long-term challenges, and launched key initiatives that will drive the Observatory forward for a decade or more.

NRAO federal funding for 2015 was as expected, and operations costs remained relatively constant. Despite an increasingly complex political situation in the U.S. Congress, the National Science Foundation (NSF) and research, in general, enjoyed bipartisan Congressional support. Over the past several years, we have endeavored to develop NRAO's intellectual property activities and sources of commercial income consistent with our mission and culture. These efforts are now returning significant benefits to NRAO as they steadily grow and mature.

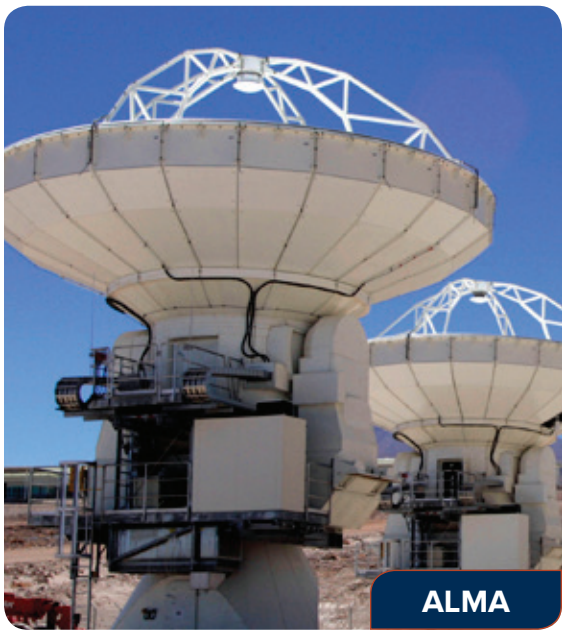
Late in 2015, our parent organization – Associated Universities, Inc. (AUI) – won the contract to manage NRAO for another ten years. The AUI proposal for the next decade – 1 October 2016 through 30 September 2026 – includes important initiatives for the Observatory and the community, including: Science Ready Data Products (SRDP) for NRAO instruments; a next-generation Very Large Array concept (ngVLA); a major overhaul of existing VLA infrastructure; continued innovative development for the Atacama Large Millimeter/submillimeter Array (ALMA); and growth of the Central Development Laboratory research and development efforts. Diversity and inclusion will also be important goals as we move forward. These initiatives will impact and benefit the global community of astronomers. I am also pleased to report that a new tri-lateral management agreement for ALMA was signed with our European and Japanese colleagues.

NSF divestment of the Green Bank Telescope (GBT) and the Very Long Baseline Array (VLBA) remains an important issue that AUI and NRAO are working on at high priority. New partners and interests have emerged for GBT and the VLBA, and the discussion with the NSF is focused on defining new capabilities and organization models, and not about closing the telescopes. The GBT and VLBA have long futures, but the efforts to define these will likely require a few more years.

As ever, the NRAO staff is a critical part of the Observatory's future as we embrace necessary changes, develop new capabilities, and open scientific and technical frontiers in collaboration. We are proud to be a strong and exceptionally capable research organization, dedicated to serving our international community

Brief Bio: *Anthony (Tony) J. Beasley was appointed as NRAO Director by the AUI Board of Trustees effective 21 May 2012. After receiving his Bachelor's in Physics in 1986 and his Doctorate in Astrophysics in 1991 from the University of Sydney, Beasley joined NRAO as a Postdoctoral Fellow in 1991. He was appointed as a Deputy Assistant Director in 1997, and served as Assistant Director from 1998 to 2000. In 2000, he left NRAO to become Project Manager for the Combined Array for Research in Millimeter-wave Astronomy. In 2004, he returned to NRAO as an Assistant Director and Project Manager for the Atacama Large Millimeter/submillimeter Array in Chile. Prior to his arrival at NRAO, Beasley served as the Chief Operating Officer and Project Manager of the NSF-funded National Ecological Observatory Network (NEON), a continental-scale ecological observatory designed to detect ecological change and enable forecasting of its impacts.*

Created in 1956 by the National Science Foundation and Associated Universities, Inc., the National Radio Astronomy Observatory designs, builds, and operates the most capable astronomical telescopes and instruments at radio wavelengths. In 2015, NRAO operated a complementary suite of four world-class telescopes, each the world leader in its domain: the international Atacama Large Millimeter/submillimeter Array (ALMA), the Karl G. Jansky Very Large Array (VLA), the Robert C. Byrd Green Bank Telescope (GBT), and the Very Long Baseline Array (VLBA). Observing time on these telescopes is allocated solely on the scientific merit of the proposed research.


ALMA

ALMA is the largest ground-based global astronomy endeavor in history. Composed of 66 high-precision antennas on an excellent, 5000m+ elevation site in northern Chile, ALMA is delivering orders of magnitude improvements in millimeter-wavelength sensitivity, frequency coverage, resolution, imaging, and spectral capabilities. ALMA's capabilities span wavelengths from 9.6 to 0.3 mm (31 – 950 GHz), a key part of the electromagnetic spectrum for observing the first stars and galaxies, directly imaging planetary formation, and studying the energy output from supermassive black holes in starburst galaxies. The first ALMA Early Science programs were completed in 2012, as construction continued and was completed in September 2014, as scheduled. The community's strong interest in ALMA has been repeatedly demonstrated by the substantial over-subscription for its Early Science observing time.

The updated Jansky VLA has scientific capabilities at the adjacent centimeter-wavelength range that are comparable to ALMA and that exceed the original VLA capabilities by one to four orders of magnitude. These new capabilities were delivered on schedule and on budget via the Expanded

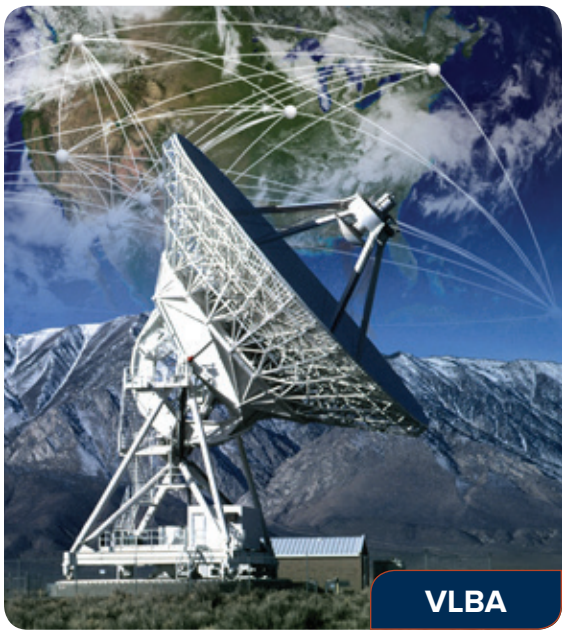

VLA

Very Large Array Project, and the array is meeting all of the project's technical specifications and scientific objectives. The Jansky VLA transitioned to full science operations in January 2013 as the world's most capable and versatile centimeter-wave imaging array and is yielding dramatic new science results that range from Galactic protostellar clouds to the molecular gas in early galaxies.

With comparable collecting area and sensitivity to ALMA and VLA, the 100m GBT is the preeminent filled-aperture radio telescope operating at meter to millimeter wavelengths. Its 2.3 acre collecting area, unblocked aperture, and excellent surface accuracy enable a wide range of forefront science, including precision pulsar timing to detect gravitational wave radiation, testing the strong field limit of General Relativity, and observing distant neutral hydrogen emission.

The VLBA is the premier dedicated Very Long Baseline Interferometer (VLBI) array. Astrometry with the VLBA has reached the precision of a few micro-arcseconds, supporting distance and proper motion measurements of astronomical objects in the solar neighborhood, across the Milky Way, within the Local Group, and moving with the Hubble flow. When used in conjunction with the phased VLA and the GBT, the resultant High Sensitivity Array (HSA) greatly enhances the sensitivity for VLBI observations and broadens the range of novel scientific research.

The Central Development Laboratory (CDL) conducts the crucial research and development that continually improves



operational NRAO telescopes and helps realize next generation facilities. CDL oversees a science-driven research and development program that supports the astronomy community's highest priority science goals, such as the detection of gravitational waves via pulsar timing, and the study of the epoch of reionization.

NRAO Headquarters in Charlottesville, Virginia is home to the North American ALMA Science Center (NAASC), Business & Administration, Human Resources, Education & Public Outreach, Program Management, and the Director's Office.

NRAO telescopes are serving the broad and diverse astronomy community and are enabling university researchers to address many of the most fundamental astrophysical questions of our time. Operating individually or synergistically with optical, infrared, and X-ray telescopes, NRAO is opening new frontiers over a broad range of modern astrophysics. The Observatory's 2015 science highlights include advances in our understanding of: proto-planetary disks and extrasolar planet formation; astrochemistry; the

early phases of star formation; pulsar physics; molecular gas in early, high-redshift disk and starburst galaxies; high energy physics; the environments of supermassive black holes; the three-dimensional structure of our Galaxy; and much more.

In addition to research, the NRAO broadly impacts science and society via its education and public outreach programs. NRAO science, technology, engineering, art, and mathematics (STEAM) education programs are introducing numerous young people every year to the excitement and opportunities of STEAM careers.

After more than five decades of continual improvement under AUI management, the NRAO comprises the nation's core competency in radio astronomy, an invaluable resource for the astronomy community in the U.S. and around the world.

SCIENCE HIGHLIGHTS

ALMA has entered routine operation with its full range of baselines, and the Jansky VLA has likewise demonstrated the full capability of its new systems. Together, these two new facilities have realized their order-of-magnitude leap in observational capabilities over previous facilities from 1 GHz up to 1 THz.

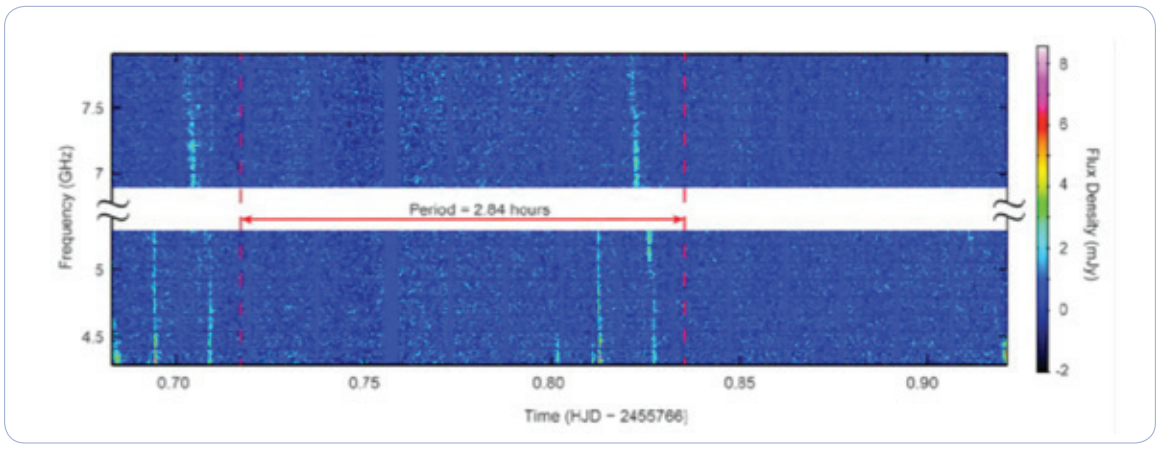
In parallel, the GBT continues to expand in scope, including wide-field continuum and spectroscopic cameras operating at 20 and 90 GHz, while the VLBA remains the premier instrument on the planet for millarcsecond imaging and sub-milliarcsecond astrometry. Particularly gratifying has been the demonstration of the power of combined observations from NRAO facilities, such as combined GBT and VLA imaging to obtain information over an unprecedented range of spatial scales, and comparative studies from submillimeter through centimeter wavelengths with ALMA, VLA, and GBT.

These NRAO facilities are realizing some of the highest priority science identified in *New Worlds, New Horizons,* including precision cosmological measurements, tests of fundamental physics, and study of astrophysics and chemistry from our Galaxy to the first galaxies in the Universe. These programs are probing deep into the earliest, most intense, and optically obscured phases of planet, star, galaxy, and black hole formation; revealing the cool dense gas from which stars form and providing essential tools for studying magnetic fields and high-energy cosmic phenomena. Line and continuum ultra-deep fields are becoming routine, exploring the evolution of galaxies at unprecedented distances and resolution. This section briefly highlights a sample of the exciting science results obtained with NRAO telescopes in 2015.

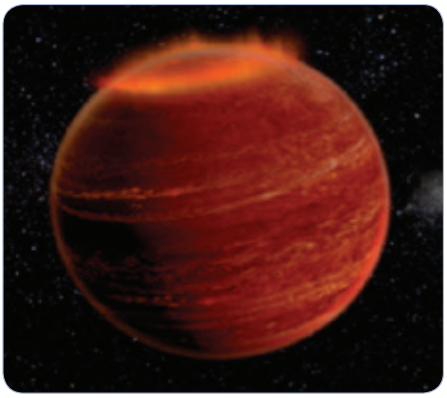
These represent just a snapshot of the broad, high-impact science programs that the NRAO facilities are enabling the community to pursue.

A Brown Dwarf Exo-aurora

Using the VLA, Keck, and Palomar, auroral emission has been discovered from the M8.5 brown dwarf J1835+3259 at a distance of 5.7 parsecs from the Earth. VLA dynamic spectra show circularly polarized cyclotron emission 10^4 times stronger than Jovian auroral emission. The measured magnetic fields are very strong: B ~2000 Gauss. The aurorae are powered by processes originating far out in the magnetosphere of the star, implying large-scale magnetospheric currents with luminosities far greater than those seen in our Solar System. The aurora may indicate a strong star-planet interaction, representing a major factor in driving exo-space weather, thereby dictating exoplanet environments. Brown dwarf systems are prime candidates for searches for life, hence, understanding their interplanetary environment is critical.



[Above] *Dynamic VLA spectra of a brown dwarf, indicating auroral emission.* **[Right]** *Artist's concept of such an aurora.*

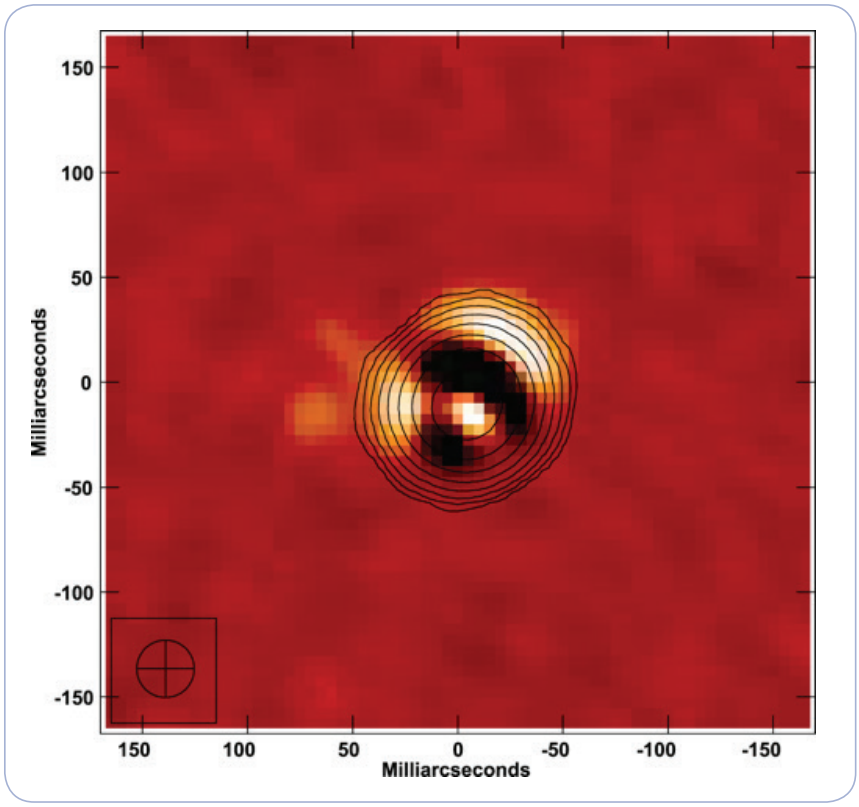


Science Team: G. Hallinan (Caltech), S. P. Littlefair (University of Sheffield), G. Cotter (Oxford University), S. Bourke (Caltech), L. K. Harding (JPL), J. S. Pineda (Caltech), R. P. Butler (National University of Ireland), A. Golden (Yeshiva University), G. Basri (UC, Berkeley), J. G. Doyle (Armagh Observatory), M. M. Kao (Caltech), S. V. Berdyugina (Kiepenheuer Institut), A. Kuznetsov (Institute of Solar-Terrestrial Physics), M. P. Rupen (NRAO), and A. Antonova (University of Sofia)..

Publication: *Magnetospherically Driven Optical and Radio Aurorae at the End of the Stellar Main Sequence,* 2015, Nature, 523, 568.

The Radio Photosphere of Mira

Matthews et al. present data that highlight the power of the VLA and ALMA for the study of evolved star atmospheres. The authors measured the millimeter wavelength continuum emission from the long period variable Mira (o Ceti) at 46, 96, and 230 GHz ($\lambda \sim 7$, 3, and 1 mm) and determined the radio photospheric sizes of the symbiotic binary star, Mira AB. The stellar photosphere is resolved in the asymptotic giant branch star, with a decreasing size with increasing frequency, as expected due to opacity. The radio photosphere is flattened by 10-20%. The authors find evidence for brightness non-uniformities, possibly caused by large-scale convective cells, similar to what has been previously proposed to explain the surface irregularities on the supergiant Betelgeuse. Mira's hot companion, Mira B, was detected at all three wavelengths, with a radius for its radio-emitting surface of 2×10^{13} cm.



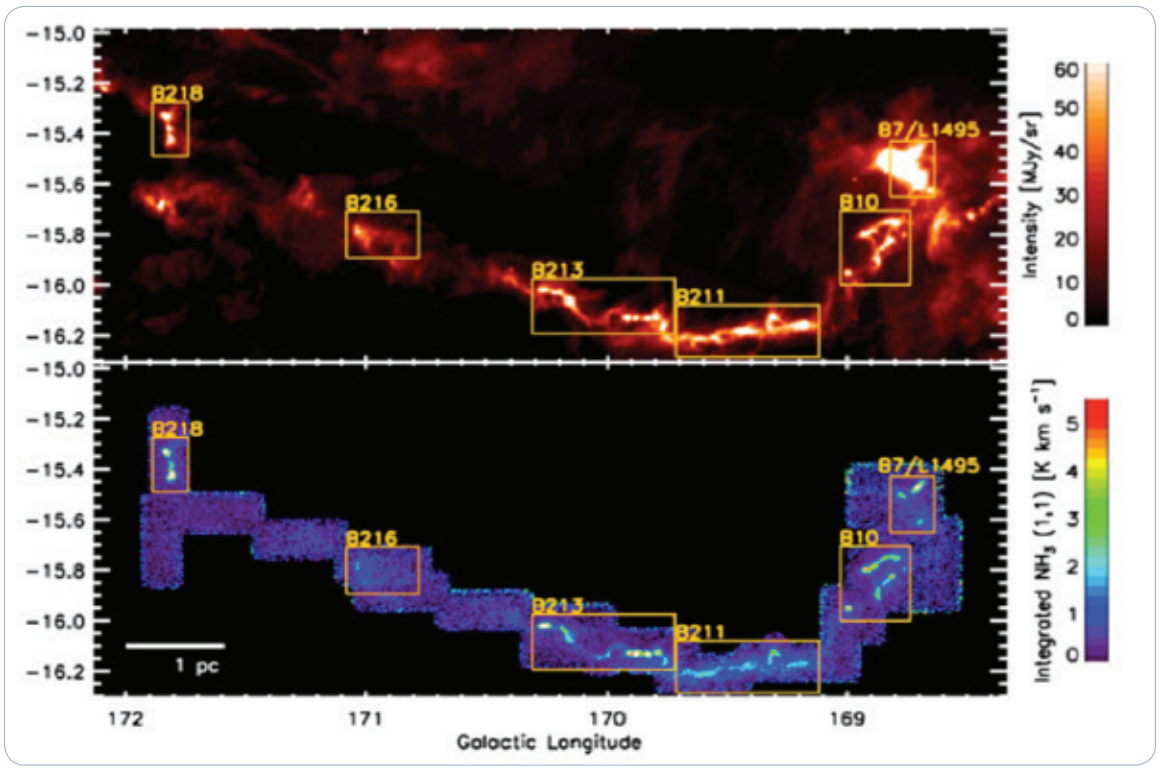
A 229 GHz emission map of Mira A plotted on an image of the residuals after subtraction of the best-fitting uniform elliptical disk model. The residuals range from −1.4 to 0.9 mJy/beam, with the peak positive residual slightly southwest of the nominal disk center. In comparison, the peak surface brightness of the observed stellar emission is 71.1 mJy/beam. The restoring beam is at lower left.

Science Team: L.D. Matthews (MIT Haystack Observatory), M.J. Reid (Harvard-Smithsonian Center for Astrophysics), and K.M. Menten (Max-Planck-Institut für Radioastronomie).

Publication: *New Measurements of the Radio Photosphere of Mira Based on Data from the JVLA and ALMA,* 2015, Astrophysical Journal, 808, 36.

Star-forming Filaments

The L1495-B218 star-forming filament extends in a remarkably linear structure over ~3 degrees (8 parsecs) in Taurus. GBT imaging with the new K-band array reveals the gas distribution via ammonia (NH_3) in unprecedented detail. The NH_3 peaks are associated with far-infrared peaks, with clump masses ~1 to 10 $M_\odot$. Approximately 25% of the clumps are gravitationally bound, and associated with star formation. The unbound clumps are mostly pressure-confined. The data suggest that a dense core may form as a pressure-confined structure, evolve to a gravitationally bound core, and collapse to form a protostar.



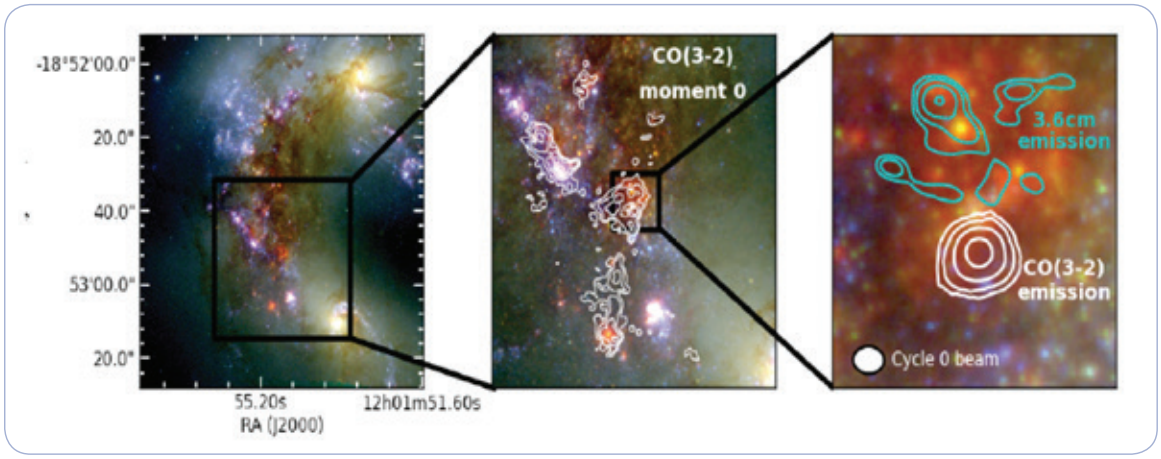
[Top] *500 micron dust continuum emission L1495-B218 (Herschel).* **[Bottom]** *GBT map of integrated intensity of NH_3 (Seo et al.).*

Science Team: Young Min Seo (University of Arizona), Yancy L. Shirley (University of Arizona; NRAO), Paul Goldsmith (JPL), Derek Ward-Thompson (University of Central Lancashire), Jason M. Kirk (University of Central Lancashire), Markus Schmalzl (Leiden), Jeong-Eun Lee (Kyung Hee University), Rachel Friesen (University of Toronto), Glen Langston (NSF), Joe Masters (NRAO), and Robert W. Garwood (NRAO).

Publication: *An Ammonia Spectral Map of the L1495-B218 Filaments in the Taurus Molecular Cloud. I. Physical Properties of Filaments and Dense Cores,* 2015, Astrophysical Journal, 805, 185.

Identifying a Proto-Super Star Cluster

Johnson et al. have conducted an analysis of the physical conditions in an extreme molecular cloud in the Antennae merging galaxies, a cloud that has properties consistent with those of the super star cluster molecular clouds that are believed to be the birthplaces of globular clusters. Using ALMA CO(3-2) and 870 μm continuum observations of the Antennae, this extreme molecular cloud was determined to have a radius of 24 parsecs or less and a mass of more than 5 x 10^6 $M_\odot$. The cloud appears capable of forming a globular cluster, but the lack of associated thermal radio emission indicates that star formation has not yet altered the environment. Given its mass and kinetic energy, for the cloud to be confined as its appearance strongly suggests, it must be subject to an external pressure 10,000 times higher than typical interstellar pressure. This finding supports theories that high pressures are required to form globular clusters and may explain why extreme environments like the Antennae are preferred environments for their generation. Given the cloud temperature of ~25 K, the internal pressure must be dominated by non-thermal processes, most likely turbulence. We expect the molecular cloud to collapse and begin star formation in less than or about 1 Myr.



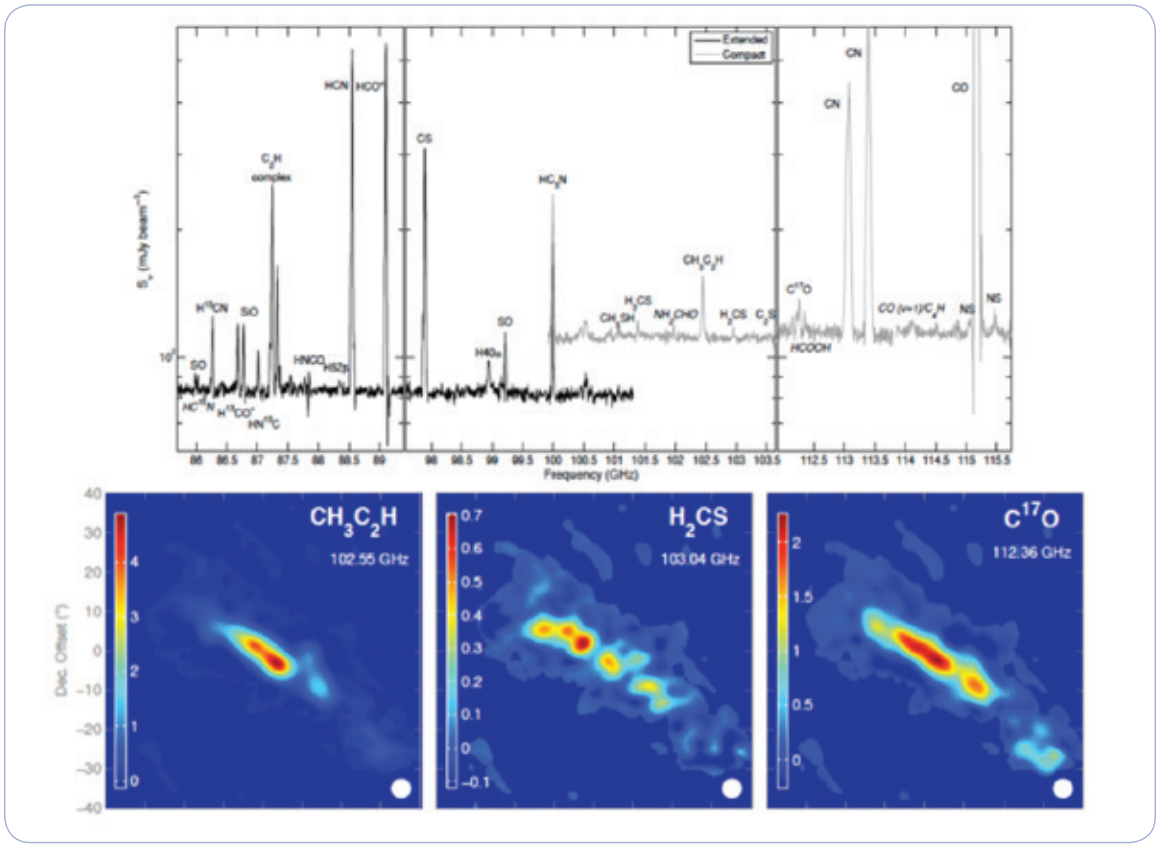
Candidate proto super star cluster molecular cloud in the overlap region of the Antennae merging galaxies. **[Left]** *Hubble Space Telescope image of the central area of the Antennae overlap region (red = Paα, green = F814W, blue = F435W).* **[Center]** *A magnified view of the overlap region with contours from the ALMA CO(3-2) moment 0 map.* **[Right]** *A zoomed view of the region surrounding the candidate proto super star cluster molecular cloud with CO(3-2) contours of the molecular cloud and 3.6 cm radio emission. The Cycle 0 synthesized beam was 0.56 x 0.43 arcseconds.*

Science Team: K.E. Johnson (University of Virginia), A.K. Leroy (NRAO), R. Indebetouw (University of Virginia, NRAO), C.L. Brogan (NRAO), B.C. Whitmore (STScI), J. Hibbard (NRAO), K. Sheth (NRAO), and A.S. Evans (University of Virginia, NRAO).

Publication: *The Physical Conditions in a Pre-super Star Cluster Molecular Cloud in the Antennae Galaxies,* 2015, Astrophysical Journal, 806, 35.

Astrochemistry of a Starburst

Meier et al. present a 50 parsec resolution imaging study of molecular gas species in the central kiloparsec of the nearby starburst galaxy NGC 253 based on ALMA observations. More than 50 emission lines are seen from more than 30 complex molecules emitting at 86 – 115 GHz (ALMA 3mm band). The dramatic variation seen in the HNCO / SiO line ratio suggests that some of the chemical signatures of shocked gas are being erased in the presence of dominating central radiation fields (traced by C_2H and CN). High-density molecular gas tracers – including HCN, HCO+, and CN – are detected at the base of the molecular outflow, driven by the starburst.



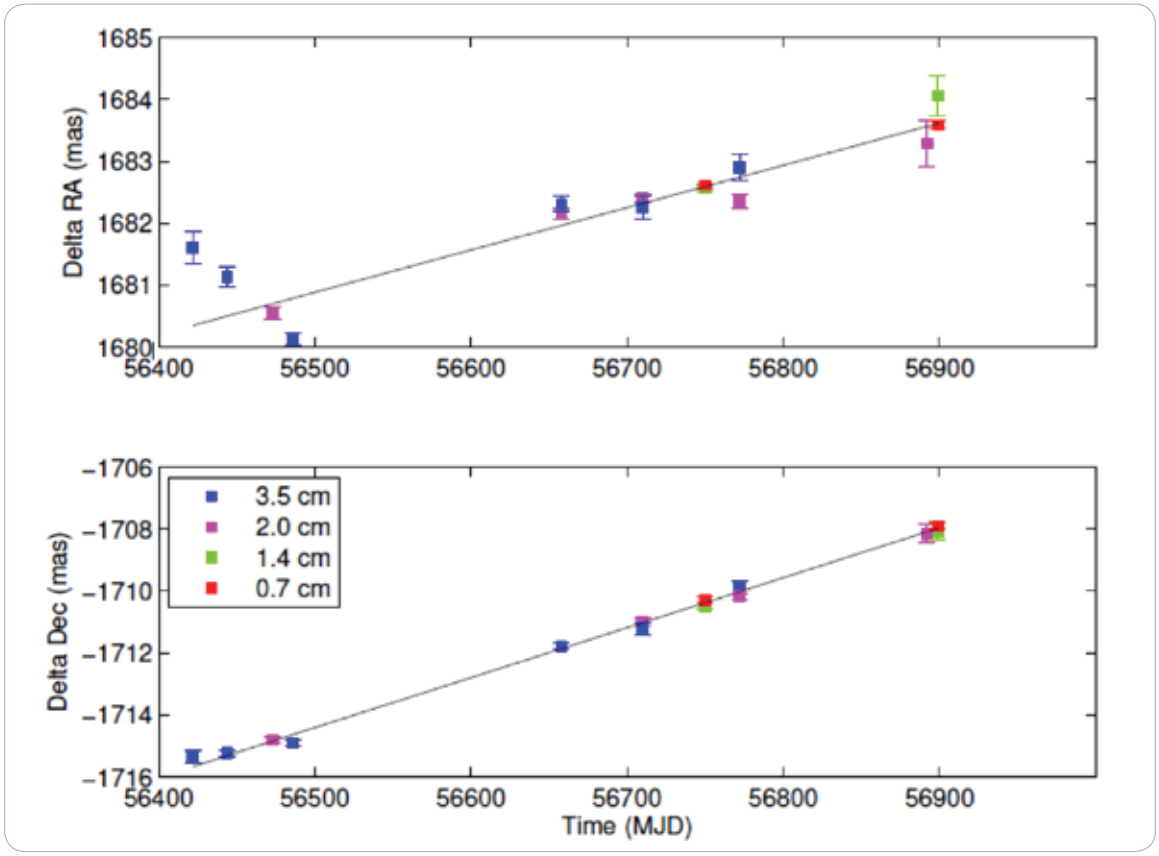
ALMA spectrum and molecular line images of the starburst nucleus of NGC 253.

Science Team: David S. Meier (New Mexico Tech, NRAO), Fabian Walter (Max-Planck Institut für Astronomie, NRAO), Alberto D. Bolatto (Maryland), Adam K. Leroy (NRAO), Jürgen Ott (NRAO), Erik Rosolowsky (Univerfity of Alberta), Sylvain Veilleux (University of Maryland), Steven R. Warren (University of Maryland), Axel Weiß (Max-Planck Institut für Astronomie), Martin A. Zwann (ESO), and Laura K. Zschaechner (Max-Planck Institut für Astronomie).

Publication: *ALMA Multi-line Imaging of the Nearby Starburst NGC 253, 2015,* Astrophysical Journal, 801, 63.

A Pulsar Orbiting the Galactic Center

Bower et al. used the VLBA to determine the proper motion of pulsar J1745-2900 relative to the Galactic Center. The pulsar has a transverse velocity of 236 ± 11 km/s at a projected separation of 0.097 parsecs from Sgr A*. The angular broadening with frequency is similar to Sgr A*. The velocity and position is consistent with a bound orbit originating in the clockwise disk of massive stars orbiting Sgr A* and a natal velocity kick of < 500 km/s. These results for PSR J1745-2900 support the hypothesis that Galactic Center pulsars can originate in the inner stellar disk, and deepens the mystery regarding the small number of detected Galactic Center pulsars to date.



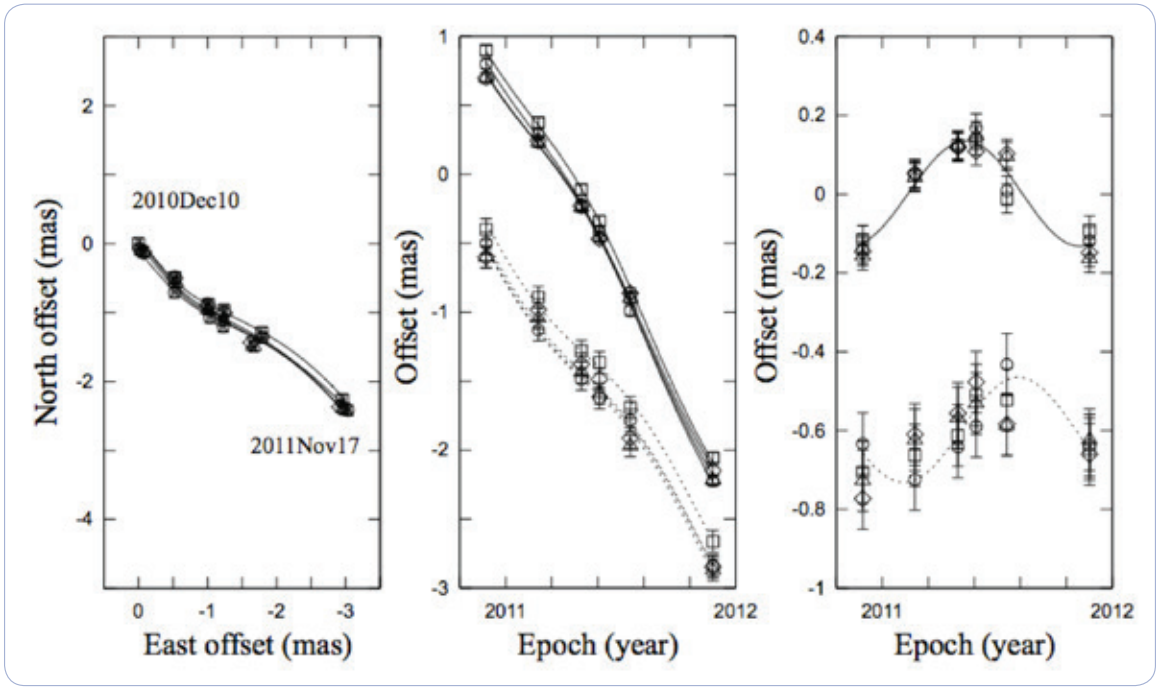
Position as a function of time for PSR J1745-2900 relative to Sgr A.*

Science Team: Geoffrey C. Bower (ASIAA), Adam Deller (ASTRON), Paul Demorest (NRAO), Andreas Brunthaler (Max-Planck Institut für Radioastronomie), Heino Falcke (ASTRON, Max-Planck Institut für Radioastronomie, Radboud University), Monike Moscibrodzka (Radboud University), Ryan M. O'Leary (JILA), Ralph P. Eatough (Max-Planck Institut für Radioastronomie), Michael Kramer (Max-Planck Institut für Astronomie, Jodrell Bank), K.J. Lee (Max-Planck Institut für Radiostronomie), Laura Spitler (Max-Planck Institut für Radiostronomie), Gregory Desvignes (Max-Planck Institut für Radiostronomie), Anthony P. Rushton (University of Oxford, University of Southampton), Sheperd Doeleman (MIT Haystack Observatory, Harvard-Smithsonian Center for Astrophysics), and Mark J. Reid (Harvard-Smithsonian Center for Astrophysics).

Publication: *The Proper Motion of the Galactic Center Pulsar Relative to Sagittarius A*,* 2015, Astrophysical Journal, 798, 120.

The Structure of the Outer Galaxy

Hachisuka et al. report parallaxes and proper motions of three water maser sources in high-mass star-forming regions in the Outer Spiral Arm of the Milky Way. The observations were conducted with the VLBA as part of Bar and Spiral Structure Legacy Survey (BeSSeL) and double the number of such measurements in the literature. The Outer Arm has a pitch angle of 14.9° ± 2.7° and a Galactocentric distance of 14.1 ± 0.6 kiloparsecs toward the Galactic anti-center. The average motion of these sources toward the Galactic Center is 10.7 ± 2.1 km/sec, and there is no sign of a significant fall in the rotation curve out to 15 kiloparsecs from the Galactic Center. The three-dimensional locations of these star-forming regions are consistent with a Galactic warp of several hundred parsecs from the plane.



VLBA parallax and proper motion measurements of maser spot in G097.53+0318 in the outer Galaxy.

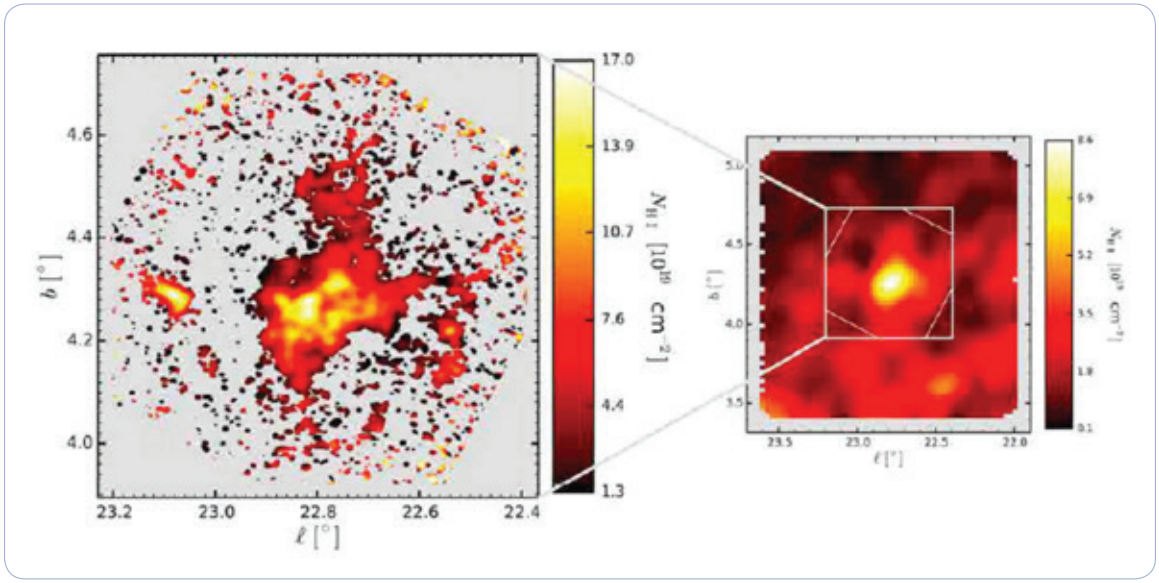
Science Team: K. Hachisuka (Yamaguchi University, Shanghai Astronomical Observatory), Y.K. Choi (Korean Astronomy and Space Institute), M.J. Reid (Harvard-Smithsonian Center for Astrophysics), A. Brunthaler (Max-Planck Institut für Radioastronomie), K.M. Menten (Max-Planck Institut für Radioastronomie), A. Sanna (Max-Planck Institut für Radioastronomie), and T.M. Dame (Harvard-Smithsonian Center for Astrophysics).

Publication: *Parallaxes of Star-forming Regions in the Outer Spiral Arm of the Milky Way,* 2015, Astrophysical Journal, 800, 2.

Imaging Diffuse Galactic Neutral Hydrogen

Pidopryhora et al. have observed a set of diffuse interstellar clouds in the inner Galaxy within a few hundred parsecs of the Galactic plane at an angular resolution of one arcminute, combining data from the Green Bank Telescope and the Very Large Array. At the distance of the clouds, the linear resolution ranges from ~1.9 to ~2.8 parsecs. These clouds have been selected to be somewhat outside of the Galactic plane, and thus are not confused with unrelated emission, but in other respects they are a Galactic population. They are located near the tangent points in the inner Galaxy, and thus at a quantifiable distance: 2.3 < R < 6.0 kiloparsecs from the Galactic Center and 1000 < z < 610 parsecs from the Galactic plane. These are the first images of the diffuse neutral hydrogen (HI) clouds that may constitute a considerable fraction of the interstellar medium (ISM). Peak H I column densities are ~ 10^{20} cm^{-1}. Cloud diameters range from 10 to 100 parsecs, with masses from a hundred to a few thousands $M_{\odot}$. The clouds shapes are highly irregular, and some clouds show evidence of two distinct thermal phases as predicted by thermal equilibrium models of the interstellar medium.

The clouds show no morphological consistency of any kind, except that their shapes are highly irregular. One cloud may lie within the hot wind from the nucleus of the Galaxy, and some clouds show evidence of two distinct thermal phases as would be expected from equilibrium models of the ISM.



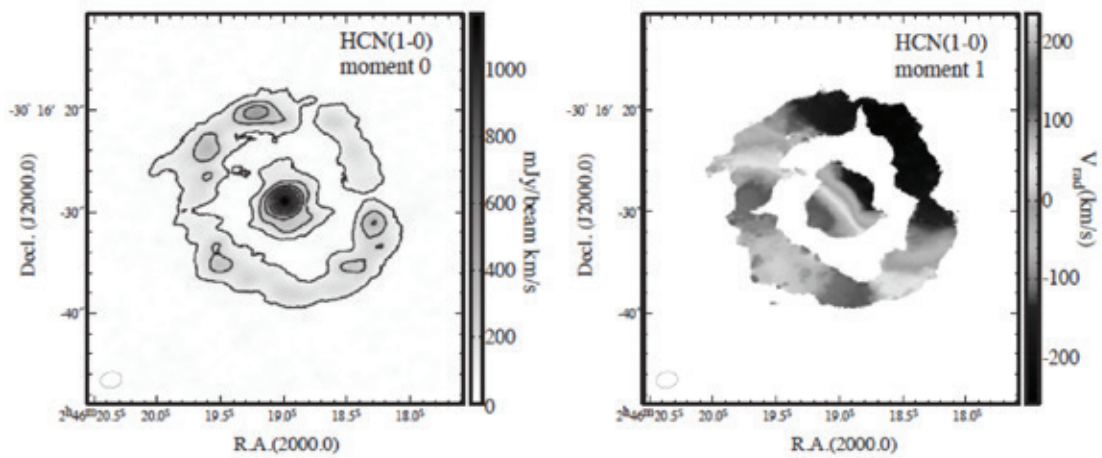
[Left] *(VLA + GBT) image of G22.8+4.3 neutral hydrogen at 1 arcmin resolution.* **[Right]** *The GBT data by itself. The main cloud has a mass of 70 $M_{\odot}$ and a size of 20 parsecs.*

Science Team: Y. Pidopryhora (University of Tasmania, Argelander-Institut für Astronomie), Felix J. Lockman (NRAO), J. M. Dickey (University of Tasmania), and M. P. Rupen (NRAO, DRAO).

Publication: *High-resolution Images of Diffuse Neutral Clouds in the Milky Way. I. Observations, Imaging, and Basic Cloud Properties,* 2015, Astrophysical Journal Supplement, 219, 16.

Measuring a Supermassive Black Hole Mass

Onishi et al. present an estimate of the mass of the supermassive black hole in the nearby type-1 Seyfert galaxy NGC 1097 obtained by observing this galaxy with ALMA and analyzing the dynamics of the HCN (J = 1 – 0) and HCO+ (J = 1 – 0) emission line in the inner few hundred parsecs. From the observed dense molecular gas dynamics, and assuming a host galaxy inclination of 46 degrees, the authors calculate a well-determined central black hole mass of 1.40 x 10^8 $M_\odot$ and an I-band mass-to-light ratio of 5.14 using HCN (J = 1–0). The measured supermassive black hole mass is in good agreement with the supermassive black hole mass and bulge velocity dispersion relationship. This result showcases ALMA's potential for deriving accurate supermassive black hole masses, especially for nearby late-type galaxies. Larger samples and accurate supermassive black hole masses will further elucidate the relationship between the black hole and host galaxy properties and constrain the evolutionary growth of galaxies and black holes.



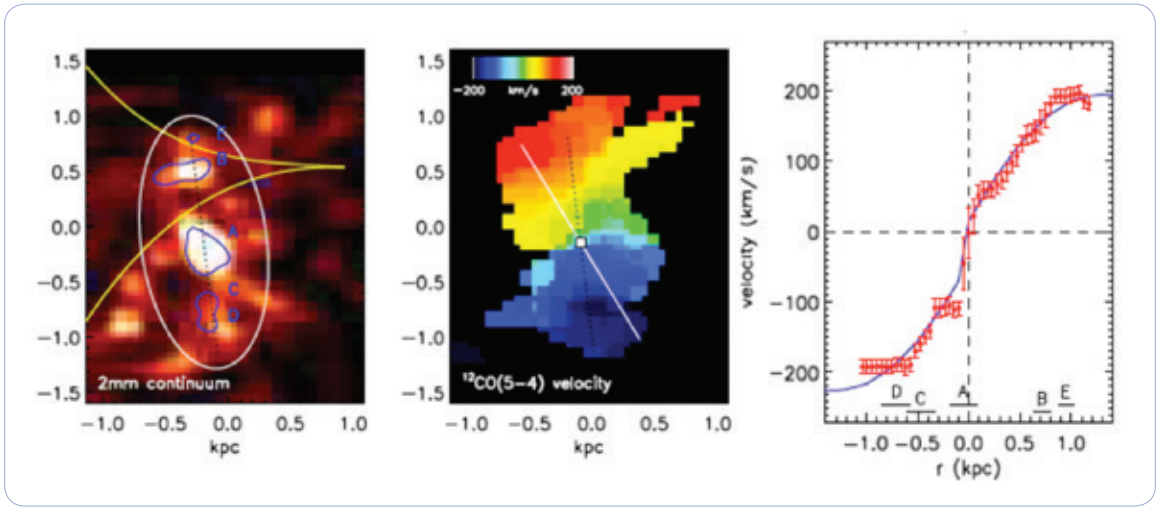
HCN moment images and position velocity plots for NGC 1097 at ~2 arcsec (100 parsec) resolution.

Science Team: K. Onishi (SOKENDAI, NAOJ), S. Iguchi (SOKENDAI, NAOJ), K. Sheth (NRAO), and K. Kohno (University of Tokyo).

Publication: *A Measurement of the Black Hole Mass in NGC 1097 Using ALMA,* 2015, Astrophysical Journal, 806, 39.

Dynamics of the First Galaxies: CO

Swinbank et al. exploit long-baseline ALMA submillimeter observations of the lensed star-forming galaxy SDP 81 at z = 3.042 to investigate the properties of the interstellar medium (ISM) on scales of 50–100 parsecs. The kinematics of the ^{12}CO gas within this system are well described by a rotationally supported disk with an inclination-corrected rotation speed 320 ± 20 km/s, and a dynamical mass of (3.5 ± 1.0) x 10^{10} $M_{\odot}$ within a radius of 1.5 kpc. The disk is gas-rich and unstable and so will collapse into star-forming regions with Jeans length ~ 130 parsecs. The authors identify five star-forming regions within the interstellar medium on these scales and show that their scaling relations between luminosity, line widths, and sizes are significantly offset from those typical of molecular clouds in local galaxies. These offsets are likely to be caused by the high external hydrostatic pressure for the ISM, which is ~10^4 times higher than the typical ISM pressure in the Milky Way. The physical conditions of the star-forming ISM and giant molecular clouds appear to be similar to those found in the densest environments in the local Universe, such as those in the Galactic Center.



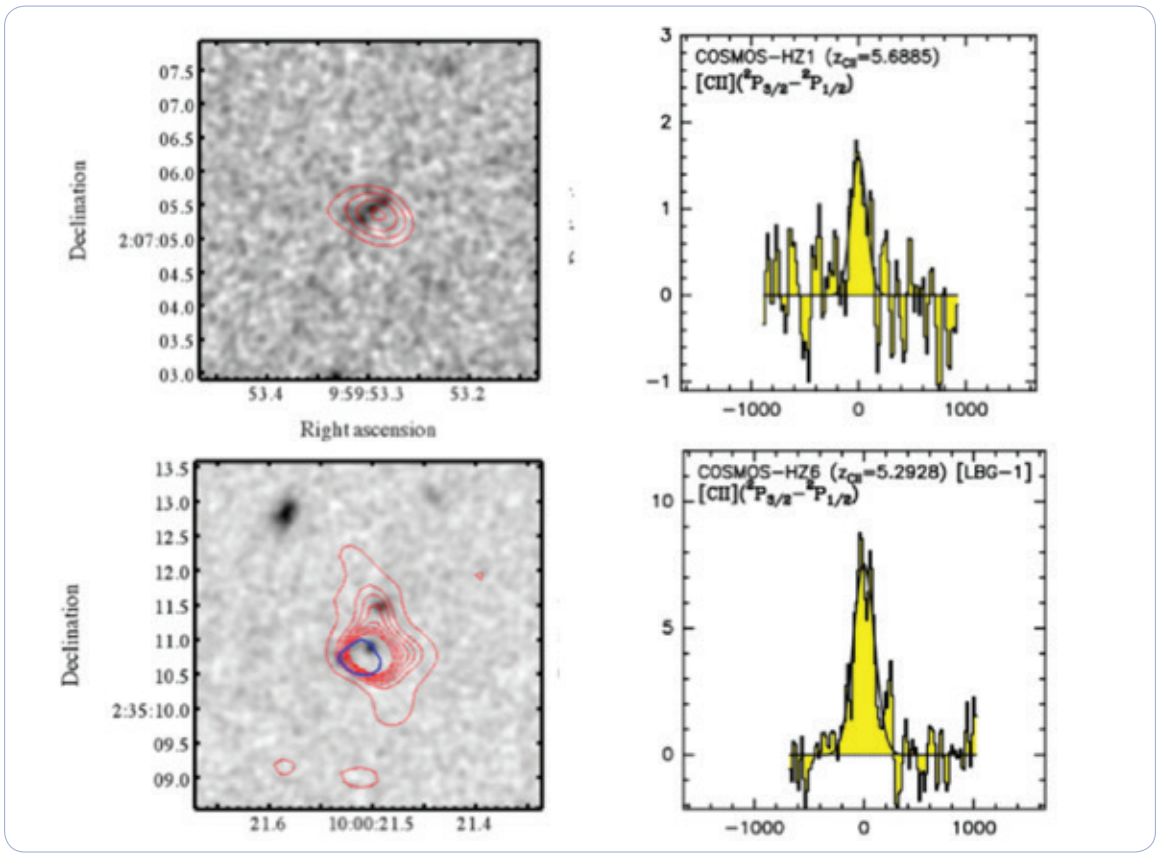
Source plane distribution of dust continuum and CO in SDP81 with a resolution of 50 parsecs. **[Left]** *Source plane 2.1mm image with star-forming clumps identified. The solid line is the caustic curve from the best-fit lens model.* **[Center]** *^{12}CO(5-4) line of sight velocity field. The solid white line is the major kinematic axis.* **[Right]** *The 1D velocity profile of the gas disk with the best-fit dynamical model.*

Science Team: A.M. Swinbank (Durham), S. Dye (Nottingham), J.W. Nightgale (Nottingham), C. Furlanetto (Nottingham, CAPES), Ian Smail (Durham), A. Cooray (Caltech), H. Dannerbauer (Wien), L. Dunne (Canterbury, Edinburgh), S. Eales (Cardiff), R. Gavazzi (Paris), T. Hunter (NRAO), R.J. Ivison (Edinburgh, ESO), M. Negrello (INAF), I. Oteo (Edinburgh, ESO), R. Smit (Durham), P. Van der Werf (Leiden), C. Vlahakis (JAO, ESO).

Publication: *ALMA Resolves the Properties of Star-forming Regions in a Dense Gas Disk at z ~3,* 2015, Astrophysical Journal Letters, 806, L17.

Physics and Dynamics of the First Galaxies

The sensitivity of ALMA has opened up a new era in the study of galaxy formation through the use of the strong atomic fine structure lines coming from the cool ISM, in particular, the [CII] 158 micron line. This is the strongest emission line from star-forming galaxies from the far-infrared through the radio, and is the dominant cooling mechanism for cool interstellar gas. This line redshifts into the ALMA bands at z > 1. Capak et al. have detected [CII] in samples of typical star-forming galaxies – star formation rates of a few to 100 $M_{\odot}$ per year – at z = 5.2 to 6.2. This represents a new window on galaxy formation in terms of studying gas dynamics and dark matter, ISM physics, and determining redshifts for the first galaxies.



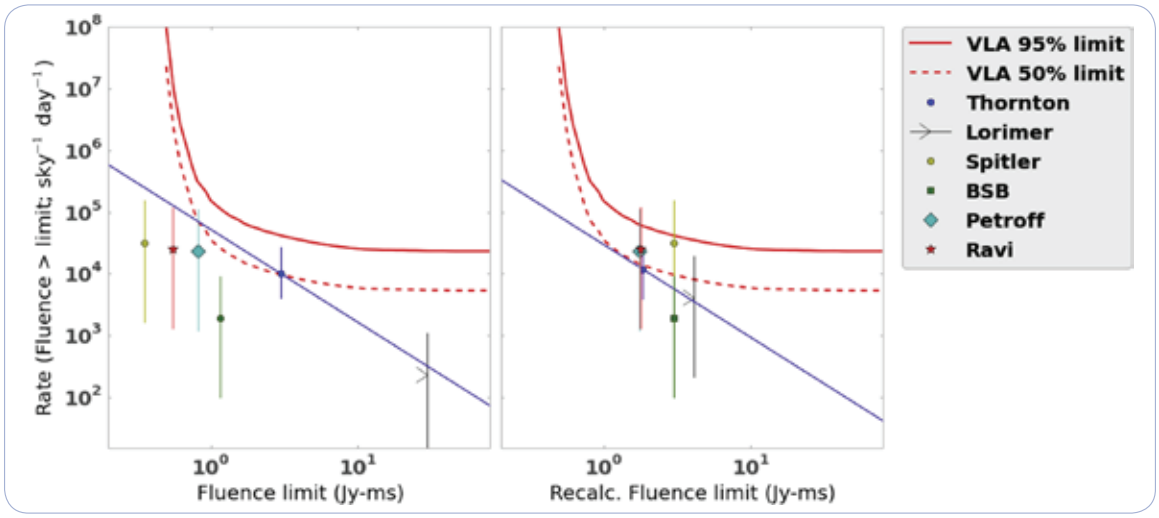
[CII] 158 micron emission and thermal dust emission from z ~5.5 galaxies

Science Team: P.L. Capak (IPAC, Caltech), C. Carilli (NRAO, Cavendish), G. Jones (New Mexico Tech), C.M. Casey (University of Texas), D. Riechers (Cornell University), K. Sheth (NRAO), C.M. Carollo (ETH Zurich), O. Ilbert (CNRS), A. Karim (Argelander Institute für Astronomie), O. LeFevre (CNRS), S. Lilly (NRAO), N. Scovill (Caltech), V. Smolcic (University of Zagreb), and L. Yan (IPAC, Caltech).

Publication: *Galaxies at Redshifts 5 to 6 with Systematically Low Dust Content and High [C II] Emission, 2015,* Nature 522, 455.

Fast Radio Bursts

Fast Radio Bursts (FRBs) are millisecond radio bursts identified in single dish observations, but as yet not precisely localized on the sky, nor associated with any astrophysical object. These sources could originate at cosmological distances, possibly signifying the death of binary neutron stars, and hence present critical cosmological probes. However, localization is crucial. Law et al. have searched for the enigmatic Fast Radio Bursts, with the VLA. These VLA observations demonstrate the ability to perform imaging searches on timescales of 5 milliseconds over 166 hours at 1.4 GHz, to a depth of 15 mJy, using a spectral mode of 256 x 1 MHz channels. Thus far, no FRB has been detected, and the limits are approaching that expected for the areal and temporal density of the sources.



[Left] *FRB rates and VLA rate limit as a function of limiting fluence as quoted in or inferred from Lorimer et al. 2007 (Science, 318, 777); Thornton et al. 2013 (Science, 341, 53); Burke-Spolaor & Bannister 2014 (ApJ, 792, 19); Petroff et al. 2015 (MNRAS, 447, 246); Ravi et al. 2015 (ApJ, 799, 5); and Spitler et al. 2014 (ApJ, 790, 101). The blue line shows an extrapolation of the rate of Thornton et al., assuming a Euclidean distribution (-3.2 power-law slope) from a fluence limit of 3 Jy ms. The VLA 50% and 95% upper limits are shown with a dashed and solid line, respectively. The fluence limit of Lorimer et al. 2007 is a lower limit calculated in a reanalysis by Keane & Petroff 2015 (MNRAS, 447, 2852).* **[Right]** *As the left panel, but for recalculated flux limits. All flux limits assume a 3 ms pulse width and that FRBs originate outside the Galaxy with dispersion measure of 779 pc cm−3. The rate estimate of Lorimer et al. 2007 is recalculated for a field-of-view appropriate for the full-width-half-maximum.*

Science Team: Casey J. Law (UC, Berkeley), Geoffry C. Bower (ASIAA), Sarah Burke-Spolaor (JPL, NRAO), Bryan Butler (NRAO), Earl Lawrence (Los Alamos), T. Joseph W. Lazio (JPL), Chris Mattmann (JPL), Michael Rupen (NRC Herzberg), Andrew Siemon (UC, Berkeley), and Scott VanderWiel (Los Alamos).

Publication: *A Millisecond Interferometric Search for Fast Radio Bursts with the Very Large Array,* 2015, Astrophysical Journal, 807, 16.

Composite image of the barred spiral galaxy NGC 1097. By studying the motion of two molecules, ALMA was able to determine that the supermassive black hole at the galactic center has a mass 140 million times greater than our Sun. The ALMA data is in red (HCO+) and green/orange (HCN) superimposed on an optical image taken by the Hubble Space Telescope. Credit: ALMA (NRAO/ESO/NAOJ), K. Onishi; NASA/ESA Hubble Space Telescope, E. Sturdivant; NRAO/AUI/NSF.

NORTH AMERICAN ALMA OPERATIONS

North America American ALMA Operations includes:

- Science Operations at the North American ALMA Science Center (NAASC)
- The North American share of the ALMA Development Program
- The North American share of Offsite Technical Support undertaken outside Chile
- Activities of the AUI/NRAO Office of Chilean Affairs
- The North American share of ALMA Operations in Chile
- Education and Public Outreach (EPO) programs and Diversity initiatives

Photos by Pablo Carillo

The NAASC is located at the NRAO Headquarters in Charlottesville, Virginia, and is responsible for supporting the scientific use of ALMA by astronomers in North America. The NAASC has three management groups: Telescope Support, User Support, and Science User Support.

The NAASC Telescope Support Group supports the operations of the Joint ALMA Observatory (JAO) from North America and via temporary deployments to Chile. The NAASC provides domain-expert assistance to the JAO Extension of Capabilities effort in areas where the NAASC has key expertise that is missing or understaffed at the JAO.

The NAASC User Support Group is responsible for direct support of the North American ALMA user community, including Calls for Proposals, community training events, and additional ALMA outreach events associated with major science meetings, such as the semi-annual American Astronomical Society (AAS) meetings.

The NAASC Science User Support Group supports multiple community programs for students and scientific professionals, including the Student Observing Support (SOS) Program funded by North American ALMA and managed by the Science Support & Research (SSR) department.

Cycle 2 & Cycle 1 Science Operations

The ALMA program for Cycle 2 and Cycle 1 carryover science observations concluded on 28 September 2015. More than 80% of the time assigned for A- and B-ranked projects was successfully executed, in addition to a number of C-ranked projects. In total, over 2000 hours of ALMA observations were executed, as planned for Cycle 2 with Cycle 1 carryover.

In addition to the high completion rate of A- and B-ranked 12m proposals, more than 99% of the 7m and over 96% of the Total Power projects were finished.

Cycle 2 also featured the stunning results from the Long Baseline Campaign, for which North America made key contributions, and the results defined the power and potential of ALMA to a worldwide audience. A host of ground-breaking publications have appeared in numerous fields of astrophysics, including proto-planetary disks, the early Universe, and much more.

Cycle 3 Call for Proposals

The ALMA Cycle 3 Call for Proposals was published 24 March 2015, inviting members of the astronomy community to propose scientific programs scheduled on ALMA beginning in October 2015. ALMA capabilities added for Cycle 3 included Band 10, and baselines up to 10 km for Bands 3, 4, and 6. The Cycle 3 proposal submission deadline was 15:00 UT on 23 April 2015.

ALMA received 1582 unique proposals by the close of the Cycle 3 submission process, compared to 1382 proposals in Cycle 2. A total of 9037 hours was requested for the array of 12m telescopes, a 24% increase over the 7314 hours requested in Cycle 2. The total time requested for standard observing modes was 6913 hours and for non-standard modes 2124 hours. Forty-seven countries represented by more than 1100 individual Principal Investigators and three times that many proposers – the total registration pool included 6428 persons – were represented in the submitted proposals.

The fractions of proposals coming from the three Executives, Chile, and outside the partnership was similar to those received in previous cycles:

• North America	29%
• Europe	42%
• East Asia	19%
• Chile	8%
• Outside	3%

The distribution of the proposals across the ALMA Cycle 3 science categories was:

• Cosmology and the High Redshift Universe	21%
• Galaxies and Galactic Nuclei	25%
• Interstellar Medium, Star Formation and Astrochemistry	26%
• Circumstellar Disks, Exoplanets and the Solar System	20%
• Stellar Evolution and the Sun	8%

The Cycle 3 proposals were sorted and sent to the referees, and the Review Panels met 22-26 June 2015 in Osaka, Japan. The final Cycle 3 science program was determined in August, and all proposers were notified.

NRAO Community Days

In advance of the ALMA Cycle 3 Call for Proposals, NRAO staffed and supported Community Day Events at a number of North American institutions. These Community Days strive to provide users with the knowledge they need to carry out cutting-edge scientific research using NRAO facilities. The Observatory is particularly keen to reach new users, and no experience with radio astronomy is required to participate.

The NRAO Community Days are one- or two-day events designed in cooperation with host institutions, and participation is free. Community Days generally include science talks, an introduction to submillimeter interferometry, and hands-on workshops designed to assist potential users with proposal preparation, observation planning, and data reduction for ALMA Cycle 3. Participants bring their laptops to participate in the hands-on sessions. NRAO provides access to the requisite software, which is available for free download, as well as the small ALMA dataset that is used in the demonstrations.

NRAO Community Days were held at these institutions and on these dates in 2015:

- Universidad Nacional Autonoma de Mexico, Morelia, Mexico — 26 – 27 February
- Florida Institute of Technology, Melbourne, Florida — 9 – 10 March
- Star and Planet Formation in the Southwest, Tucson, Arizona — 27 March
- University of California, San Diego, California — 31 March – 1 April
- Space Telescope Science Institute, Baltimore, Maryland — 13 – 14 April

Cycle 3 Science Operations

ALMA began on 1 October 2015 to execute Cycle 3 science observations for the 402 proposals that were highly ranked, with antennas moved to the C36-8 high-resolution configuration, which offers a maximum baseline of 9.7 km. In addition, of the 36 Cycle 2 A-ranked projects, seven were transferred to the Cycle 3 queue because they were not completed.

A detailed report on the results of the Cycle 3 proposal review process is available; the abstracts of accepted Cycle 3 proposals are also available at the ALMA Science Portal.

Observational Evidence of Gas Accretion onto Galaxies?

A North American ALMA Science Center Workshop, 9 – 10 October 2015

This well-attended NAASC workshop examined the observational evidence of the process of concentrating the baryon content of the Universe into dark haloes. To address this key astrophysical issue, workshop attendees reviewed and discussed:

(1) the latest observations on the inter-galactic medium (IGM) and circum-galactic medium (CGM) at different redshifts, largely from quasar absorption lines;

(2) the latest observations of filaments in the IGM, from emission of the large scale diffuse ionized gas, the intra-cluster medium, and neutral IGM;

(3) the exchange of gas between the IGM/CGM and the galaxies/haloes in the general field, group, and cluster environments, and in the larger structure of filaments; and

(4) future observations to delineate observationally the important processes of mass exchange between galaxies and the IGM.

Group photo, NAASC Workshop, 9 – 10 October 2015.

Cycle 4 Pre-Announcement & Capabilities

The ALMA Cycle 4 pre-announcement was released 14 December 2015. The Cycle 4 Call for Proposals for science observing with ALMA from October 2016 – September 2017 will be issued 22 March 2016, with an anticipated deadline for proposal submission on 21 April 2016.

Proposers will be able to request more antennas and several new capabilities, including:

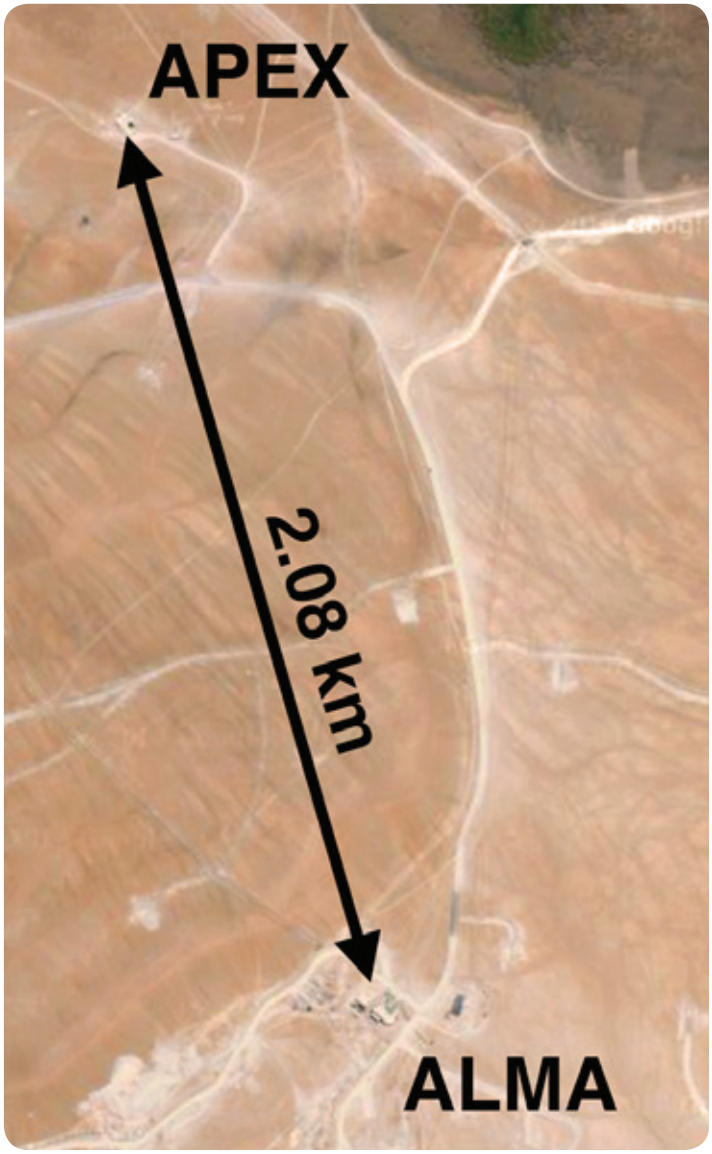
- Compact Array stand-alone mode,
- Large Programs,
- Millimeter wavelength very long baseline observations, and
- Solar observations.

ALMA VLBI First Light

On 13 Jan 2015, a team including members from the ALMA Phasing Project (APP), the Joint ALMA Observatory (JAO) and the Atacama Pathfinder Experiment (APEX) telescope made the first Very Long Baseline Interferometry (VLBI) observations at 1.3mm with ALMA.

Over a ~2 km baseline between ALMA and the APEX site, the successful detection of quasar 0522-364 verified major components of the new ALMA Phasing System. This detection was obtained using only five seconds of data, sent via Internet from Chile to the Massachusetts Institute of Technology – Haystack Observatory VLBI correlator. A full analysis will follow once VLBI disk modules with more data from the observations arrive in Massachusetts.

Both APEX and ALMA used completely independent hydrogen masers, electronics, and backends, making this a true VLBI experiment. The high signal to noise of the detection is evident from the clear peaks in the delay rate for both the multi-band and single-band delays.



New North American ALMA Regional Center Manager

Anthony Remijan became the new manager of the North America ALMA Regional Center (ARC) effective 1 October 2015, taking over from John Hibbard.

Remijan comes to this new role after ten years at NRAO and the North American ALMA Science Center (NAASC), following postdoctoral work at NASA – Goddard and Ph.D. studies at the University of Illinois. Remijan has held three prior and successful management roles at NRAO – head of the ALMA Helpdesk Working Group, Science User Support Division Head, and ALMA Program Scientist for the Extension and Optimization of Capabilities Group at the Joint ALMA Observatory. He also led the Splatalogue development group and has participated in numerous other service roles. Remijan's science program focuses on the astrochemistry of large and biologically significant molecules, the study of cometary chemistry, and he has participated in numerous interstellar molecule discoveries and analyses.

We are grateful to John Hibbard for his long and extraordinary contributions as North America ARC Manager. Hibbard held this position since the inception of the ARC system, and he is one of the original authors of the ALMA Operations Plan that has served as the guidebook throughout ALMA early operations. Hibbard has been a leader in ALMA not only at the North American ARC, but in the development and execution of international policies, procedures, and processes.

ALMA Development Program

A Call for ALMA/NA Development Studies was issued 16 March 2015. To support this new Call, an informational webinar was held 25 March at NRAO headquarters in Charlottesville.

This Call invited proposals to conduct studies of ideas that may be further developed and implemented in a subsequent ALMA Development funding cycle. The primary aims of this Call for Project Proposals were to:

- encourage the flow of development ideas from the North American ALMA operations community into the ALMA Development Program Plan;
- support the development of conceptual and detailed designs by the North American ALMA operations community for possible future inclusion in the ALMA Development Program Plan; and
- support ALMA-relevant, long-term research and development by the North American operations community.

Limited funding was available from NRAO to support North American-based Projects, allocated on a competitive basis. Projects partly or fully supported from external sources were also solicited. All members of the North American ALMA operations partnership, and the North American radio astronomy community at-large, were invited to participate in the ALMA Development Program.

Study proposals were due 12 June 2015. A panel of highly qualified members of the astronomical community reviewed the submitted proposals. To avoid conflict of interest, none of the review panel members were affiliated with NRAO. Panel

members submitted anonymous grades and rankings, then discussed the results of the rankings in a teleconference. Fifteen valid proposals were received from 56 proposers representing 20 institutions requesting a total of $2.528M USD. Seven studies from 33 proposers representing ten institutions fit within the funding envelope of ~$1M USD and were proposed for North American funding with the consent of the National Science Foundation (see Table-1).

Table 1: Proposed ALMA Development Studies Program (Title/Team)

Extensions & Enhancements to the ALMA Phasing System	L. Matthews (MIT), G. Crew (MIT), S. Doeleman (SAO), V. Fish (MIT), M. Hecht (MIT)
Spectral Resolution and Bandwidth Upgrade of the ALMA Correlator	R. Lacasse (NRAO), R. Escoffier (NRAO), J. Greenberg, (NRAO), A. Sáez (JAO), R. Treacy (NRAO), J. Webber (NRAO), A. Baudry (Univ. Bordeaux), R. Amestica (JAO), M. Stan (Univ. Virginia)
Improving the Calibration of Atmospheric Spectral Features	T. Hunter (NRAO), N. Phillips, (JAO), D. Broguière (IRAM)
Pulsars, Magnetars, and Transients with Phased ALMA	J. Cordes (Cornell), S. Chatterjee (Cornell), G. Crew (MIT), S. Doeleman (MIT), M. Kramer (MPIfR), J. Lazio (JPL), S. Ransom (NRAO)
Feature Extraction and Data Cube Visualization through Topology	P. Rosen (Univ. Utah), B. Wang, (Univ. Utah), C. Johnson (Univ. Utah), J. Kern (NRAO), B. Mills (NRAO)
Advanced Materials and On-wafer Chip Evaluation: 2nd Generation	A. Lichtenberger (Univ. Virginia), J. Lu (Univ. Virginia)
Digital Correlation and Phased Array Architectures	J. Weintroub (SAO), A. Baudry (Univ. Bordeaux), B. R. Carlson (NRC-Canada), S. Doeleman (SAO), R. Escoffier (NRAO), R. Lacasse (NRAO), K. Rosenfeld (MIT), M. Rupen (NRC-Canada)

The initial ALMA Development Projects reached fruition in 2015. The first ALMA Band 5 cartridge – delivered from ESO with North America providing the local oscillator portion – was integrated into a dewar at the Operations Support Facility at the ALMA site. It passed its final acceptance in June and further units are being integrated. Integration of Band 5 (164-211 GHz) is expected to be complete in 2017. Testing continued of the fiber optic network that is replacing a microwave link and connecting the Array Operations Site and Operations Support Facility to the JAO and the world.

Photos by Pablo Carrillo

NEW MEXICO OPERATIONS

Very Large Array Operations

The NRAO continued to offer a suite of robust and scientifically powerful observational capabilities on the Very Large Array (VLA), designed and tailored to address the highest priority scientific needs of the general community. These scientific needs drove enhancements of the VLA as well. To increase science return on topics as varied as astrochemistry, star formation, protoplanetary/protostellar disks, and the molecular phase of galaxy formation in the early Universe, the VLA underwent improvements in its Atmospheric Phase Interferometer (API) to increase scheduling reliability, 3-bit samplers to improve sensitivity, and frequency averaging was offered through the Resident Shared Risk Observing (RSRO) program for the first time. Aiming for delivery of wide and deep continuum surveys, an on-the-fly mosaicking mode was implemented and offered, and the two-year science operations of the VLA Low Band Ionospheric and Transient Experiment (VLITE) was initiated. VLITE works as a commensal system capable of observing with the prime focus feeds at 330 MHz simultaneously, but independently, of the Time Allocation Committee-approved science pointing carried out with the Cassegrain feeds and the Wideband Interferometric Digital Architecture (WIDAR) correlator. Deep, narrow continuum and neutral hydrogen surveys continued to explore galaxy evolution, while the community approved the all-sky component of the VLA Sky Survey (VLASS).

NRAO continued to offer three types of observing programs to VLA users: General Observing (GO), Shared Risk Observing (SRO) and Resident Shared Risk Observing (RSRO). Observing capabilities offered for semester 2015B under all programs were the same as 2015A, because of limited software resources in the Data Management and Software Department available for updating user tools. New capabilities for semester 2016A comprised access to the new 4-band system and frequency averaging in the correlator, available through the RSRO program. All array reconfigurations were successfully completed as planned, and a VLA control room was established in Socorro that is now used during evening and night shifts on weekends.

A large fraction of the available scientific support was allocated to maintaining receiver, antenna, and array performance and ensuring that the NRAO user community had access to quality instrumentation and updated information to effectively use the VLA. Operational tasks carried out by the scientific staff in support of these functions are briefly described below.

Support Calls for Proposals: Update of user documentation for offered capabilities for the 2015B and 2016A Call for Proposals, scientific testing of user tools needed to prepare proposals (Proposal Submission Tool, General Observing Spectral Line Tool, Exposure Calculator), technical reviews for proposals and evaluation of proposals for RSRO contributions.

Hardware, Software, and Operational Documentation: Technical documentation detailing hardware and software functionality for staff and users, operational procedures and documentation for the operations staff. The VLA Observational Status Summary was updated before the 2015B and 2016A Call for Proposals, along with the Guide to Observing with the VLA.

Track and Measure VLA Performance: The sensitivity and gain response of each antenna at each band was characterized periodically. Surface accuracy checks with holography were carried out to ensure optimal efficiency at the highest frequency bands. Antenna positions, collimation offsets and pointing accuracy were determined when the array was moved into a new configuration.

Scientific Testing of Antennas Completing Major Maintenance: Antenna positions, collimation offsets and pointing accuracy were determined each time an antenna came out of the Antenna Assembly Building after a maintenance overhaul. The performance of the new Antenna Control Units was evaluated.

System Health and Maintenance Feedback: Routine health checks were performed to determine if there were any hardware failures that must be followed up with maintenance tickets. Radio-Frequency Interference (RFI) monitoring tests were carried out to characterize and help mitigate RFI contamination in observing bands.

Data Quality Assurance Checks: Data quality was evaluated based on the Pipeline results, and test observations were run to identify and diagnose problems that were not caught by the standardized tests and engineering checks.

Calibration Data: Extensive, multi-configuration observations of calibrators were made to develop models of primary calibrators that can be applied during the data calibration process. In addition, the standard flux density run to monitor the flux densities of our standard calibrators was carried out.

In addition to the standard support tasks above, the following required scientific support to become operational in 2015.

New Atmospheric Phase Interferometer (API): The API continuously measures the atmospheric stability, and is primarily used to guide the dynamic scheduler as to when weather conditions are appropriate for high frequency observations. The old API has been replaced with a more robust, four-element API, the output from which was incorporated into regular operations.

VLITE: Final tests of VLITE requiring the extended B-configuration were carried out in 2015, and VLITE was integrated into operations.

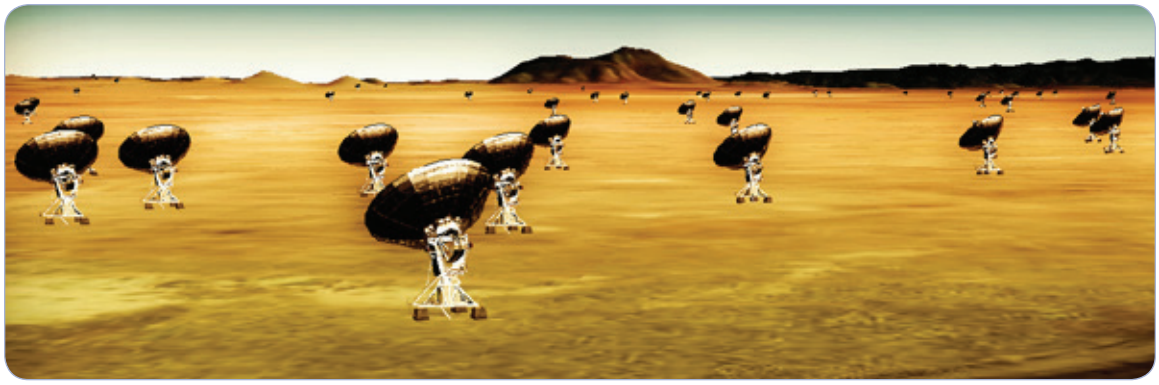
New 3-bit Samplers: The new 3-bit sampler modules were tested and evaluated by scientific staff as they were installed.

Frequency Averaging in Correlator Back-End: The ability to do frequency averaging in the correlator back-end has the potential to reduce data rates and data storage requirements for continuum observations. This capability was implemented in 2015 and offered through the RSRO program for semester 2016A.

New Mexico Operations Transitions

After several years of outstanding service leading the NRAO New Mexico facilities and personnel, Dale Frail stepped down in September 2015 from his role as the NRAO Assistant Director for New Mexico Operations. Dale will pursue research and a well-earned scientific sabbatical over the coming year and will return to the Observatory in 2016.

Mark McKinnon assumed the role of Assistant Director for New Mexico Operations on an interim basis, beginning in late September 2015. Mark has a substantial history of leadership and management in Socorro and at the NRAO, including his terms as the North American Project Manager for ALMA, the Director of the New Initiatives Office, and Project Manager for the Next Generation Very Large Array.



A Next Generation Very Large Array

New Worlds, New Horizons laid out an ambitious panorama of astronomical discovery for this decade. Radio astronomy is playing a leading role in opening this discovery space, with telescopes such as the Jansky VLA, ALMA, and the GBT in the vanguard. Radio telescopes are imaging the earliest phases of planet formation, studying the cool dust and gas that drive star formation in galaxies across cosmic time, observing energetic and time varying phenomena ranging from compact stars to distant Active Galactic Nuclei (AGN), and testing the fundamental laws of physics and cosmology.

Approaching the mid-point in the decade in 2015, and anticipating exciting new observational capabilities from instruments like the Square Kilometre Array and the James Webb Space Telescope, the NRAO invited the community to consider the future of radio instrumentation in the coming decade, and beyond, at a one-day workshop that preceded the American Astronomical Society January meeting in Seattle, Washington.

This *Next Generation Very Large Array (ngVLA) Workshop* – organized by NRAO and envisioned as the first in a series – was held 4 January 2015 to broaden discussion, develop a deeper understanding of the future science opportunities at meter to submillimeter wavelengths, and foster new interactions with the U.S. university community. This workshop included discussion of the scientific and technological opportunities and challenges in radio astronomy, as well as U.S. and international interests in producing powerful new capabilities for the astronomy community.

The workshop focused on the scientific impact of a facility operating in the centimeter to millimeter wavelength regime with a substantially larger (5 – 10X) collecting area, and improved spatial resolution relative to the current VLA. Such a facility will open a new window on imaging cool thermal objects in the Universe at milli-arcsecond resolution.

The workshop included invited talks by experts in the field, breakout sessions, report-outs by the working groups, and open forums that broadly discussed new and expanded science areas for radio astronomy, and the key technological and operational developments needed in the next decade to enable scientific progress. To facilitate and organize the discussion, four working groups were established to consider key science programs that could be addressed.

- *Cradle of Life:* (proto-)planetary systems and formation, cloud cores to stars, astrochemistry/biology, Solar System, the Search for Extraterrestial Life.

- *Galaxy Ecosystems (baryon cycle):* Galactic structure, interstellar medium and star formation, star formation laws, nearby galaxies, outflows and inflows, supermassive black holes.

- *Galaxy Assembly through Cosmic Time (high z Universe):* cool gas and dust, dynamics, Active Galactic Nuclei (AGN) and supermassive black holes.

- *Time Domain, Cosmology, Physics:* Transient sky, synoptic surveys, AGN physics, high energy phenomena, stellar phenomena, pulsars.

An ngVLA Technical Workshop was held in Pasadena, California on 8-9 April 2015 that focused on science opportunities and enabling technologies for a next-generation centimeter-to-millimeter wavelength interferometer. The principal conclusion from this workshop was that the technical requirements for achieving a scientifically transformational ngVLA demand only a plausible extrapolation of current technologies.

A second Technical Workshop, broadly patterned after the first, was held 8-9 December 2015 at NRAO– Socorro, and addressed a number of key topics that included ngVLA operation concepts, computer architectures, time and frequency distribution, and data transmission.

A second ngVLA Workshop was proposed by the NRAO for the January 2016 American Astronomical Society (AAS) meeting in Kissimmee, Florida and has been accepted by the AAS. The agenda for this ngVLA Workshop includes the presentation and discussion of the community science case and high-level technical issues, with substantial time for open discussion.

Very Large Array Sky Survey

The NRAO announced in December 2015 that it would proceed with the highly anticipated All-Sky portion of the Very Large Array Sky Survey (VLASS), subject to the successful passing of its preliminary and critical design reviews in 2016.

This decision followed the recommendation of the VLA Sky Survey Community Review panel chaired by Andrew Baker (Rutgers), which reviewed the complete VLA Sky Survey proposal and Technical Implementation Plan on 3-5 March 2015 and made a number of key recommendations. The Review Panel judged the VLASS All-Sky tier to be well-matched to: (a) groundbreaking transient and polarization science that will be enabled as soon as the first data products are released, and (b) the desire for user-friendly data products. The panel assessed that the proposed new VLASS would be a clear advance over the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty-one centimeters (FIRST) survey in terms of area, frequency, and angular resolution.

Thus, the VLASS will be a three-epoch (32-month cadence), all-sky, S-band (2-4 GHz) continuum polarimetry survey with 2.5-arcsecond spatial resolution. The survey will span seven years and six VLA configuration cycles. The total VLA telescope time required for the survey is ~5400 hours, or ~900 hours per configuration cycle.

Pilot observations will be acquired in the B-configuration in summer 2016 to support the critical design review. Observations for the full survey are expected to begin in October 2017, with quick-look images produced within two weeks of observation and final images and catalogs available for the first half of the first epoch available from the archive on or before February 2019. The basic data products currently anticipated include raw visibility data, calibrated data, quick-look images, and more.

In the first few months of 2016, the NRAO will establish the VLASS Project Office and complete the detailed planning and technical testing needed for observations to commence. NRAO will also publish a call for the community to contribute ideas and resources for the development of Enhanced Data Products from the survey, which will be considered at the preliminary design review. These potential Enhanced Data Products include transient object catalogs and alerts (enabling synergies with Large Synoptic Survey Telescope science), full spectral resolution image cubes, catalogs of multi-wavelength associations to VLASS sources, and more.

The Observatory is grateful to Stefi Baum (Manitoba) and Eric Murphy (NRAO) for leading the Survey Science Group Governing Council for the VLASS proposal efforts in 2015. The NRAO VLASS Project Office will continue to consult the Survey Science Group in 2016 and beyond, and will seek the Council's assistance in communicating the survey's compelling scientific opportunities to the community.

CASA Pipeline for the Very Large Array

Beginning 8 September 2015, the Very Large Array (VLA) transitioned to using the Common Astronomy Software Applications (CASA) pipeline. With this transition, the VLA and ALMA pipelines provide a common user interface and similar weblog output. For convenience, the CASA pipeline is distributed for both OSX and Linux in an integrated package, requiring no additional downloads or files. The first version accepted for official use by the VLA was based on CASA-4.3.1 and is available for download from the CASA website.

From the Archives: Hein's Trein

On 30 January 1974, following several years of discussion on transporter requirements and possible designs, E-Systems Inc. was awarded the contract for design and fabrication of transporter #1 for the Very Large Array.

The transporter was crucial to making the Very Large Array a flexible instrument that could operate in multiple array configurations. An 11 February 1977 memo stated, "We tend to underestimate the complexity of the design and construction of the vehicle, which picks up 220-ton antennas and transports them through 90 [deg] intersections. That it works as well as it does is an engineering achievement of the first order..."

Transporter #1 was named Hein's Trein, honoring long-time NRAO Associate Director Hein Hvatum.

Very Long Baseline Array Operations

The Very Long Baseline Array (VLBA) remained the world's preeminent facility for micro-arcsecond astrometric studies, and sub-milliarcsecond imaging in 2015. A wide range of science returns were achieved through precision astrometry including fundamental cosmology, Galactic structure, distances to local star-forming regions and clusters, and local galaxy dynamics. Imaging applications included the time-evolution of the black hole – accretion disk – jet environments of AGN, carried out in parallel with high energy National Aeronautics and Space Administration (NASA) missions such as the Swift, Fermi and Chandra satellites. New capabilities continued to be added with a focus on increasing the number of compatible observing modes of the various stations of the High Sensitivity Array (HSA). The emphasis in telescope operations in 2015 was to improve the reliability of the array through the retirement of legacy hardware and software, and on-going infrastructure maintenance.

NRAO continued to offer three types of observing programs to VLBA users in 2015: General Observing (GO), Shared Risk Observing (SRO) and Resident Shared Risk Observing (RSRO). For semester 2015B the DDC-8 mode on Effelsberg was commissioned and moved from the RSRO to the SRO program ahead of the original schedule, and was then moved to the GO program for semester 2016A. The Large Millimeter Telescope Alfonso Serrano (LMT) in Mexico was offered as part of the HSA for 3mm VLBI through the RSRO program, and beginning in semester 2015B the LMT was also offered on a "best effort" basis for inclusion in the Global 3mm VLBI Array (GMVA).

Operational tasks carried out by during 2015 in support of maintaining receiver, antenna and array performance and ensuring that the user community had access to quality instrumentation and the updated information required to effectively use the VLBA are briefly described below.

Support Calls for Proposals: update of user documentation for the offered capabilities for the 2015B and 2016A Call for Proposals, scientific testing of user tools needed to prepare proposals (e.g., PST, Sensitivity Calculator), technical reviews for proposals and evaluation of proposals for RSRO contributions.

Hardware, Software, and Operational Documentation: Technical documentation detailing hardware and software functionality for staff and users, operational procedures and documentation for the operations staff. The VLBA Observational Status Summary was updated before each Call for Proposals.

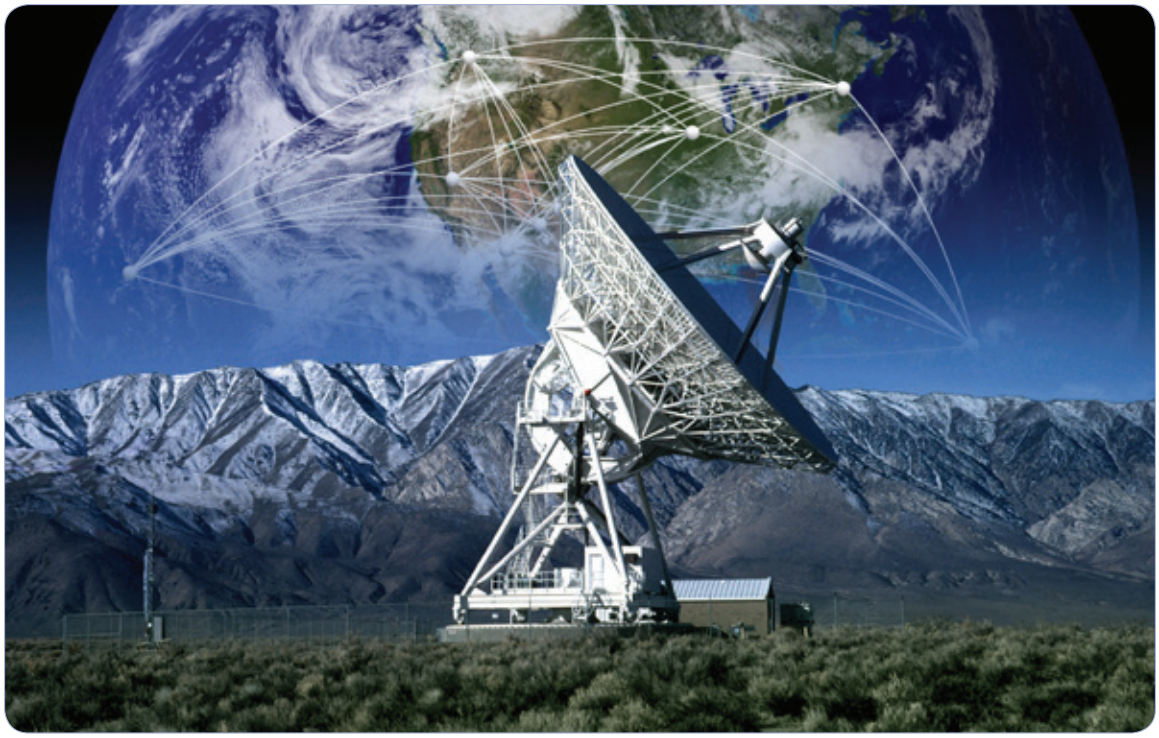
Track and Measure VLBA Sensitivity, Pointing, Focus: The sensitivity, pointing and focus of each antenna at each band were characterized periodically, as receivers and equipment were replaced or as software was upgraded.

Clock Maintenance: Accurate time keeping is central to VLBI, and is provided by hydrogen masers and reference signals inserted into the astronomical data. Quality assurance checks were performed periodically by scientific staff and data analysts.

RFI Characterization and Mitigation: RFI tests to characterize and help mitigate RFI contamination in the observing bands were performed.

System Health and Maintenance Feedback: Routine health checks and analysis of the data to determine if there are any hardware failures were followed up with maintenance tickets.

Data Quality Assurance: Data quality was evaluated and test observations run to identify and diagnose problems that were not caught by engineering checks.



Coordination for Global mm VLBI and the HSA: The VLBA occasionally observed in parallel with other observatories, as requested by users whose scientific goals require the inclusion of baselines to large-aperture and/or distant facilities. Scheduling and correlation of these observations required coordination with local schedulers at each participating observatory, a significantly more complex process than normal VLBA-only observations require.

Tiger Team Visits: Two VLBA stations per year were scheduled to receive major maintenance visits by the VLBA Tiger Team in 2015, comprising eight personnel from the antenna mechanics and the Electronics Division servo groups. The Owens Valley VLBA station received a major maintenance visit by the VLBA Tiger Team in 2015, but the planned major maintenance visit to St. Croix was switched to Mauna Kea following a lightning strike there. The schedule of the Mauna Kea visit was then delayed to late 2015 to avoid manpower conflicts with the VLA array reconfiguration, and to allow time to prepare additional equipment for the trip.

Technical Upgrades: The legacy VME computers that control the operation of the VLBA antennas are reaching end-of-life. As part of the Sensitivity Upgrade project, new hardware has been installed at the VLBA stations, and this new hardware is controlled with a modified version of the EVLA Executor. For the computer that hosts the Executor to be able to communicate with the legacy hardware, an interface box has been designed and tested in the laboratory. An operational unit was installed at the Los Alamos site and successfully tested in 2015.

Observing Capability Enhancements: In 2015, capability enhancements focused on increasing the number of compatible observing modes on stations of the HSA and on starting to include the LMT in the HSA for 3mm VLBI. Scientific and operations staff worked with colleagues at Effelsberg to commission and document DDC-8 observing at that telescope for inclusion in HSA observations, with the goal of offering this mode through the SRO program in 2016B. This work proceeded so smoothly that this mode was offered a year early, for semester 2015B.

WEST VIRGINIA OPERATIONS

Green Bank Telescope Operations

In 2015, the GBT remained the world's premier single-dish radio telescope operating at meter to millimeter wavelengths. Its enormous 100-meter diameter collecting area, unblocked aperture, and excellent surface accuracy provide unprecedented sensitivity across the telescope's full 0.1 - 116 GHz operating range. The GBT is used by hundreds of scientists each year for a large and varied series of programs. It has a collecting area and sensitivity comparable to ALMA and the VLA and thus excellent response to point sources such as pulsars. But as a filled aperture it also has the highest possible sensitivity to extended, low surface-brightness emission of the kind associated with comets, molecular clouds, and distortions of the cosmic microwave background. The GBT also joins the VLBA for interferometric observations to provide a critical threshold of sensitivity for the highest angular resolution studies. The single focal plane is ideal for rapid, wide-field imaging using multi-pixel cameras, and with access to 85% of the celestial sphere, it also serves as the wide-field imaging complement to ALMA and the VLA. Operation of the GBT is highly efficient, and it is used for astronomy ~6500 hours every year, with 2-3000 hours per year available to high frequency science.

State-of-the-art instruments now under development in collaboration with university groups will continue to keep the GBT equipped with the latest technology. Graduate students use the GBT to gain hands-on experience with a major telescope, an increasingly rare opportunity and critical for their training.

The telescope's oversubscription rate in 2015 varied from 2 – 2.5X, a decrease from previous oversubscription rates which have been ~4X or higher. The GBT is scheduled dynamically to match project needs to the available weather. Green Bank has several thousand hours of clear skies with a perceptible water vapor content under 10mm throughout the year, allowing extensive operations at short wavelengths. Since 2010, ~2000 hours have been available for weather-dependent high-frequency observations, a number which should increase as telescope control is improved.

The GBT has the best protection of any U.S. observatory from many forms of man-made radio frequency interference as it is located in the National Radio Quiet Zone and the West Virginia Radio Astronomy Zone. The facility's location in a lightly populated valley in the Monongahela National Forest, surrounded by extensive ranges of mountains in all directions, provides further protection from interfering signals.

The Green Bank facility is also a major resource for education and public outreach, and as such is an outstanding advocate for basic research and the work of the National Science Foundation. The facility produces nationally acclaimed programs in education, and the training of science and engineering students and teachers. These activities operate from the Green Bank Science Center, and with its auditorium, classrooms, and large exhibit hall, is visited by 50,000 people every year. Thousands of K-12 teachers and students partake of residential educational programs using older radio telescopes no longer involved in research. The facility's laboratories, utilities and support facilities make it an attractive location for independent research experiments and it serves as the field station for several university-based research instruments.

The science delivered by the GBT in 2015 was extremely varied, from searching for nanohertz gravitational waves through pulsar timing, to discovery and confirmation of new interstellar molecules, mapping the star formation regions and potential in the Milky Way and other galaxies, and studying the Sunyaev-Zel'dovich effect in distant galaxy clusters.

The total amount of science on the GBT in 2015 remained at ~6500 hours, with ~600 hours provided to a number of universities and other research organizations through private contracts, while the remaining hours were available under NRAO's open skies policy to all qualified astronomers.

GBT Instrument Development

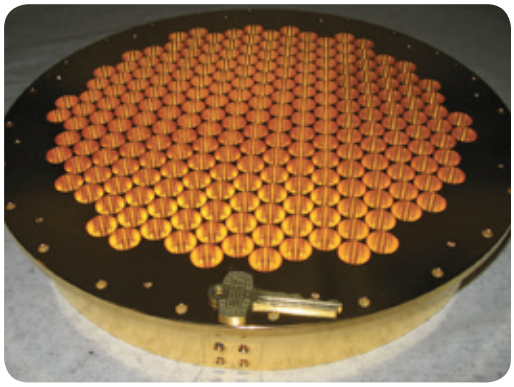
Two new instruments were under development in 2015 for future use on the GBT. Both are being built by university partners for specific science programs with the telescope and were intended to be completed in 2015, though neither achieved this goal. As a result, these new instruments are scheduled for commissioning in 2016. NRAO staff are assigned to these projects to aid in their installation and commissioning, but all project milestones are controlled by the non-NRAO project PIs.

ARGUS

In 2014, a team led by Sarah Church (Stanford University) began the construction of a 16-pixel, 75–115.3 GHz traditional feed horn array, funded by NSF. The GBT is the best telescope in the world for molecular line research in the 70–100 GHz band. The camera will capitalize on that fact by using the GBT sensitivity to create on-the-fly images of cometary molecules. When combined with the GBT sensitivity, the camera will be the only system in the world that can provide information about the structure of comets as they move through the Solar System. Development of the instrument is delayed and is currently expected to complete in 2016.

Multiplexed Squid TES Array at Ninety GHz (MUSTANG) MUSTANG 1.5 / 2

In 2013, a group led by the University of Pennsylvania began building a new 75-105 GHz bolometer array for the GBT. This array was assembled from new frequency-domain microwave SQUID (mSQUID) multiplexers recently developed by NIST, and contoured feed horns. The array was deployed for one season in 2015. However, the instrument suffered from noise and other problems resulting in only a limited science output. During the same year, the PI secured sufficient funding to expand the total number of pixels on the instrument to ~200 pixels total. As a result, when the instrument was removed from the GBT in FY15, it was returned to the PI for work on the instrument noise and to upgrade its size. Delivery and commissioning of this new instrument (MUSTANG 2) is scheduled in 2016. As with ARGUS, though, all project milestones are controlled by the non-NRAO project PIs.



The MUSTANG-2 array of 223 feed horns, which are machined out of a single aluminum block that has been gold-coated. Dual-polarization detector modules are affixed to each feed.

The MUSTANG-2 camera employs many of the technologies used in its predecessor, which was used by GBT observers from 2009 to 2013 – including Transition Edge Sensor (TES) bolometers, Superconducting QUantum Interference Device (SQUID) amplifiers to read out the detectors, a low-vibration pulse tube refrigerator, and closed-cycle helium-3 and helium-4 refrigerators to cool the detectors to 300 mK.

MUSTANG-2 features many improvements: more sensitive microstrip- and feedhorn-coupled TES bolometers, a wider (75-105 GHz) band pass, a 5x larger instantaneous field-of-view, and much more robust cryogenic performance. Readout is accomplished via four ROACH boards using a microwave-resonator multiplexer that has been adapted for use with TES detectors. The receiver has been designed to accommodate 223 dual-polarization detectors, and the full 223 feedhorn detector array has been fabricated and deployed on the GBT. Available funding permitted populating only 64 of the 223 feeds.

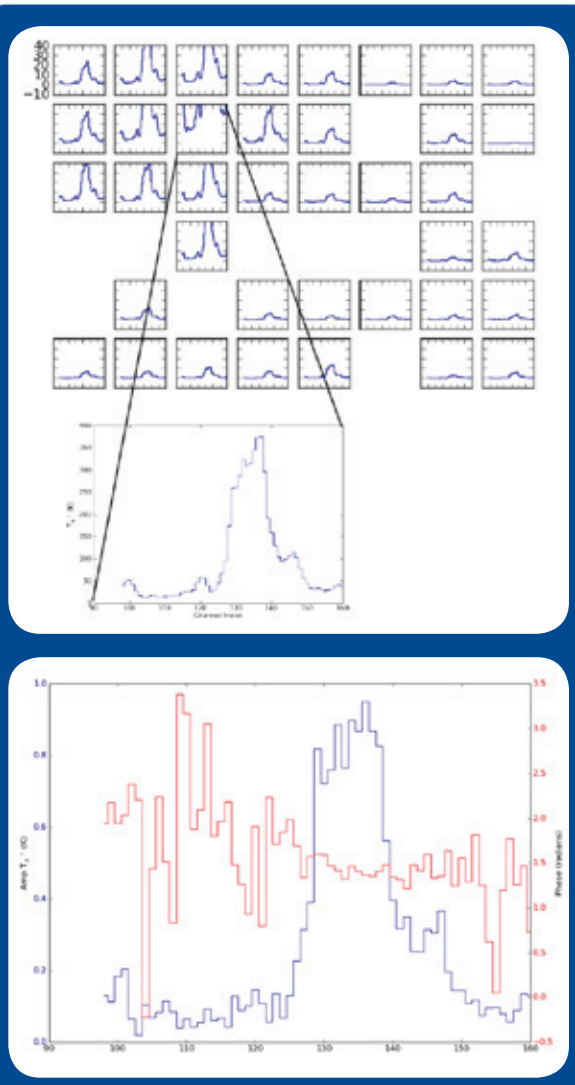
Similar to its predecessor, MUSTANG-2 will have a ~8.5 arcsec FWHM beam on the GBT. It is available for early science observing in collaboration with the instrument team. MUSTANG-2 will excel at making high-resolution images of the Sunyaev-Zel'dovich effect, and mapping the large-scale context of star formation in our own Galaxy and nearby galaxies.

A W-band Focal Plane Phased Array Feed Receiver

The Phased Array for Millimeter Astronomy (PHAMAS), a W-band focal plane phased array receiver covering 70–97 GHz, was installed on the GBT for tests in late October 2015. The array is planned to eventually have 64 elements, and be able to synthesize up to 225 Nyquist-sampled beams on the sky in a single pointing. These beams are formed by vector summing combinations of the individual elements, to best match the focal plane Airy disk.

In its initial form, PHAMAS has 38 working elements – set by the number of IF fibers to the GBT control room – which is adequate to evaluate the operation on the GBT. The array uses cryogenic Monolithic Millimeter-wave Integrated Circuit (MMIC) preamplifiers in a compact dewar, with further gain and down-conversion done with room temperature electronics. The entire cluster of 64 feed horns is 48 mm square, as is necessary for proper focal plane sampling of the GBT f/1.9 optics. Tests showed that calibration of the array phase and gain response – convolved with the telescope response – could be achieved by observations of Mars, 3C454.3, and Orion SiO masers. The convolved response is used to compute cross-correlations between elements, which are then used as weights in the vector sums of elements. The absolute phase and gain response of the array was measured with a noise source mounted on the prime focus boom, and this, along with the sky calibration, enabled quick measurement of the GBT surface errors, since the calibration function is equivalent to a holography map.

The upper figure shows the cross-correlation of every element amplitude against the reference element, which was pointed towards the Orion SiO maser point source. The reference element is seen as the second row from the top and third column from the left. The data shown is for 30 seconds integration for each of the ON and OFF positions. Missing grid elements are



[TOP] *Amplitude of the cross-correlation between each array element and the reference element at row 2, column 3, pointed at the Orion SiO maser source. To accentuate the appearance of the antenna Airy disk, the y-axis is shown for a scale of -10 to 40 K. The reference pixel is shown offset with its full-scale of 0 – 400 K.* **[Bottom]** *The cross-correlation amplitude (shown in blue) and phase (shown in red) of element in row 2, column 8 (where the cross-correlation signal peak amplitude is less than 1K) with respect to the reference pixel.*

due to elements that were turned off for this experiment. Preliminary analysis showed system temperatures in the range 150 – 180K, and aperture efficiencies well in line with expectations. The x-axis is in frequency channel space and covers a bandwidth of ~6 MHz. The first nulls of the Airy disk in the focal plane are expected to be separated by approximately three elements, but the surface was not set for these observations so a more complex focal plane function was expected.

The lower figure (previous page) plots the row 2, col 8 element cross-correlation showing structure in the weakest location in the focal-plane, which in intensity units is 4×10^{-6} times as strong as the central position. The minimum intensity sidelobe required for efficient beamforming is ~200x larger, so there was adequate noise margin to calibrate on much weaker sources.

These initial engineering observations were exceptionally encouraging. This was the first demonstration of an astronomical, focal-plane phased array feed working at millimeter wavelengths. These results show that such an instrument, capable of forming hundreds of simultaneous beams, fully spatially sampling the sky, is realistic. Unlike a conventional feed-horn array, such an instrument would be able to intrinsically correct for phase errors due to large-scale surface deformations, which are a significant component of the GBT surface error budget at high frequency.

These first results from the October 2015 commissioning run demonstrate the basic operation of the instrument. The next stage is to generate the equivalent formed beams for these observations. Although conceptually well understood, this is a formidable data processing challenge. The next steps for the instrument are to enable all 64 elements, and to develop a wideband beamformer.

The Principal Investigator for this instrument is Neal Erickson (University of Massachusetts). This work was funded by the NSF under grant AST-1106205.

Celebrating the 140-Foot Telescope

On 13 October 2015, 50 years to the day after the dedication of the 140-foot Telescope on 13 October 1965, 70 retirees and friends and 80 current employees gathered in Green Bank, West Virginia to celebrate the 50th anniversary of that dedication. The day began with two brief talks. The first, by Frank Ghigo, described the construction of the telescope and attendant challenges. The second talk, by Dave Hogg, described the many exciting observations acquired in the first few years of this telescope's operation and how they changed our view of the Universe.

The day also included a proclamation from the Governor of West Virginia honoring the telescope, in-depth tours of the telescope, and an exhibit in the rooms at the entrance level of photos and objects illustrating the telescope's construction and use. Items were collected for a 140-Foot Telescope time capsule that was later buried. The afternoon festivities included opening the time capsule buried at the 300-foot Telescope during its 25th anniversary symposium in 1987, with Bob Vance, Rich Lacasse, and Bob Simon revealing several treasures. The afternoon ended back at the Jansky Lab, where attendees enjoyed showings of the two Peter B. Good films from the mid-1960s – The Lift and Construction of the 140-Foot Telescope – and several recently digitized 2-3 minute films from 1958-1959, including the 14 August 1958 ground-breaking, the concrete pour for the pedestal, and the original shaft moving up the road from the Bartow, West Virginia rail siding in September 1959.

[RIGHT] Director David Heeschen speaking at dedication, 13 October 1965. [INSET] Group photo of 50th celebration attendees, 13 October 2015.

Other Green Bank Telescopes

In addition to the GBT, the Green Bank, West Virginia research facilities include several telescopes and host several independent experiments.

140-foot Telescope
The long-term contract for the 140-foot telescope to function as an Earth Station (downlink station) for the Russian Roscosmos State Corporation for Space Activities RadioASTRON (Spektr-R) satellite continued through 2015.

20-meter Telescope
The Green Bank 20m telescope was a key participant in the NRAO Education and Public Outreach program, collaborating with the University of North Carolina SkyNET Robotic Telescope Network. The 20-meter telescope also conducted commensal monitoring for Fast Radio Bursts as part of a program developed by NRAO, West Virginia University, and Virginia Tech.

40-foot Telescope
The 40ft diameter site telescope was used exclusively in 2015 by the NRAO Education and Public Outreach programs for student and teacher projects.

Precision Array for Probing the Epoch of Reionization (PAPER)
PAPER is a collaboration between NRAO, the University of Virginia, and the University of California, Berkeley. The array was deployed at the Green Bank site in 2004 for testing and confirmation of any signals found with its larger sister array in the Karoo, South Africa. The instrument is no longer in use and is being replaced by the Hydrogen Epoch of Reionization Array (HERA).

Hydrogen Epoch of Reionization Array (HERA)
HERA is being built in Green Bank as a test construction and data acquisition array. The final array is to be built in the Karoo in South Africa. Construction of the first of three antennas of the HERA project was completed in 2015.

Low Frequency All-Sky Monitoring array (LoFASM)
LoFASM has one of its four stations on the Green Bank site. The instrument has been in operation since 2012.

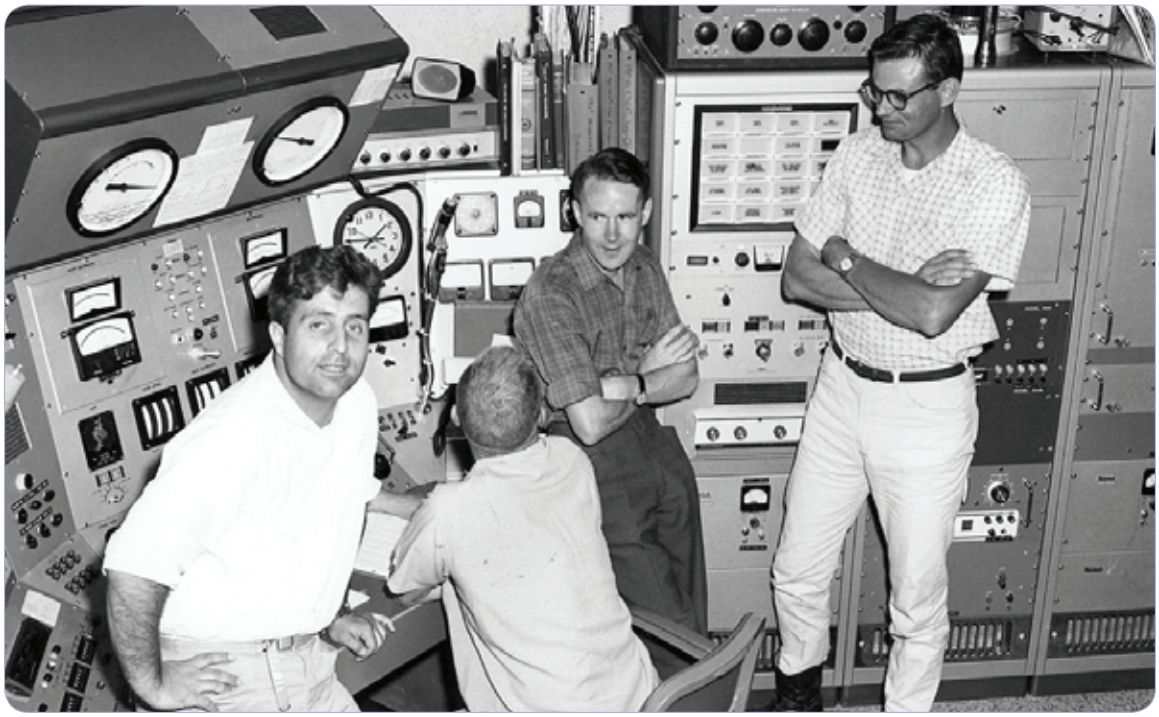
Magnetometers along the Eastern Atlantic Seaboard for Undergraduate Research and Education (MEASURE)
West Virginia University installed a magnetometer on the Green Bank site as part of the University of California-led MEASURE project to study magnetosphere dynamics. This project is staffed and run through the West Virginia University.

The Future of Planetary Radio Astronomy

A workshop titled *The Future of Planetary Radio Astronomy with Single-dish Telescopes* was held at the NRAO facilities in Green Bank, West Virginia on 9 – 10 June 2015.

Topics discussed in this workshop included: radar studies of near-earth asteroids, mapping of planet and lunar surfaces, chemical compositions of comets, asteroids, and planetary atmospheres, and origins of solar systems. This workshop brought together researchers to discuss how large single-dish telescopes such as the 100-m GBT and the 300-m Arecibo Observatory can best contribute to future research in these and other topics, including new and improved capabilities and instrumentation. The intimate setting of the NRAO – Green Bank facilities fostered a highly-interactive meeting.

From the Archives: Radio Recombination Line Detection



July 2015 was the 50th anniversary of the 9 July 1965 detection of radio recombination lines by Bertil Hoglund and Peter Mezger. The detection was accomplished with the brand new 140-foot telescope prior to its formal dedication in October 1965, and ushered in an entirely new field of radio astronomy research. In this image, taken 2.5 weeks later on 27 July 1965, [left to right] Peter Mezger, Troy Henderson, Bertil Hoglund, and Neil Albaugh are in the 140-foot telescope control room, perhaps considering other observations to undertake with this new NRAO research instrument.

SCIENCE SUPPORT & RESEARCH

The NRAO Science Support and Research (SSR) department coordinates, aligns, and manages the collective efforts of the three NRAO sites — Charlottesville, Virginia; Socorro, New Mexico; and Green Bank, West Virginia — to support science users of NRAO facilities, to broaden the Observatory's impact through education and visitor programs, and to oversee the research and performance of the scientific staff. It does so through two groups:

- Telescope Time Allocation (TTA) manages the process and tools by which users prepare and submit proposals for use of NRAO telescopes, as well as the proposal evaluation and time allocation process.

- Science User Support (SUS) is responsible for providing the scientific community with the support necessary to execute successful scientific programs with NRAO facilities including the GBT, VLA, VLBA and ALMA.

In addition, SSR provides two observatory-wide services: (1) NRAO reference comprises the NRAO Library and the Historical Archives, (2) Statistics and metrics aggregates data for internal use and to report various metrics to the NSF, to AUI, and to external review committees.

SSR also oversees the research activities of the NRAO scientific staff, staff performance review, staff development activities, the Jansky Fellowship program and postdocs, NRAO student programs, and various other scientific activities such as the Jansky Lecture, scientific meetings, colloquia, and seminars.

U.S. Radio Futures

In 2015, the NRAO initiated the organization and execution of a series of three conferences for the astronomy community to enable broad discussion of potential U.S. futures for radio-millimeter-submillimeter (RMS) science in the 2020's and beyond. Funded by the Kavli Foundation and Associated Universities, Inc. (AUI), the first conference in this Kavli Conference Series – hereafter "Futures I" – was held 15-17 December 2015 in Chicago, Illinois with 116 scientists from universities, observatories, and laboratories from around the U.S. in attendance and representing virtually every field of modern astrophysics.

An executive Organizing Committee (OC) was formed and convened by NRAO, AUI, and the Kavli Foundation to define and guide the three-event Kavli Conference Series.

Organizing Committee (OC), Kavli Conference Series

- Tony Beasley (NRAO Director)
- Roger Blandford (Stanford University)
- John Carlstrom (University of Chicago)
- Martha Haynes (Cornell University)
- Jackie Hewitt (Massachusetts Institute of Technology)
- Joseph Lazio (Jet Propulsion Laboratory)
- Tony Readhead (California Institute of Technology)
- Mark Reid (Harvard-Smithsonian Center for Astrophysics)

This OC assembled and charged the requisite Scientific Organizing Committee (SOC):

- Mark Reid (Harvard-Smithsonian Center for Astrophysics, Co-Chair)
- Jean Turner (University of California, Los Angeles, Co-Chair)
- Avery Broderick (University of Waterloo)
- Sarah Church (Stanford University)
- Lee Hartmann (University of Michigan)
- John Kovac (Harvard-Smithsonian Center for Astrophysics)
- Maura McLaughlin (West Virginia University)
- Alice Shapley (University of California, Los Angeles)
- Dave Wilner (Harvard-Smithsonian Center for Astrophysics)
- Min Yun (University of Massachusetts – Amherst)

The Futures I conference was structured around key science themes that: (a) reflect community priorities identified in the *New Worlds, New Horizons* Decadal Survey conducted by the National Academy of Sciences and published in 2010, (b) are likely to be important in the forthcoming decade, and (c) that require observations at RMS wavelengths to address.

Four Science Working Groups (SWGs) were formed to address key scientific themes:

- *Cradle of Life* — Chairs: Lee Hartmann, David Wilner
- *Formation & Evolution of Galaxies* — Chairs: Alice Shapley, Min Yun
- *Fundamental Physics* — Chairs: Avery Broderick, Maura McLaughlin
- *Cosmology & Cosmic Dawn* — Chairs: John Kovac, Sarah Church

Seventeen Futures I presentations addressed the *Cradle of Life* theme, seeking scientific insight into fundamental questions such as: (a) what are the mechanisms and physics of star formation across the entire stellar mass range, (b) how do circumstellar disks form and evolve, and (c) how do planetary systems develop within circumstellar disks?

Seventeen Futures I presentations addressed the *Formation & Evolution of Galaxies* theme, seeking scientific insight into fundamental questions such as: (a) how does gas flow into and out of galaxies, (b) to what extent can galaxy interactions be tracked, and (c) how well do the Milky Way and other galaxies in the Local Group serve as models for galaxies across the Universe?

Fifteen Futures I presentations addressed the *Fundamental Physics* theme, seeking scientific insight into fundamental questions such as: how can the Universe be used as a laboratory for testing the extremes of physical laws, including relativistic magneto-hydrodynamics, nuclear equations of state, physics near event horizons, and theories of gravity?

Ten Futures I presentations addressed the *Cosmology & Cosmic Dawn* theme, seeking scientific insight into fundamental questions such as: (a) to what extent can the early Universe be probed, and (b) how did the Universe transition from a largely neutral state to a largely ionized state?

Ten presentations described the status of new astronomical facilities now under construction that are expected to make signification contributions to the exploration of the Futures I science themes.

The Futures I conference comprehensively investigated and discussed potential U.S. futures for RMS science in the 2020's and beyond. The 116 attendees at Futures I produced a compelling set of Science Working Group Reports that are key inputs to the exploration of the scope, feasibility, and transformational science expected from the leading future RMS instrument and technique options and will inform and guide the presentations and discussions at the Futures II and Futures III Kavli Conferences.

The second U.S. Radio Futures conferences in the Kavli Conference Series, Futures II, will be held 3-5 August 2016 in Baltimore, Maryland.

Parallel sessions at Futures II in Baltimore will broadly discuss potential RMS *Flagship* and *Small/Midscale* initiatives over the planned 2.5 days of the conference. *Flagship* options are defined as major investments for instruments with widespread community benefit and support that will require funding by or on a scale comparable to the NSF – Major Research Equipment and Facility Construction (MREFC) program. *Small/Midscale* initiatives are significant investments that might be funded via the NSF Mid-Scale Initiative Program (MSIP), such as experiments emerging from smaller groups and collaborations.

The third U.S. Radio Futures conference in the Kavli Conference Series will be held in August 2017 at a location on the U.S. west coast.

Day-1 of the Futures I conference, 15 December 2015, at the Hyatt Regency O'Hare in Chicago.

NRAO Calls for Proposals

VLA | GBT | VLBA, HSA, VLBI

The NRAO published two Calls for Proposals for the GBT, the VLBA/HSA, and the VLA in 2015. The Semester 2015B Call for Proposals was released 2 January with a submission deadline of 2 February, and (b) the 2016A Call for Proposals was released 1 July 2015 with a submission deadline of 3 August. The February proposal deadline applies to requests for time from 1 August through 31 January, and the annual August proposal deadline applies to requests for time from 1 February through 31 July.

The NRAO proposal evaluation and time allocation process is panel-based. Members of the scientific community review proposals based on their scientific merit via eight Science Review Panels:

- Solar System, Stars & Planetary Systems (SSP)
- Star Formation (SFM)
- Normal Galaxies, Groups, and Clusters (NGA)
- Extragalactic Structures (EGS)
- Energetic Transients and Pulsars (ETP)
- Interstellar Medium (ISM)
- Active Galactic Nuclei (AGN)
- High Redshift and Source Surveys (HIZ)

Each SRP has six members: five panelists and a Chair, each of whom normally serve a two-year term. The Time Allocation Committee (TAC) consists of the SRP chairs and is charged each Semester with recommending a science program to the NRAO Director.

NRAO received 276 and 324 proposals in response to the Semester 2015B and 2016A Calls for Proposals, respectively. These proposals were reviewed for scientific merit by the Science Review Panels and for technical feasibility by NRAO staff.

For Semester 2015B, the reviews were completed in March 2015 and then considered by the TAC at a face-to-face meeting on 27-28 April at NRAO Headquarters. The recommended 2015B program was reviewed and approved on 14 May 2015. A disposition letter was sent to the Principal Investigator and Co-Investigators of each proposal on 28 May 2015. The TAC report containing information for proposers and observers, including statistics and telescope pressure plots, was released the same day, and the approved science program was posted to the NRAO science website.

For Semester 2016A, the reviews were completed in September 2015 and then considered by the TAC at a face-to-face meeting at NRAO – Socorro on 19-20 October 2015. The recommended 2016A program was reviewed and approved on 4 November 2015. Disposition letters were sent to the Principal Investigator and Co-Investigators of each proposal on 13 November 2015. The TAC report was posted to the NRAO science website the same day.

NRAO welcomes community feedback on its process for telescope time allocation via the Proposal Review department of the Observatory Helpdesk.

Radio Astronomy Summer Schools

The NRAO and the National Astronomy and Ionosphere Center (NAIC) organized the eighth NAIC-NRAO summer school on single dish radio astronomy in 2015. For the first time, this single dish school was followed by a three-day course on radio interferometry, including hands-on imaging and analysis of ALMA data.

The Single-Dish School was held 5–10 July 2015 at NRAO in Green Bank, West Virginia. The School provides graduate students, post-docs, and experts in other fields of astronomy with background knowledge and practical experience with the techniques and applications of single-dish radio astronomy. The School includes a series of lectures from experts in the field. Participants also take part in a hands-on project using either the Arecibo Telescope or the GBT. The hands-on component is a significant part of the program, allowing participants to make observations, analyze the data acquired, and interpret the results all during the course of the week.

The Interferometry School was held 12–14 July 2015, also at NRAO – Green Bank. The Interferometry School included two days of lectures on radio interferometry at a level appropriate for graduate students in astrophysics. The final day of the school featured hands-on work to image and analyze ALMA data using the Common Astronomy Software Analysis (CASA) software package.

Jansky Fellows

The NRAO Jansky Fellowship program provides outstanding opportunities for research in astronomy. Jansky Fellows formulate and carry out investigations either independently or in collaboration with others within the wide framework of interests of the Observatory. The program is open each fall to candidates with interest in radio astronomy instrumentation, computation, and theory, and prior radio experience is not required. Multi-wavelength projects leading to a synergy with NRAO instruments are encouraged. Two new Jansky Fellows joined NRAO in fall 2015.

Tanmoy Laskar completed his Ph.D. from Harvard University, working with Professor Edo Berger on the diversity and versatility of γ-ray bursts. He is an expert at multi-wavelength observations and modeling, as well as radio instrumentation, and studies time-domain astrophysics with a focus on energetic transients. Tanmoy began his Jansky Fellowship at the University of California, Berkeley in fall 2015.

Dustin Madison completed his Ph.D. at Cornell University with Professor Jim Cordes, then joined NRAO in Charlottesville. Dustin works with pulsar timing observations to detect and characterize gravitational waves from sources such as binary supermassive black holes. His work has been primarily as a member of the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), a group utilizing the high-precision pulsar timing capabilities of the 300m Arecibo Observatory and the 100m NRAO Green Bank Telescope.

Jansky Lectureship

Associated Universities, Inc. (AUI), and the NRAO awarded the 2015 Karl G. Jansky Lectureship to Dr. Nick Z. Scoville of the California Institute of Technology (Caltech). The Jansky Lectureship is an honor established by the trustees of AUI to recognize outstanding contributions to the advancement of radio astronomy.

Scoville leads the Cosmic Evolution Survey (COSMOS), a project that uses data from virtually every large space- and ground-based telescope, including the NRAO Very Large Array, to study the large-scale structure of the Universe and the evolution of galaxies. Begun in 2004 with a large allocation of observing time on the Hubble Space Telescope, COSMOS has detected more than a million galaxies back to the first billion years of the Universe. Scoville is using ALMA to investigate the evolution of star formation in the early Universe and colliding starburst galaxies.

A professor at Caltech since 1983, Scoville received his Ph.D. from Columbia University in 1972. He was a pioneer in millimeter-wave astronomy and is a leading expert in studies of galaxy evolution, the nature of the dense interstellar molecular gas in galaxies, and in the process of star formation, both in the nearby and in the distant, early Universe. He is a past director of Caltech's Owens Valley Radio Observatory, and has served on numerous national committees. Author of more than 600 publications in observational and theoretical astrophysics, Scoville's previous awards include a Guggenheim Fellowship, the Aaronson Award of the University of Arizona, and serving as Bishop Lecturer at Columbia University.

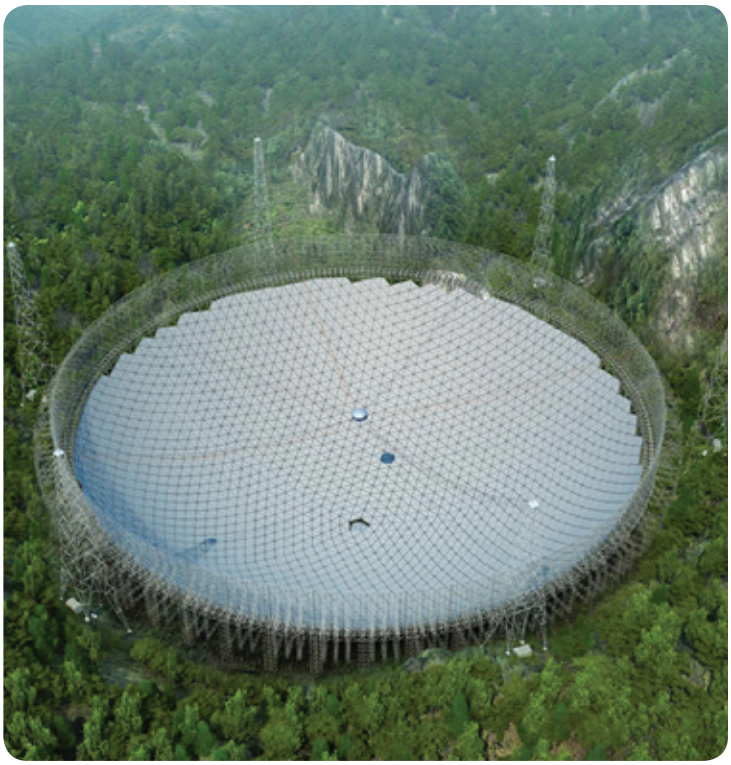
Page Charge & Student Observing Support

NRAO has had a longstanding policy of providing page charge support to authors affiliated with U.S. institutions publishing papers that report original observations utilizing the VLA, VLBA, and/or the GBT, contain an original analysis of archival data from these instruments, and/or are based on a significant amount of previously unpublished data from these telescopes. Beginning in 2012, this policy was extended to include ALMA. The NRAO has been the only U.S. ground-based observatory to provide page charge support to its users in recent years. Unfortunately, as the result of a challenging 2014 budget climate, the Observatory had to suspend page charge support for our user community. In 2015, however, page charge support for NRAO users was restored.

The NRAO was also able to restore the NRAO Student Observing Support (SOS) program for its North American instruments in 2015. The program, with the exception of ALMA, was suspended last year as a result of budgetary pressures. The program supports research using NRAO telescopes by graduate and undergraduate students at U.S. universities and colleges. Student Observing Support proposals associated with observing proposals submitted for the VLA, GBT, the VLBA for the 2016A observing semester are eligible, as well as those submitted through the North American Executive for ALMA. No action is required on the part of applicants at the time of proposal submission. Solicitations for applications for SOS support were included with 2016A proposal disposition letters in November 2015, and successful ALMA Cycle 3 Principal Investigators were contacted in the same time frame. Outstanding applications for support for student observing with all instruments will be competitively selected early in 2016.

4th China–U.S. Workshop on Radio Astronomy

NRAO and the Shanghai Astronomical Observatory (SHAO) organized the fourth in a series of China – U.S. radio astronomy workshops, which was held in Shanghai, China 14–16 October 2015. The title of this workshop was *Scientific and Technical Drivers for the Next Generation of Radio Telescopes*. Its primary purpose was to build and further strengthen collaborations between the U.S. and Chinese radio astronomy communities. The workshop included discussions on science and instrumentation, with a focus on projects and programs that will feed into the next generation of radio astronomy facilities, such as the Five-hundred-meter Aperture Spherical Telescope (FAST) the next-generation Very Large Array (ngVLA), and future Very Long Baseline Interferometry capabilities in space and on the ground.

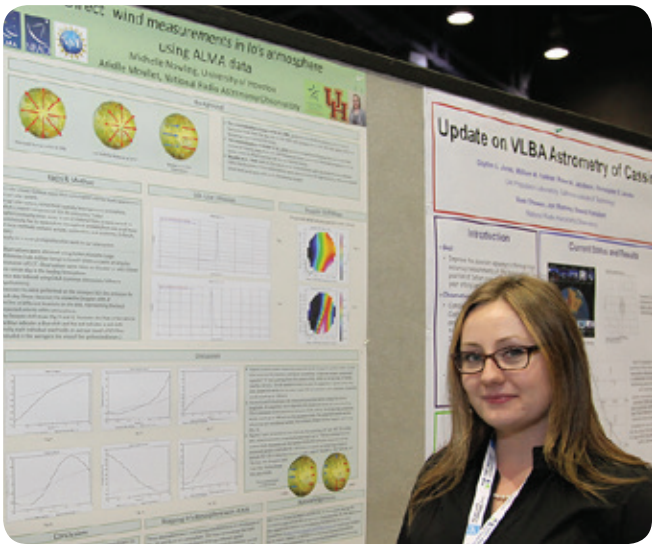


The Five-hundred-meter Aperture Spherical Telescope (FAST), located in a natural basin of the Dawodang depression in Pingtang County, Guizhou Province, southwest China.

AAS Presentations by NRAO Summer Students

Twenty-five of the 2014 NRAO Summer Student program participants presented the results of their research projects at the January 2015 American Astronomical Society meeting in Seattle, Washington. The table below lists the title of each presentation, the session and paper number, and the complete author list.

Monday, 5 January 2015



AAS photo © 2015 Joson Images.

137.11 *Direct Wind Measurements in Io's Atmosphere,* Michelle Nowling (pictured at right), Arielle Moullet.

137.24 *Photonic Local Oscillator Test System for the Atacama Large Millimeter/submillimeter Array,* Cathleen Gross, Christophe Jacques.

140.01 *Multi-epoch, Ultraviolet Spectroscopy of Type Ia Supernovae,* Aaron Beaudoin, Ryan J. Foley.

141.12. *Chemical Complexity in the Shocked Outflow L1157 Revealed by CARMA,* Niklaus M. Dollhopf, Brett A. McGuire, P. B. Carroll, Anthony J. Remijan.

141.27. *Tracing the Dense Molecular Gas in the Large Magellanic Cloud,* Rebecca C. Levy, Juergen Ott, David S. Meier, Annie Hughes.

142.01. *The Discovery of New Ammonia Masers in the Galactic Center,* Alex Teachey, Elisabeth A. Mills, David S. Meier, Juergen Ott, Natalie Butterfield, Cornelia C. Lang, Mark Morris.

142.02. *Location of Deuterated Ammonia in Sagittarius B2,* Aspen Clements, Elisabeth Mills.

142.03. *Targeted VLA Observations of 22 GHz Water Masers Towards the Galactic Center,* Matthew Rickert, Juergen Ott, Farhad Yusef-Zadeh, David S. Meier.

142.05. *Densities of Galactic Center Clouds,* Jonathan Barnes, Elisabeth A. Mills, Mark Morris.

143.23. *A General Purpose Stacking Technique to Analyze Low Brightness Signal,* Daniel Wavle, Adam K. Leroy, Jennifer Donovan Meyer.

143.40. *Spectral Indices of Faint Radio Sources,* Hansung B. Gim, Christopher A. Hales, Emmanuel Momjian, Min Su Yun.

143.46. *Host Galaxies of submicro-Jansky Radio Sources,* Kristen Luchsinger, Mark Lacy.

Tuesday, 6 January 2015

248.15. *Metallicities of Low Mass Inefficient Star Forming Dwarfs in S4G: Testing the Closed Box Paradigm,* Myles McKay, Sabrina Stierwalt, Kartik Sheth, Dr. Bonita de Swardt, Donald K. Walter.

250.22. *Mapping the Star Formation in NGC 1097 Using the JVLA,* Aara'L Yarber, Kartik Sheth, Dana S. Balser, Sarah J. Wood.

250.25. *An Unusual DRAGN: The Spiral Galaxy, 0313-192,* Gia Johnson, Minnie Mao, Emmanuel Momjian.

251.04. *The Uses of Fine Structure Lines in Constraining the Physical Properties of a Starburst,* Moiya McTier, Drew Brisbin.

256.06. *6.7 GHz Methanol Masers Associated with Jets in Very Early High Mass Protostars,* Viviana Rosero, Peter Hofner, Mark J. Claussen, Stan Kurtz, Riccardo Cesaroni, Luca Moscadelli.

256.07. *Ammonia and HC7N Emission in Starless Dense Cores,* Tierra M. Candelaria, Scott Schnee.

Wednesday, 7 January 2015

336.28. *An Analysis of Offset, Gain, and Phase Corrections in Analog to Digital Converters,* Devin Cody, John Ford.

336.30. *A Blind Search for Neutral Hydrogen,* Julia Gross, Emmanuel Momjian, Jacqueline H. Van Gorkom.

336.34. *A Pipeline for High Resolution Radio Images,* Brianna P. Thomas, Alison B. Peck, Jacqueline Hodge, Anthony J. Beasley.

337.15. *Systematic and Performance Tests of the Hard X-ray Polarimeter X-Calibur,* Ryan Endsley, Matthias Beilicke, Fabian Kislat, Henric Krawczynski.

346.12 *On the Sensitivity of Black Widow Pulsars to the Stochastic Gravitational Wave Background,* Christopher Bochenek, Scott M. Ransom, Paul Demorest.

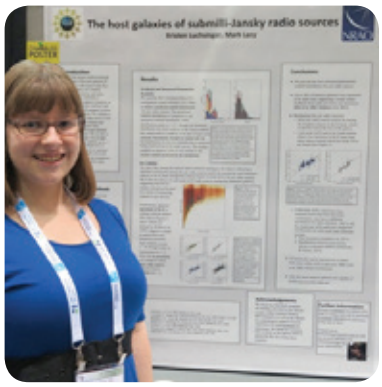
347.07. *Constraining the Orbits of the Supermassive Binary Blackhole Pair 0402+379,* Ben Holland, Alison B. Peck, Gregory B. Taylor, Robert T. Zavala, Roger W. Romani.

Thursday, 8 January 2015

452.01 *A Green Bank Telescope 21cm survey of HI clouds in the Milky Way's Nuclear Wind,* Sara Denbo, Ryan Endsley, Jay Lockman, Alyson Ford.

Summer Student Awarded Chambliss Medal

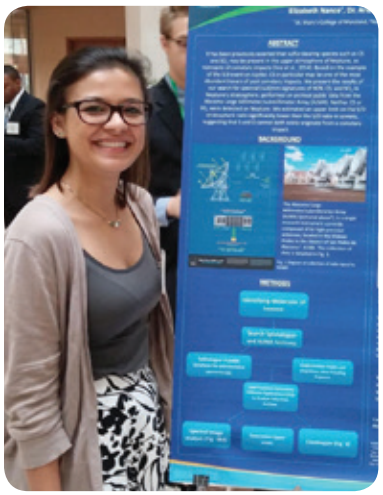
The Chambliss Astronomy Achievement Student Awards are given to recognize exemplary research by undergraduate and graduate students who present poster papers at AAS meetings. Awardees are honored with a Chambliss medal or, in the case of an honorable mention, a certificate.



Kristen Luchsinger at the Seattle AAS Meeting.

At the January 2015 AAS meeting in Seattle, undergraduate Kristen Luchsinger (St. John's College) was awarded a Chambliss Medal for the research she conducted as a participant in the 2014 NRAO Summer Student Research Assistantships program. In collaboration with NRAO Scientist Mark Lacy, Kristen studied the host galaxies of faint, sub-milliJansky radio sources. Kristen combined a deep 1.4 GHz radio survey in the Lockman Hole with infrared and optical data in the same field to make the largest study to date of the redshift distribution, brightnesses – determined via the relation between the near-infrared K-magnitude of the host galaxy and redshift – and stellar masses of the hosts of sources with typical radio flux densities ~100 μJy.

Kristen used mid-infrared diagnostics to show that this μJy radio source population contains a roughly equal mix of star-forming galaxies, low accretion rate, radio-loud AGN, and high accretion rate AGN (Seyfert galaxies and radio quiet quasars). Using these classifications, Kristen demonstrated that, like their radio-bright counterparts, micro-Jansky radio sources are hosted in galaxies with high stellar luminosities, but only the low accretion rate, radio-loud objects are hosted by galaxies as luminous as those that host the very radio-luminous objects that dominate surveys at bright radio flux limits ~0.1-1 Jy.

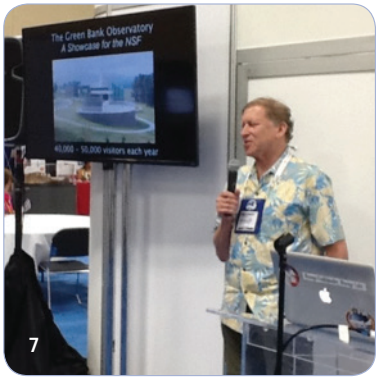

Elizabeth Nance (St. Mary's College of Maryland) at the October REU Symposium at NSF Headquarters.

Invited Summer Student Presentation at NSF

NRAO Research Experiences for Undergraduates (REU) student Elizabeth Nance (St. Mary's College of Maryland) was one of four astronomy students invited to present her research at the REU Symposium in Arlington, Virginia in October 2015. This symposium was organized by the Council on Undergraduate Research and gave Elizabeth the opportunity to display an outstanding poster on her research in the atrium of the National Science Foundation (NSF) headquarters, with students from a variety of STEM fields and a number of NSF Program Officers and REU Coordinators in attendance.

Elizabeth's research on *The Composition of the Upper Atmosphere of Neptune* was carried out in Charlottesville under the guidance of NRAO scientific staff member, Arielle Moullet. NRAO Student Programs Coordinator Alison Peck accompanied Elizabeth to Arlington and participated in a number of workshops for REU program organizers on recruiting, broadening participation, and professional development curricula for summer student programs.

The XXIXth IAU General Assembly



[1] The new NRAO exhibit debuted at the Hawaii Convention Center in Honolulu. [2] Tania Burchell and Brian Kent with local students at an AUI-sponsored event. [3] Hawaii Convention Center, Honolulu. [4] NRAO Director Tony Beasley speaking at the NSF pavilion. [5] NSF Director France Córdova visits with Mark Adams at the NRAO exhibit. [6] Honolulu students participate in a hands-on experiment with Tim Spuck at the AUI exhibit. [7] NRAO Green Bank scientist Jay Lockman speaking at the NSF pavilion. [8] One of many busy coffee breaks in the exhibit hall.

DATA MANAGEMENT AND SOFTWARE

The NRAO Data Management and Software (DMS) department made key contributions to the Observatory's science goals in 2015. The new NRAO archive interface and reprocessing capability was deployed for testing. Pipeline capabilities were enhanced, notably via further development of imaging capabilities, but also including operational improvements such as automatic invocation of the VLA calibration pipeline. The ALMA Systems group supported science observing, while preparing the needed capabilities for later cycles, such as sub-arrays. As ALMA moved into more routine science operations the emphasis continued to shift from adding new features to improving system stability, reliability, and diagnostic information. The Green Bank and New Mexico Systems groups provided support for observing and the planned new observing capabilities, including for the high data rate Versatile GBT Astronomical Spectrometer (VEGAS). In 2015, NRAO made its computing facilities available to the external community through direct cluster access. CASA High Performance Computing and parallelization facilities have been developed and are undergoing testing and verification. Progress in 2015 on key DMS initiatives is detailed in the following sections.

CASA Development

Development of the Common Astronomy Software Applications (CASA) package, the NRAO post-processing software, continued to emphasize support for the VLA and ALMA, unlocking the scientific potential of these world-leading telescopes. In 2015, NRAO continued to add capabilities and support the evolving understanding of the requirements of these forefront telescopes.

The CASA 4.3 release expanded the capabilities of the CASA-based pipeline, and improved the handling of weights throughout the package. CASA 4.4 introduced the Calibration Library in plotMS, cutting disk space requirements by ~1/3, and supporting data reduction and the pipeline for the VLA 2015B semester.

The external CASA Users Committee provided valuable feedback to the CASA team, including emphasis on improved communication and focus on robustness and reliability. The CASA team executed a user survey at the committee's suggestion, directly gathering information on the requirements of the user community. The first edition of a new CASA electronic newsletter (CASA News) was published and distributed internationally, establishing a new flow of information from the CASA team to the community.

The international CASA development team, led by NRAO, continued to increase support for single dish data reduction and high-performance computing capabilities. Integration of CASA parallel capabilities with the standard reduction pipelines was completed, and testing and verification are on-going. The team continued to support and develop new imaging and calibration algorithms through a close connection to the NRAO algorithm research and development group. CASA's connection to the wider radio community continues to grow with collaborations such as the Cube Analysis and Rendering Tool for Astronomy (CARTA) and ALMA Data Mining Toolkit (ADMIT) teams.

The CASA pipeline was used throughout the ALMA Cycle 2 data reduction for calibration of standard modes of observing, while undergoing continued development and commissioning. Over 70% of standard mode projects were delivered based on the pipeline calibration, although in most cases additional manual flagging was required. Pipeline reduction, and the subsequent reference imaging, were conducted at the North American and other ALMA Regional Centers. Interferometric and single dish observations are supported by the ALMA pipeline, although only the interferometric calibrations have been accepted by the ALMA project. Single dish capabilities, primarily the responsibility of the National Astronomical Observatory of Japan, underwent acceptance testing in late 2015.

The VLA continuum Stokes I calibration heuristics in the CASA pipeline underwent validation, and the CASA pipeline became the production VLA calibration pipeline. As a result, ALMA and the VLA are using the CASA pipeline for calibration in production. Further pipeline work focused heavily on imaging throughout 2015, although improvements in the calibration pipeline were made as well.

The scope of CASA automated testing was expanded to include all supported platforms and multiple code branches. Testing for ALMA control and correlator software was migrated to the ALMA Integrated Computing Team (Chile) as agreed, with provisions to keep NRAO code development and unit testing coordinated with the team.

User-facing Proposal & Observing Tools

The Proposal Submission Tool (PST) was updated to support functionality required for the 2015B and 2016A NRAO Calls for Proposals. Similarly, the Proposal Handling Tool was updated to support required functionality for the NRAO Time Allocation Committee meetings for the 2015B and 2016A observing semesters.

The Observation Preparation Tool (OPT) for the VLA was also updated to support new instrumental capabilities during each observing semester. This included support for commissioning, including Resident Shared Risk Observing and, once commissioned, for general observing. Updates for commissioning occur in the semester prior to when they are needed for general observing.

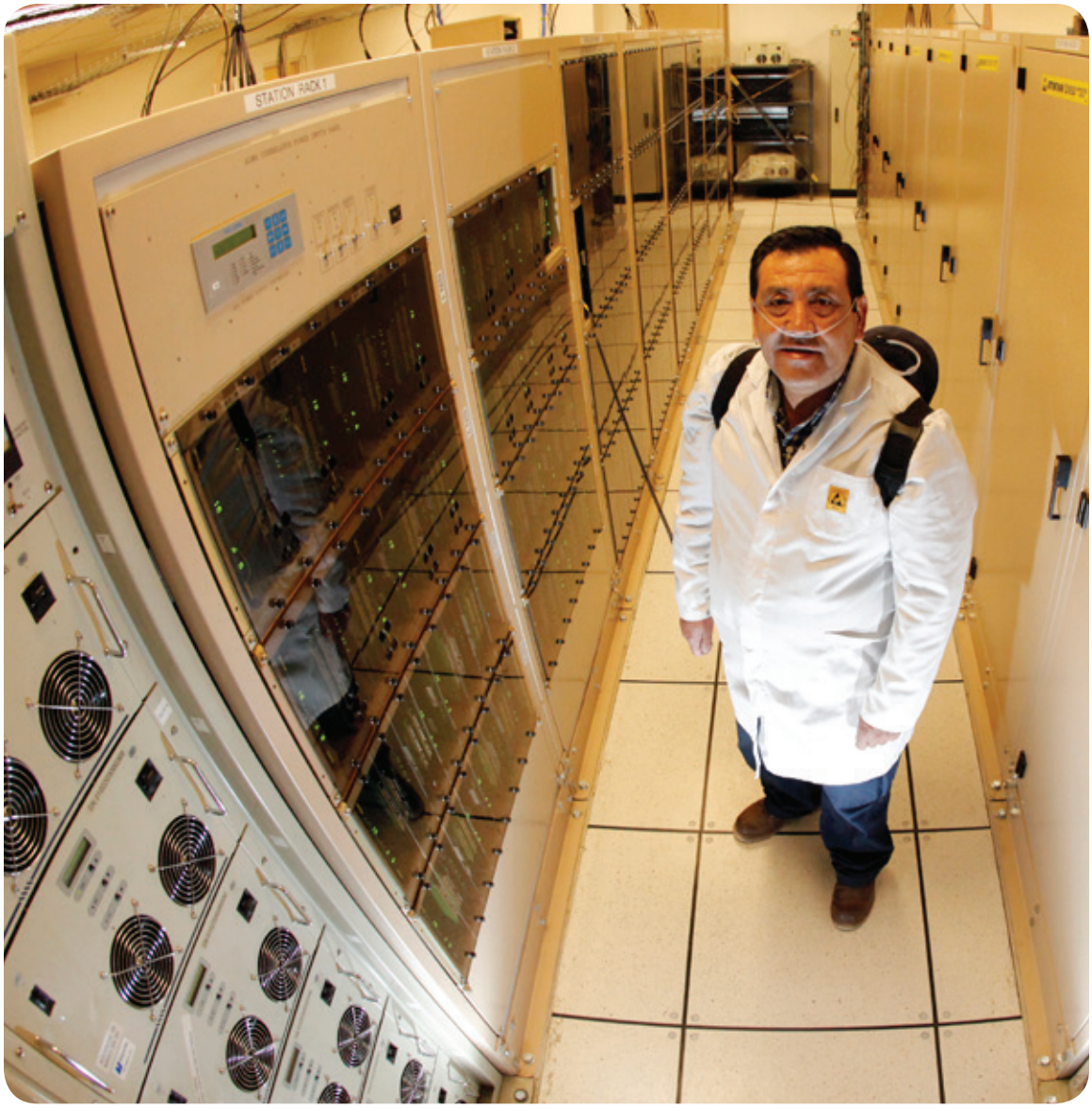
A tools redesign project reviewed the current design of the Observatory's user-facing tools, in particular the Proposal Submission Tool, Proposal Handling Tool, and Observation Preparation Tool. Recent user and time allocation review committee feedback provided usability and performance improvement suggestions for the tools. It is believed that an approach which identifies and combines common functions between the tools may be a productive way to make the toolset more functional and easier to use. Some progress was made in FY2015, but due to resource limitations and a lack of clear science requirements, this milestone was rescheduled for 2016.

ALMA System Software

NRAO is responsible for delivering software to the JAO as part of the Integrated Computing Team, which is staffed by personnel from the three ALMA Executives and the JAO. In North America, some effort is also provided by the National Research Council of Canada for the ALMA Archive Subsystem. The bulk of the NRAO work done by the ALMA System Software group consists of Offsite Maintenance and Repair, though the group is also responsible for the NRAO software contribution to the ALMA Phasing Project.

The NRAO ALMA System Software group contributed to the following ALMA ICT tasks in 2015.

Control / Correlator Software: This software controls and monitors all ALMA equipment other than the ALMA Atacama Compact Array correlator and is entirely an NRAO responsibility. This software interprets the scheduling blocks and converts them to low-level commands that are sent to the hardware at the appropriate time. It collects the data requested by the observer, does some post-processing to reduce data volume, and writes to the archive for use by the data reduction software. It also collects data for performance monitoring of all equipment, and includes many online Graphical User Interfaces.



Working at the 5000 meter elevations of the ALMA Array Operations Site often requires use of supplemental oxygen to ensure employee safety and optimal performance.

Scheduling: The NRAO is responsible for the software that dynamically selects what to observe based on observing conditions and hardware availability. The dynamic scheduling parameters and weights are the responsibility of JAO Division of Science Operations. A more limited mode of this same software allows an observer to queue observations or manually specify each observation. This software allows observers to specify which antennas are to be used for each observation by defining one or more arrays. The scheduling algorithms in this software are also used in an offline mode to aid in observation planning.

The focus in 2015 was on improving operational stability. The delivered items included improved operations support, added baseline correlator sub-array capability, a new QuickLook graphical user interface, new flags in the ALMA Science Data Model flag table, improved control error handling and reporting, and completion of the ALMA Phasing Project. The ALMA Dynamic Scheduling tool was also deployed to production, and is intended to be the primary Cycle 3 scheduling tool.

VLA / VLBA System Software

VLA/VLBA system software functional priorities are defined by New Mexico Operations within resource limits provided by DMS. DMS is responsible for non-functional prioritization, such as software maintenance items and technology choices.

VLA / VLBA Support for Commissioning & Observing: New capabilities were supported in the system software. This included completing the VLA Atmospheric Phase Interferometer and weather station operators' screens, implementing VLA frequency averaging in the correlator backend, and software support for new VLA High Sensitivity Array observing modes.

VLITE / VLA integration: Software development and maintenance support was provided for the integration of VLA Ionospheric and Transient Experiment (VLITE) operation into normal VLA operations. Much or most of the software required was already in place by the end of the VLITE construction project; however, integration into VLA operations required some software modifications and changes to databases used in VLA operations.

VLA frequency averaging: Frequency averaging in the VLA correlator became an operational capability in 2015. This capability enables the reduction in visibility data rates from the correlator for continuum observing.

VLA pointing table: The Science Data Model pointing table can now be written by the VLA Meta-data Capture and Format subsystem, when required. Final requirements for what goes into the pointing table other than azimuth and elevation are being developed. The pointing table will be needed for the VLASS, during solar and planetary observing, and for the implementation of more capable tipping scans.

VLBA Graphical User Interface: A new operator graphical user interface (GUI) for the VLBA was deployed for evaluation. The new GUI is based on updated Java technology, and incorporates improved operator access to site data at each VLBA station and improved browsing and graphing of real-time monitor data.

GBT System Software

GBT system software functional priorities are defined by West Virginia Operations within resource limits provided by DMS. DMS is responsible for non-functional prioritization, e.g., software maintenance items, technology choices, and similar. Notable progress was made in 2015 with the following GBT system software priorities.

Operations Software: The Green Bank Operations Division uses a web application to log and report detailed GBT usage. The application employs obsolete technology, is undocumented, and is unsupported by GBT staff. In 2014, a resource was assigned to begin gathering requirements for re-writing the application. The new system will utilize the same technology used by all GB web applications as well as provide the same features and appearance. This effort continued through 2015 with final delivery expected in 2016.

Pulsar Modes: This project will implement pulsar modes in the VEGAS spectrometer. This effort began in 2015 and will be complete in 2016.

GBT Pipeline: DMS completed pipeline work to support the highest non-pulsar VEGAS data rates necessary for mapping. This used the GBT streaming infrastructure and involved parallelization of the data stream.

The capabilities and use-cases of the GBT Pipeline were expanded in 2015. Working with the GBT staff, a prioritized list of improvements needed for expanding the role of the GBT Pipeline was developed. These improvements included user interface enhancements, additional mapping use cases, additional VEGAS modes.

The environment and resources available at the Pittsburgh Supercomputing Center (PSC) were evaluated for potential use by the GBT Pipeline. DMS successfully installed and processed data with the GBT Mapping Pipeline in the PSC environment, and provided feedback to PSC on configuration considerations and utility of the environment.

Scientific Information Services

The Scientific Information Services (SIS) division enables transparent sharing of highly skilled Information Services resources for both telescope supporting science responsibilities (SIS), as well as general staff IT support duties.

Helpdesk: For expedience during the go-live for the VLA and the multi-ALMA Regional Center implementation of ALMA Observer support, two separate instances of the same Kayako commercial helpdesk software were delivered. In 2015, an integrated observer helpdesk supporting all NRAO instruments and the three ALMA regions – North America, East Asia, Europe – was implemented, ensuring appropriate Knowledgebase views, depending on observer affiliation.

NAASC observer post-processing access: Following the success of the VLA cluster access initiative last year, the NAASC compute cluster was expanded from 40 to 64 nodes to support Principal Investigator data reduction workload for interactive and pipeline tasks.

Network enhancement: A campaign of bandwidth enhancement was initiated in 2015 to increase the Charlottesville and Socorro bandwidth to 10 Gb/s to align with Green Bank, and to provision fiber access to at least three additional VLBA sites, to more than 200 Mb/s, as funds become available.

Externally hosted resource access evaluation: Due to the projected rise in demand for Principal Investigator data processing resources, NRAO continued to evaluate options, such as the Extreme Science and Engineering Discovery Environment (XSEDE).

Multi-core evaluation: To support parallel algorithmic development, SIS purchased a multi-core evaluation system hosting an Nvidia Graphics Processing Unit and Intel Many Integrated Core co-processor architectures. A system was configured to inform future strategic shifts to support this processor rich environment, in an input / output intensive regime that typifies observational radio astronomy data analysis.

Disaster Recovery: As NRAO reliance on massive storage arrays increases, the potential for catastrophic data loss must be managed. In 2015, SIS evaluated options for low cost backup solutions, and will be implementing solutions as funding allows in 2016.

CENTRAL DEVELOPMENT LABORATORY

The NRAO Central Development Lab (CDL) continues to be a world leader in cryogenic microwave circuit technology, supporting the evolution of NRAO's existing facilities and providing the technology and expertise required for the next generation of radio astronomy instruments. This is accomplished through development of multiple enabling technologies: low noise amplifiers, millimeter and sub-millimeter detectors, optics, and electromagnetic components, digital signal processing, and new receiver architectures including cryogenic phased array feeds. The CDL has a long history as a world leader in each of these fields. CDL staff have developed and produced these critical components and subsystems not only for NRAO telescopes, but also for the worldwide astronomical community. CDL research and development projects seek to develop technologies necessary for the long-range objectives of the Observatory and advance the state-of-the-art in mission-related technologies.

Repair, Maintenance, Production, Support

The CDL Amplifier Group continued to produce and repair low noise amplifiers for NRAO telescopes: 79 amplifiers were delivered mostly for the VLA, VLBA and GBT. Other observatories were also supported by this effort, including the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), Arecibo Observatory, and the Jet Propulsion Lab (JPL).

A preliminary production run of 16 ALMA Band 1 chip-and-wire amplifiers revealed excellent repeatability of performance and very good agreement with model predictions. Nine amplifiers based on CRYO-3 high-electron-mobility transistors (HEMTs) have been delivered to the ASIAA team for the development of prototype Band 1 cartridges. Given the successful integration of these amplifiers by ASIAA into two Band 1 prototype cartridges, a contract to manufacture 166 amplifiers for full production of Band 1 cartridges is pending.

An X-band (8-12 GHz) corrugated feed horn was designed for a future wide-band GBT receiver. The feed is a linear-taper horn with an aperture of 12.5" and length of 22". It uses ring-loaded corrugations in the mode converter section to provide wide-band performance. The illumination taper at the edge of the subreflector varies between -12.7 and -14.2 dB. Cross polarization is better than -25 dB, and return loss is greater than 29.4 dB. The feed horn will be machined and tested in the future.

An improved second version of the X-band orthomode transducer (OMT) has been designed. This design weighs 2.5 lbs compared to the 3.7 lbs of the first version; return loss is better than 22 dB over the 7.8 to 12.2 GHz range. A power splitter that is between the OMT and phase shifter and a circular-to-square transition has been designed.

A corrugated waveguide phase shifter with dimensions 0.2255" x 0.2147" has been designed. The device yields 90±5° differential phase for the two orthogonal polarizations in the 35-52 GHz band. Waveguide transitions to the feed horn and OMT have also been designed.

ALMA Band 2 optics development has been completed. A linear taper corrugated feed horn and three high-density polyethylene lenses were designed, built and evaluated. Each lens had a different focal length and distance from the feed horn. Each lens was mounted at the 300K plate of the ALMA cryostat and also served as vacuum window. Measurements were carried out on the ALMA cryostat and efficiencies were demonstrated to be greater than the specified 80%.

Detailed measurements of cross polarization were also carried out on the Band 2 optics at the Green Bank Anechoic chamber range with the 15K and 110K infrared filters in place. The cross polarization by each of the optical components has been quantified. The polarization efficiency of the beams in the two diagonal planes is greater than 99.1% over the 67-90 GHz band.

Research and Development

A new version of ALMA chip-and–wire Band 2 amplifiers with optimal noise and gain performance has been developed. This version utilizes individual transistors from the JPL Cryo-3 wafer but with a different gate width.

The CDL collaboration with Caltech / JPL produced cryogenic measurements on Monolithic Microwave Integrated Circuit (MMIC) low-noise amplifier modules using the Northrop Grumman 35nm InP process. These modules were optimized to meet the requirements of ALMA Band 2. Results were generally positive, with competitive noise performance and bandwidth. These interim test units were assembled with slightly too much gain, which caused some compression with room-temperature inputs. A new MMIC wafer run with many new designs is in fabrication. This run is expected to produce chips for the production of ALMA Band 2 amplifiers.

The goal of achieving less than 30 K across whole 67-90 GHz band remains elusive for all technologies. The MMIC run in progress may show improved performance and the issue of broad-band noise performance and gain flatness in a chip-and-wire amplifier is under continued investigation.

Research on noise properties of microwave transistors and amplifiers in a range of technologies – including Complementary Metal Oxide Semiconductor (CMOS) and SiGe heterojunction bipolar transistors (HBT) due to their commercial impact – resulted in several presentations while a short course on these concepts was delivered at the 2015 Wireless and Microwave Conference.

During 2015, the Digital Signal Processing Group divided the bulk of its effort between the ALMA Phasing Project (APP) and planning for future upgrades to the ALMA baseline correlator. With respect to future correlator upgrades, there were two major thrusts. The first, and the largest was the formulation of a proposal to upgrade the existing ALMA correlator by significantly increasing its spectral resolution and bandwidth. As part of this work, detailed design of a new correlator IC and high-level designs of all the required modules were completed, and costs calculated. This proposal was submitted to the NAASC. The Digital Signal Processing Group also became a co-investigator for a second correlator proposal to the NAASC.

Integrated Receiver Development: The six-channel Integrated Receiver Development backend was implemented using a Kintex-7 field-programmable gate array (FPGA) processor and is now processing live sideband-separated spectra in real-time. With it, the unformatted serial link is becoming a mature and reliable technology, as CDL has successfully demonstrated automatic de-interleaving of data streams on shared optical fibers keyed to gain mismatch, as well as the synchronization of parallel data streams on separate fibers using phase correlation slope.

CDL is taking steps to further improve the capability of this system by moving toward higher bit rates and by developing a serial-output ADC that will have profound implications for improved integration, power efficiency, radio frequency interference immunity, and bandwidth flexibility.

The integrated front-end architecture has also been improved via advanced topologies and miniaturized packaging of the reflectionless filters which are part of this technology. This has resulted in near iPod-size analog-digital-photonic front-ends, with further improvement expected upon completion of the Serial ADC.

Phased-Array Feed: The scalability of Integrated Receiver technology to large-format focal plane arrays has been amply demonstrated by the 40-channel integrated analog-digital-photonic converter. This converter was completed, tested, calibrated, and delivered to the Phased-Array Feed (PAF) program in 2015. The Integrated Receiver Development team worked closely

with the Phased-Array Feed team and the team in Green Bank, who have successfully incorporated the unformatted serial-link concept into their back-end based on designs from the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER). In the latter application, the re-timing buffers are internal to the FPGA in contrast to the Integrated Receiver development environment, where deserialization is done by an external interface card.

New patent applications have been filed this year as a direct outcome of Integrated Receiver work, both in the U.S. and abroad. These include advanced high-frequency versions of the reflectionless filters using transmission lines, as well as a novel decade-bandwidth horn (single-polarization) that may have commercial applications in submillimeter-wave to THz quasi-optical sources and detectors.

Nineteen element dual-polarization Phased-Array Feed with cryogenic SiGe HBT LNAs. Measured Tsys of 35K on the Green Bank 20m telescope.

The PAF research and development has resulted in the construction and testing of a complete working system, including a cryogenic L-band PAF receiver, downconverter and fiber optic link, data acquisition system, telescope software, and software correlation and beamforming. The system is being upgraded to improve system noise and efficiency, as well as dynamic range, linearity, and bandwidth. The bandwidth upgrade includes a collaborative effort with the Beamformer project, an NSF Advanced Technologies and Instrumentation program between NRAO-West Virginia University and Brigham Young University to build a real-time digital backend for L-band phased array science.

Hydrogen Epoch of Reionization Array (HERA): A scientific road map investigation, HERA is exploring the large-scale structure in the baryonic universe via the 21 cm line of hydrogen. The first prototype HERA 14 m parabolic dish antenna was constructed in Green Bank. A feed, based on the PAPER sleeved-dipole design, was developed and evaluated. The beam pattern at 137.5 MHz was measured using a downlink signal beam-mapping system developed at the NRAO in collaboration with Massachusetts Institute of Technology. The reflection coefficient at the feed terminals was measured over the 100-200 MHz band using a Vector Network Analyzer. Modeling was performed and agreed well with the measurements. Concerns about the impulse response of the feed/antenna system and its impact on Epoch of Reionization science measurements are currently being studied.

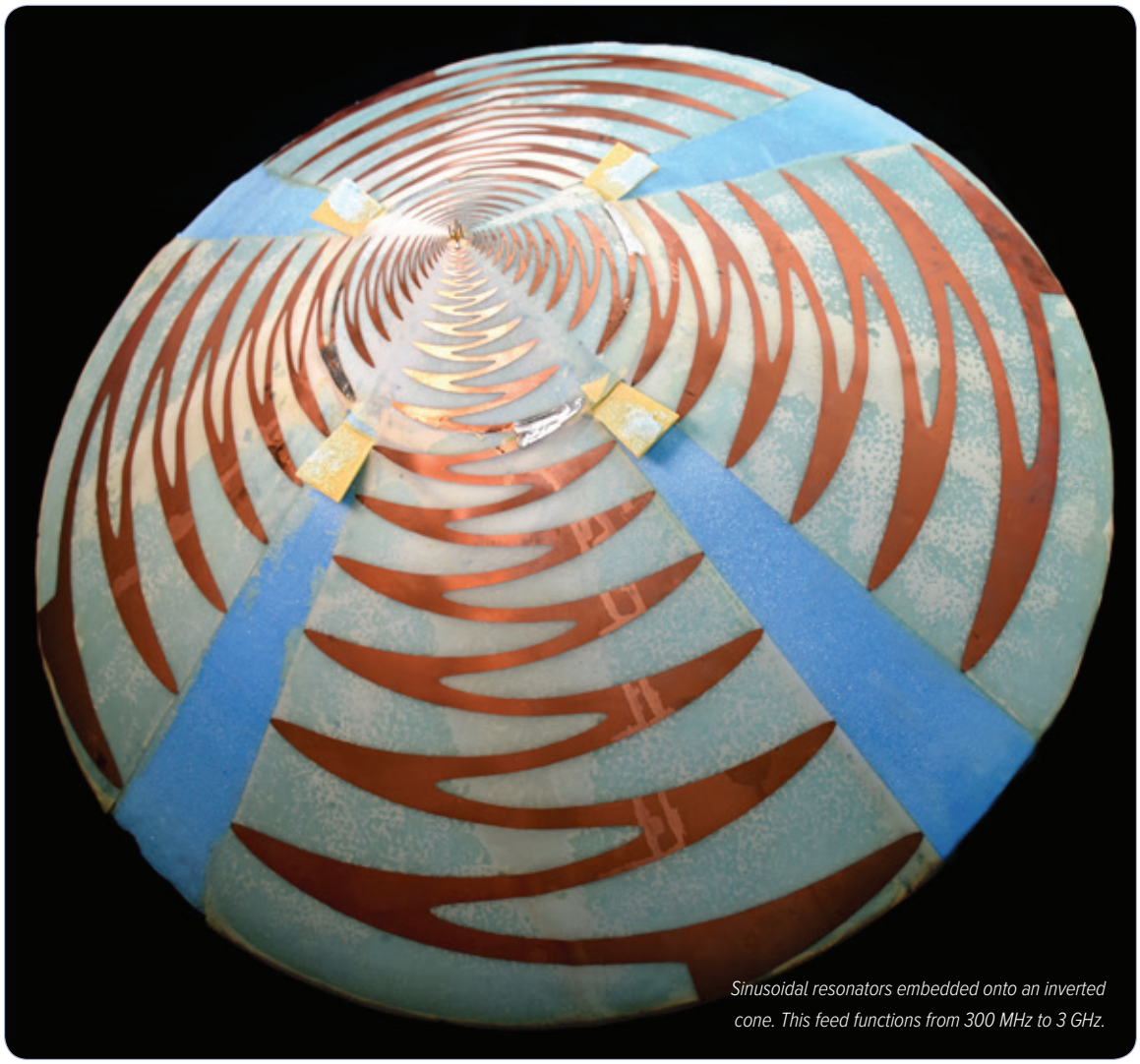
Dark Ages Radio Explorer (DARE): DARE is a proposed lunar orbiter mission intended to detect the highly-redshifted 21 cm hyperfine transition of neutral hydrogen to track the formation of the first stars, black holes, and galaxies by studying their impact on the intergalactic medium during the end of the Dark Ages and the subsequent Cosmic Dawn (z ~11-35). Using the Moon as its RFI shield, DARE will uniquely complement the efforts of the Wilkinson Microwave Anisotropy Probe.

The DARE Small Explorer proposal, led by Principal Investigator Jack Burns (University of Colorado) was declined by NASA. However, work continues toward preparations for a full Explorer-class mission, the proposal for which is due in early 2017. A radiometer instrument package capable of part-per-million accuracy in measurement of the power spectrum over the 40-120 MHz band is being developed. Work is being concentrated in three areas: (1) development of a high precision gain calibration system; (2) use of dynamic polarimetry for improved foreground isolation and measurement; and (3) an improved antenna design. The development effort combines modeling and simulations together with prototype evaluation.

An Innovative Sinuous Antenna

Research conducted at the NRAO Central Development Laboratory in 2015 has led to an innovation in wide-band radio antennas. This breakthrough technology combines traditional and new techniques to create an antenna or an antenna feed with exceptional simultaneous frequency coverage, such as an antenna that can cover a 10:1 frequency range. The patented invention is suitable for moderately low-noise systems, where wide bandwidth requirements are a priority.

A working prototype antenna covers the 300 MHz to 3 GHz range, but the invention can be implemented in any range of radio frequencies, such as 2-20 GHz, which may have a significant impact on commercial satellite communications and related uses. The patent describes the design and placement of specifically shaped sinuous resonators onto the surface of an inverted cone sitting atop a traditional ground plane. This new invention avoids the need for absorbers and other signal directing devices, which typically add unwanted noise.



Sinusoidal resonators embedded onto an inverted cone. This feed functions from 300 MHz to 3 GHz.

Resonators that are shaped and placed according to the patented design are always at ¼ wavelength above the ground plane for any given frequency to provide proper tuning and a nearly frequency independent phase center. The radio signal return loss becomes favorable over a wide frequency range with minimal ripple effect. The wide instantaneous bandwidth can accommodate frequency agile applications such as a spread spectrum radio, simultaneous multiple narrow channels, or ultra-wideband pulse communications. Using this technique allows one antenna to replace many antennas in practical use, as well as replacing multiple receivers/transmitters with one software-defined radio that can accommodate a wide range of frequencies, e.g., a 10:1 frequency range.

The applications of this technology include radio astronomy, biomedical imaging, spectrum surveillance, and satellite communications, among others. U.S. Patent #9,054,516 was issued on 9 June 2015 to NRAO researchers Richard Bradley and Rohit Gawande.

Commercial Development of NRAO Technology

NRAO has entered into a licensing agreement with Mini-Circuits, headquartered in Brooklyn, New York, to permit the use of NRAO-developed technology in a new suite of commercial electronics products. Mini-Circuits is a global leader in the design, manufacture, and distribution of radio frequency (RF), intermediate frequency (IF), and microwave components, subassemblies and test solutions for commercial, industrial, medical, space and military applications.

This new agreement, which covers a part of the NRAO portfolio of radio frequency filters known as cascadable absorptive filters, will foster the development of new radio-frequency-based technologies in a wide range of commercial applications. The underlying technologies for this novel class of filters were developed at the CDL.

Filters are a fundamental building block of nearly every RF system in existence today, and are used to eliminate unwanted signals in receiver and transmitter architectures. Traditional filters work by reflecting undesired signals back to the source, which can potentially cause systemic problems such as intermodulation products and gain ripples that adversely affect desired signals in the pass band. This new, patented filter topology, developed by NRAO scientist Matt Morgan, avoids these problems by absorbing unwanted signals in the stop band.

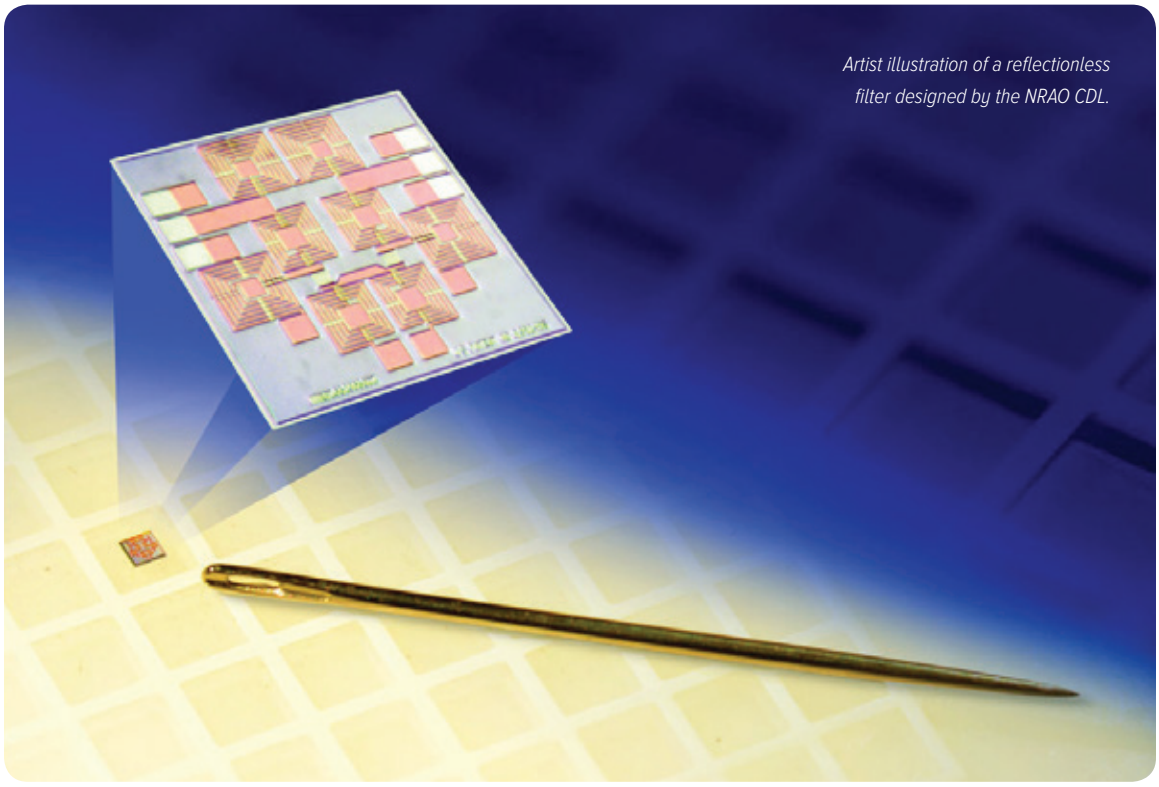
The key to the performance of these new filters is their unique topology, and the methods discovered at the CDL for extending it to create even more sophisticated designs. The result is a filter that is more compact and better suited to practical implementation than other methods for absorbing stop-band energy. For example, in contrast to terminated diplexers, these filters are symmetric and absorptive from both sides, and maintain good impedance match even in their transition bands. They also use fewer and more moderate element values than conventional filters at the same frequency, facilitating their realization as mass-producible and inexpensive printed circuits, yet still performing well even up to 40 GHz using on-chip lumped elements.

The filters in their present form are also compact. The individual GaAs die are 1 mm square, and are available for chip and wire integration, or in 3 mm Quad-Flat No-lead packages for surface mount applications. Each chip provides ~15 dB of absorption in the stop-band, and may be cascaded for additional rejection as needed. Because the filter chips provide ~20 dB return loss at all frequencies within the operating range, including pass-band, stop-band, and transition-band, they may be dispersed anywhere they are needed in the signal path of a radio frequency system without risk of causing problems via out-of-band

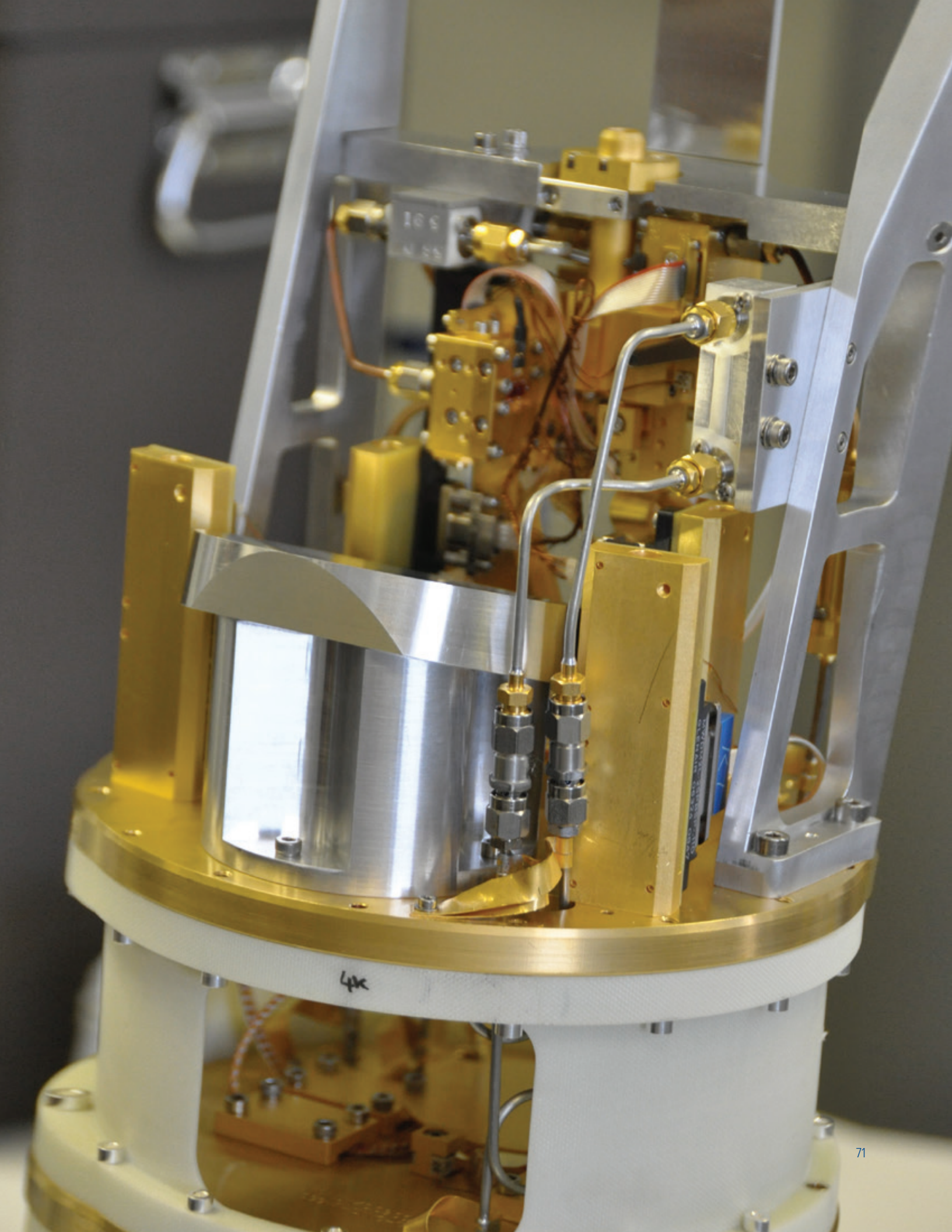
interactions with other components. Finally, as monolithically fabricated passive integrated circuits, they exhibit very uniform, temperature-stable performance, easing their use in applications where stable amplitude and phase or well-matched pairs are needed.

This reflectionless filter topology represents a breakthrough in a long-standing problem of embedding filters within RF transmit and receiver chains. These filters eliminate the need for additional attenuators and isolation amplifiers around sensitive components, enabling significant improvement in overall system dynamic range.

The licensing agreement was facilitated by the NRAO Technology Transfer Office, which was established to fulfill the U.S. Congressional directive to support commercialization of federally funded research and technology development.



Artist illustration of a reflectionless filter designed by the NRAO CDL.


4K

EDUCATION & PUBLIC OUTREACH

The NRAO Education and Public Outreach (EPO) Department provides major components of the public's return-on-investment by marshaling Observatory resources in support of Science, Technology, Engineering, and Math (STEM) education programs, and informing the interested public about the Observatory, its facilities, and the latest scientific and technical achievements of its astronomy community users and the NRAO staff.

Formal and Informal Education

The Green Bank Science Center continued to be a flagship education and Science, Technology, Engineering, and Math (STEM) destination for the general public and K-16 learners. Successful STEM education grants received no-cost extensions, and a new grant with West Virginia University to expand and broaden participation in the Pulsar Search Collaboratory was funded. The Skynet Junior Scholars program and West Virginia Space Public Outreach Team expanded the NRAO Education and Public Outreach programs reach, welcoming thousands of new learners, and STEM education staff published their results in the international astronomy education research journal, *Communicating Astronomy with the Public*. Looking ahead to a new suite of tours and programs, EPO increased staffing in 2015 from five permanent year-round staff to six, supplemented by three seasonal tour guides in summer. All the EPO metrics quoted here apply to Fiscal Year 2015.

- GB General Visitors Attendance: 46,225 visitors
- Group Visitors Onsite: 51 overnight groups, 1,840 students, ~1,000 other group visitors
- Special Events: 8 events onsite, 1,635 visitors
- STEM Programs: Physicists Inspiring the Next Generation (PING), 16 students; West Virginia Space Public Outreach Team, 30 new ambassadors and 3,400 students and teachers reached; Skynet Junior Scholars, 105 teachers/leaders and 9,100 radio observations made with 20m telescope; Pulsar Search Collaboratory, 1,700 students reached, 106 teachers trained, seven pulsars and one transient object discovered by PSC students
- Summer Training: Chautauqua Teacher Training Workshop, 45 participants; Skynet Junior Scholars Youth Leader Workshop, 16 participants.

Three student scientists from the Pocahontas Science Fair hosted by NRAO Green Bank in West Virginia.

EDUCATION & PUBLIC OUTREACH

The VLA Visitor Center is evolving to enhance and expand the STEAM learning experiences for onsite visitors. EPO installed updates to the interpretive programs inside the exhibit hall, including new looping video, interactive kiosks, and new exhibit panels. Attendance increased 40% over the previous year. EPO benefited from increased engagement by New Mexico-based scientific staff, and will be integrating scientific staff involvement more into the tour schedule in 2016. The new VLA Visitor Center project was re-envisioned mid-year to align more closely with visitor feedback and stakeholder vision.

- VLA General Visitors Total Attendance: 21,304 visitors
- Group Visitors Onsite: 114 groups, 2,850 visitors.
- Outreach to Regional Schools: 42 groups, 3,150 visitors.
- Special Events: April 2015 Open House, 828 visitors; April Enchanted Skies Star Party, 86 visitors.
- Summer Training: National Astronomy Consortium (NAC) and NSF Research Experiences for Undergraduates (REU) student tour guide training, 14 participants; Chautauqua Workshop, 10 participants.

NRAO technician Eric Chavez gives presentation to students at Parkview Elememtary School, Socorro, NM

EPO's Chilean-based educator trained thousands of teachers using the Galileo Teacher Training Program while also delivering several dozen news articles to regional papers in 2015 and supporting ALMA events onsite and within the community. In partnership with AUI, EPO helped plan and support the first Chilean STEM Educators Summit and the pilot year of the Astronomy in Chile Educator Ambassadors Program.

The Charlottesville-based EPO science visualization team produced dozens of multimedia-rich, scientist-hosted videos about radio astronomy discoveries in the Solar System and in the Local Group of galaxies surrounding our Milky Way for publication online this year. A recording studio was installed where role model interviews are conducted from across the disciplines at the

Observatory, showcasing the varied careers and career paths our staff have pursued to arrive in their jobs at NRAO. A Spanish language version of the ALMA Explorer was launched. EPO packaged the VLA Explorer and the Milky Way Explorer into kiosks that are now interactive exhibits at the VLA Visitor Center. A new exhibit panel set and looping VLA introductory video for the exhibit hall were produced. EPO led the delivery of a beta test version of a mobile app showcasing topics in NRAO-focused radio astronomy.

- **Digital Learning Products:** 64 Explorer videos; 18 data visualizations; 14 press release videos and 16 press release illustrations; 16 NRAO trading cards; 12 VLA trading cards; 6 animations; 10 exhibit panels, 2 videos, and 1 new VLA walking tour sign.

- **STEM Programs:** NAC student and mentor professional development, 24 participants; Astronomy in Chile Educator Ambassadors Program professional development, 12 participants.

- **Outreach Events Supported Offsite:** Jansky Lecture at the Paramount Theater, Virginia Regional Science Fair, Ruckersville Science Expo, Star Party on the National Mall, Piedmont Virginia Community College STEM Day, IAU General Assembly EPO Events.

News and Public Information

EPO delivered 61 news articles in Fiscal Year 2015, showcasing a balanced portfolio of discoveries and innovations from across the Observatory. Voiced-over videos were included to selected news packages as well as commissioned animations, increasing readership. NRAO news articles were accessed via our online publishing sites nearly 240,000 times, with coverage in other media outlets several orders of magnitude higher. International television and online video exposure was at record levels.

- Press Releases: VLA 11; ALMA 20; GBT 9; VLBA 1; NRAO 5.
- Tip Sheet Items: ALMA 1; NRAO/CDL 1.
- Announcements: ALMA 9; VLA 1; GBT 1; NRAO/CDL 2.

The NRAO public website received very high traffic on several occasions, overwhelming the server. EPO worked with CIS to install a new caching system that allows thousands of hits to popular press releases without damage to the bandwidth. Enhancement of the NRAO public website has struggled with a lack of experienced Joomla content management experts within the Observatory. A new web developer specializing in WordPress was recruited who will begin work in the coming year to rebuild the content in the more widely used content management system.

Social media numbers are continuing to increase, and the quarterly reach is consistently in the hundreds of thousands of unique views. Fiscal Year 2015 ended with over 65,000 total fans following the NRAO Facebook and Twitter accounts.

MANAGEMENT & ORGANIZATION

BEASLEY, ANTHONY
Director

GLENDENNING, BRIAN
Assistant Director
Data Management & Software

JEWELL, PHILIP
NA – ALMA Director
NRAO Deputy Director

DICKMAN, ROBERT
Interim Assistant Director
CDL & NIO

ADAMS, MARK
Head of Communications

BURCHELL, TANIA
Assistant Director Education
and Public Outreach

WINGATE, LORY
Assistant Director
Program Management

BASTIAN, TIMOTHY
Assistant Director Scientific
Support & Research

HARDY, EDUARDO J
Assistant Director
OCA

O'NEIL, KAREN
Assistant Director
Green Bank Operations

FRAIL, DALE
Assistant Director
Socorro Operations

GEIGER, STEVEN P
Associate Director
Business Administration

VON SCHILL, Lyndele
Program Manager
Office of Diversity & Inclusion

FRANKS, SHIRLEY
Manager, Compensation & HRIS

GILES, FAYE
Manager Human Resources

MARKS, SHEILA M
Executive Administrator

THISDELL, NICOLE
Executive Administrator

Senior Management Organization

The NRAO organization consists of departments, which are made up of divisions, which consist of groups. This organization is designed to emphasize Observatory-wide management and coordination in key areas, including Program Management, Data Management and Software, and Science Support.

Phil Jewell continued as Assistant Director for North America (NA) ALMA. Jewell oversees the NA ALMA Science Center and the ALMA Development program, coordinates the ALMA maintenance program, and is the face of ALMA to the North American scientific community. Jewell also continued in a part-time role as Deputy Director.

The New Mexico Operations Department, based in Socorro was led by Assistant Director **Dale Frail** until September 2015, when **Mark McKinnon** assumed the role on an interim basis. New Mexico Operations includes all NRAO staff engaged in the operation, maintenance, calibration, performance, and further development of the scientific capabilities of the Jansky VLA and the VLBA.

The West Virginia Operations Department, based in Green Bank and led by Assistant Director **Karen O'Neil**, includes all NRAO staff engaged in the operation, maintenance, calibration, performance, and further development of the scientific capabilities of the GBT. West Virginia operations are also a major resource for education and public outreach, including the Green Bank Science Center. The Observatory's laboratories, utilities, and support facilities also make it an attractive location for independent research experiments.

Assistant Director **Tim Bastian** leads the Science Support & Research (SSR) Department. SSR is responsible for the Observatory's scientific interface to the NRAO user community. This Observatory-wide department coordinates, aligns, and manages the collective efforts of scientific staff in Charlottesville, Socorro, and Green Bank.

The Data Management and Software (DMS) Department led by Assistant Director **Brian Glendenning** manages data archiving at NRAO, including access, distribution, provisioning, and operation. DMS manages the data reduction pipeline infrastructure implementation and technical operation; high-performance computing platform definition, acquisition, and operation; and network provisioning to the external community and between sites. DMS also has primary responsibility for all user-facing and telescope software.

Located in Charlottesville, the CDL supports the evolution of NRAO's existing facilities and provides the technology and expertise needed to the build the next generation of radio astronomy instruments. The CDL team, led on an interim basis by **Robert Dickman**, accomplishes this through development of the enabling technologies: low-noise amplifiers, millimeter and submillimeter detectors, optics and electromagnetic components, including feeds and phased arrays.

Tania Burchell assumed a senior management leadership role as interim Assistant Director for Education & Public Outreach (EPO) basis in March 2015, when John Stoke departed NRAO to pursue other opportunities. The NRAO EPO program provides major components of the public's return-on-investment, marshaling NRAO resources in support of Science, Technology, Engineering, Art, and Math (STEAM) education. EPO also informs the science-interested public about the Observatory, its facilities, and the latest technical and scientific achievements of its users and staff.

MANAGEMENT & ADMINISTRATION

Based in Charlottesville and led by Associate Director **Steven Geiger**, the Administration Services Department provides administrative and human resources management and non-programmatic services to NRAO including: business services; contracts and procurement; environmental safety and security; management and information systems; and technology transfer.

Faye Giles and **Shirley Franks** jointly lead the Human Resources (HR) Department that supports the needs of the Observatory's domestic and international staff. Ms. Giles is the HR Manager and Diversity Officer; Ms. Franks is the Manager for Compensation & HR Information Systems (HRIS). They provide professional and administrative expertise in HR areas including employment/recruitment/hiring, employee relations, diversity, succession planning, training, regulatory compliance, compensation, HR information systems, the AUI benefits interface for NRAO staff, and the HR interface to the Observatory's substantial international and local staff in Chile that support ALMA.

The NRAO/AUI Office of Chilean Affairs (OCA) supports the interests of the Observatory and its parent organization, AUI, in Chile, particularly the North American participation in the ALMA project. Led by Assistant Director **Eduardo Hardy**, OCA provides ALMA with legal, payroll, and travel support, and provides the legal and institutional support for numerous contracts and procurements for ALMA Construction and Operations in Chile. in 2013, the Office of Chilean Affairs was divided into NRAO-Chile and AUI-Chile components, with NRAO-Chile activities, led by Assistant Director Eduardo Hardy.

The Program Management (PM) Department led by Assistant Director **Lory Wingate** provides program and project management support and systems engineering services to NRAO project leaders and PIs. The key PM Department goals are to provide visibility, transparency, and consistency in reporting within NRAO and externally to NSF and outside partners or customers, identify and provide resources for program management and systems engineering needs across all NRAO projects, review new projects for alignment in supporting the Observatory's long-range strategic goals, and compile deliverables.

The Office of Diversity & Inclusion (ODI) is led by Program Manager **Lyndele von Schill**, who assumed this key role in October 2015. The ODI is attached to the Director's Office. The Communications Office (COM) led by **Mark Adams** is also attached to the Director's Office and is responsible for communicating NRAO science, accomplishments, priorities, and plans to the science community, in collaboration with NRAO scientific staff. COM personnel also collaborate with staff across the Observatory to improve internal communication, and assist the Director's Office in communicating NRAO accomplishments to external stakeholders such as the NSF and the U.S. Congress. The NRAO Chief Scientist, **Chris Carilli**, also reports to the Director's Office.

NRAO Diversity Initiatives

NRAO is committed to building and maintaining a pipeline for a diverse next generation of scientists and engineers. In the summer of 2015, the Observatory once again offered mentored internships and research opportunities to a diverse group of outstanding students from around the country. These student programs represent our recognition of the importance of diversity and the next generation to astronomy. In 2015, NRAO provided 41 internships and research opportunities for students.

The 2015 National Astronomy Consortium Workshop at Howard University.

The *National Astronomy Consortium* (NAC) is a key component of NRAO's commitment to attracting bright, talented undergraduate students to STEM fields that the NAC recognizes the importance of including underrepresented and underserved students in the field's next generation pipeline. NRAO and its partner institutions sponsored 19 NAC interns this summer for nine week internships at the Observatory's Socorro and Charlottesville sites, the Space Telescope Science Institute, NASA – Goddard Space Flight Center, and the University of Michigan. The culmination of these summer research experiences was a weekend workshop at Howard University, 29-30 August 2015, when these undergraduate students gave presentations describing their work.

The NAC is led by NRAO in partnership with the National Society of Black Physicists (NSBP), and includes a large network of affiliated institutions.

Physicists Inspiring the Next Generation (PING) is another diversity initiative led by NRAO in partnership with the Observatory's parent organization, Associated Universities, Inc., and the NSBP. The 2015 PING program offered opportunities for undergraduate students to serve as mentors during a two-week physics and astronomy research camp for middle school students at our NRAO – Green Bank research facilities.

Physicists Inspiring the Next Generation visits NRAO Green Bank.

Director – NRAO Office of Diversity & Inclusion

The Observatory was pleased to announce that Lyndele von Schill was selected as the Director for the NRAO Office of Diversity & Inclusion. In this role, she plays a key role within the Director's Office in achieving the mission of increasing and advocating for staff diversity and inclusion across the Observatory and provides leadership and oversight for NRAO's local, national and international broadening participation and diversity initiatives. Oversight and coordination of the National Astronomy Consortium and the NRAO National / International Exchange programs is an Observatory priority.

With the assistance of the NRAO Diversity Council, von Schill develops and implements creative programs and enhances existing programs to improve the recruitment, retention, and success of under-represented and under-served populations and staff. The overarching goal is to foster a work environment that is inclusive of all individuals. Von Schill works closely with all levels of staff and serves as Chair of the Diversity Council. This role closely partners with the NRAO Human Resources, Education & Public Outreach teams, and all NRAO Department Heads, to set NRAO's strategic diversity initiatives.

Von Schill obtained a B.S. in Diversity & Communication in Organizations and is pursuing a Master of Education, Learning and Technology degree. She has been actively involved in several diversity organizations on a local and state level, has a strong background in program development and management, and assumed her new role on 21 October 2015.

Communications

The NRAO Communications Office (COM) organized the NRAO presence at the winter American Astronomical Society (AAS) meeting – 4-8 January 2015 in Seattle – including a day-long next generation VLA Workshop, an NRAO Town Hall, and the NRAO and AUI participation in the meeting's multi-day exhibition. COM assisted with an invited ALMA plenary session and a two-hour Splinter Session – *New Capabilities at the NRAO* – designed to assist members of the community, especially new users, in proposing for ALMA, GBT, VLA, and/or VLBA. NRAO also actively participated in the undergraduate orientation session, and the local public outreach events organized by the AAS and sponsored by AUI.

COM personnel organized the NRAO presence at the XXIXth International Astronomical Union (IAU) General Assembly in Honolulu, Hawaii, 3-14 August 2015, which featured a re-designed NRAO exhibit. COM organized participation by NRAO scientists from Headquarters, the NAASC, the VLA, and the GBT to present talks at the NSF exhibit, including a talk by NRAO Director Tony Beasley on *Science and Discovery at the NRAO*. The NRAO and AUI staff also actively participated in four major local public outreach events organized by the AAS and sponsored by AUI, hosting and working with 200+ young people at the NRAO and AUI exhibits.

A well-received, three-hour science symposium – *Building Galaxies: Some Assembly Required* – was prepared and presented to the broader science community at the 2015 Annual Meeting of the American Association for the Advancement of Science (AAAS) –12-16 February 2015, San Jose, CA – with six speakers from NRAO and across the astronomy community. This symposium brought together leading scientists to present and discuss the newest results in the field of galaxy evolution, work being enabled by observations with orders of magnitude better sensitivity, broader wavelength coverage, and significantly increased imaging and spectral resolution compared to the best that was available just a few years ago.

COM continued to edit and publish the monthly NRAO electronic newsletter, eNews, each issue of which was distributed to 9,000+ scientists around the world. COM published a 2014 NRAO Annual Report, and managed the high-level content at the NRAO science website and the NRAO Intranet. The 2015 NRAO Research Facilities brochure was published immediately prior to the winter AAS meeting.

COM and CIS collaborated on the NRAO exhibit at the International Conference for High Performance Computing, Networking, Storage, and Analysis conference – 15-20 November 2015 in Austin, Texas – an annual gathering of 10,000+ scientists, engineers, software developers, CIOs, and IT administrators from universities, industry, and government agencies.

COM worked with Director's Office and staff across the Observatory to prepare NRAO reports, briefings, and support materials for NSF and for the 2015 Users Committee (UC), which met in Green Bank 21-22 May 2015. The ALMA North American Science Advisory Committee (ANASAC) met on 20 May for the first time as a standing sub-committee of the Users Committee.

COM also collaborated with Director's Office and the Observatory's management team on a wide variety of internal communications for the Observatory.

[Above] *Two of the three panels of the new NRAO exhibit that debuted at the IAU General Assembly in August 2015.* **[Right]** *The exhibit hall was well-attended throughout the IAU General Assembly, and the new NRAO exhibit attracted numerous scientists.*

Spectrum Management

The NRAO Spectrum Management Office was responsive to and involved in domestic and international spectrum management issues relevant to radio astronomy and the NRAO science mission in 2015.

TV band repacking: The Federal Communications Commission (FCC) revised its regulations regarding operation of cellular telephones and unlicensed devices in and around the protected radio astronomy band in TV channel 37 at 608 – 614 MHz. While preserving the band for astronomy use, requirements on out-of-band emissions for devices operating in adjacent and nearby bands were relaxed. Whether the 608 – 614 MHz band continues to be useful for astronomical observation is contingent on how the TV broadcast bands are re-packed after more broadcast spectrum is auctioned.

Iridium: The Iridium mobile-satellite (satellite phone) system has caused global interference into the 1610.6 – 1613.8 MHz protected radio astronomy band used for OH spectral line observations since its inception in the late 1990s and the level of interference is now so high that the band cannot be used for sensitive detection experiments. Iridium's next generation satellites will operate even closer to the edge of the radio astronomy band and could generate even stronger interference unless subject to regulatory measures by the FCC. NRAO filed comments with the FCC insisting: (1) that NRAO be relieved of an onerous coordination requirement emplaced in the 1990s; and (2) that the FCC compel Iridium to meet its international obligations not to interfere. Iridium has resisted coming to the negotiating table in the U.S. until its new satellites are in orbit, but Germany recently revoked Iridium's operating license and sent an official complaint of interference to the FCC and the Department of State, so there is pressure on the company and the FCC to comply.

Car radar: The FCC recently proposed to allow these radars to proliferate using very high peak output powers (300W equivalent isotropic radiated power). At that level, a single radar can produce harmful interference at distances of 150 km. NRAO has been pleading the case for FCC regulatory protection of radio astronomy sites from car radars since 2009, to little avail.

International spectrum management: Working at the International Telecommunication Union – Radiocommunication Sector (ITU-R) in Geneva, and as the vice-Chair and newly-elected Chair of the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF), the NRAO spectrum manager contributed documents dealing with:

1. Agenda Item (AI) 1.18, a new allocation to vehicular radar to fill in the remaining portion of the 76 – 81 GHz band not allocated to radar;

2. AI 1.12, whereby remote sensing satellite operators agree not to illuminate radio astronomy sites with powerful earth-mapping synthetic aperture radars that could burn out the VLA or other 10 GHz receivers;

3. AI 1.1 dealing with proliferation of wireless broadband in broader swaths of the spectrum;

4. AI 1.16 for maritime radar near 150 MHz;

5. AI 1.5, use of Ku-band fixed-satellite spectrum for command and control of pilotless aircraft in commercial air spaces.


ALMA

Observing Hours

All telescope time for each of ALMA, GBT, VLA, and VLBA is characterized in the following categories: Scheduled, Maintenance, Test, Unscheduled, or Shutdown. The sum of these categories is the total number of available hours each month: 720 hours in a 30-day month, and 744 hours in a 31-day month. Scheduled science operations time is either Astronomy or Downtime.

The observing hours for each NRAO telescope are divided into the following seven categories:

Scheduled: Planned hours of observing time for peer-reviewed science proposals

Scheduled = [Astronomy + Downtime]

Astronomy: Actual hours of observing time for peer-reviewed science proposals

Downtime: Hours lost during scheduled observing time for peer-reviewed science proposals

Maintenance: Actual hours of scheduled service of infrastructure, structure, electronics, and software.

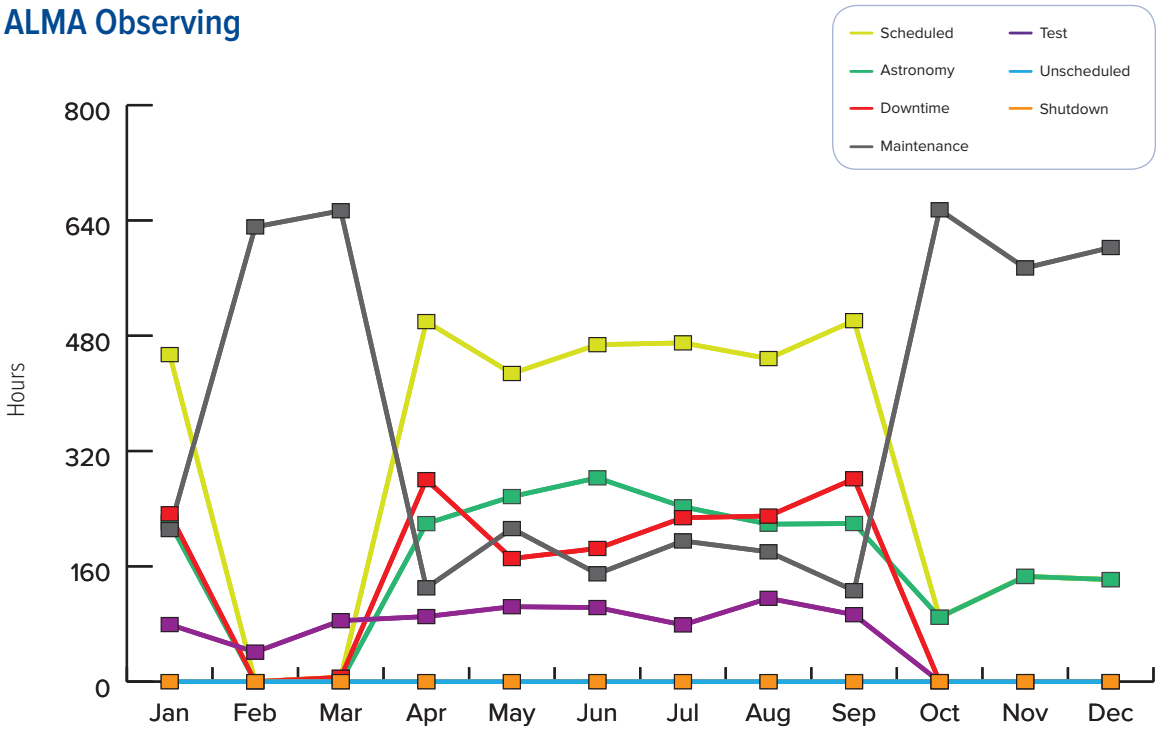
Test: Actual hours for test observations rather than peer-reviewed science proposals.

Unscheduled: Actual idle hours owing to gaps between observing programs that cannot be scheduled and to predicted, extended inclement weather.

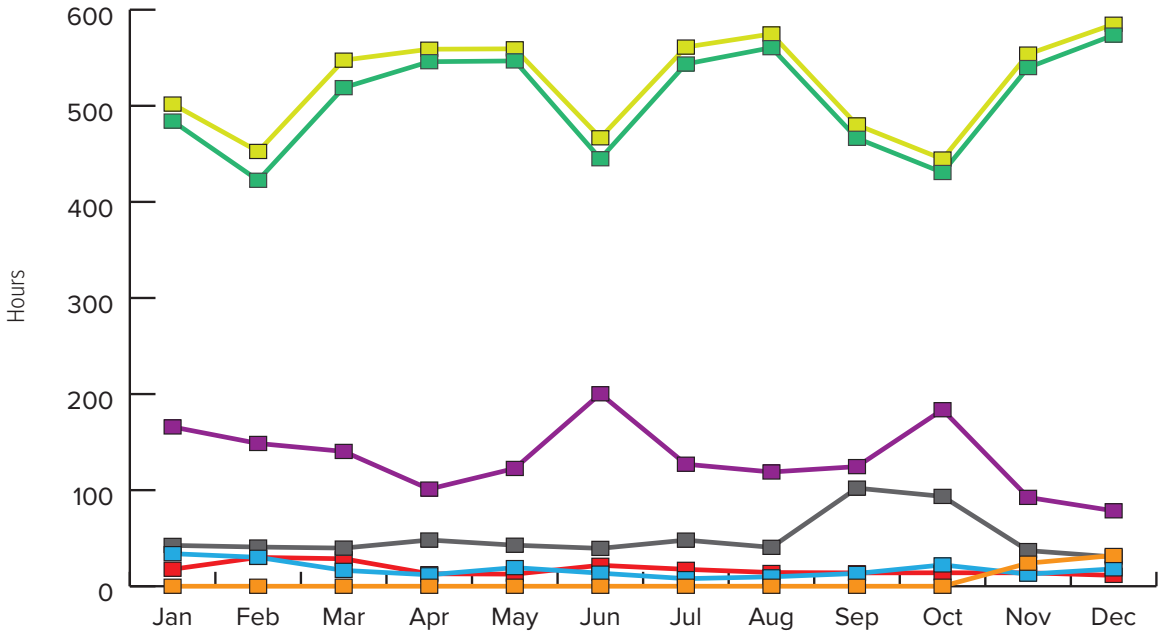
Shutdown: Actual shutdown hours, usually for a holiday. Other major shutdowns occur for major equipment work, such as GBT structural painting.

VLA photograph by Knate Myers

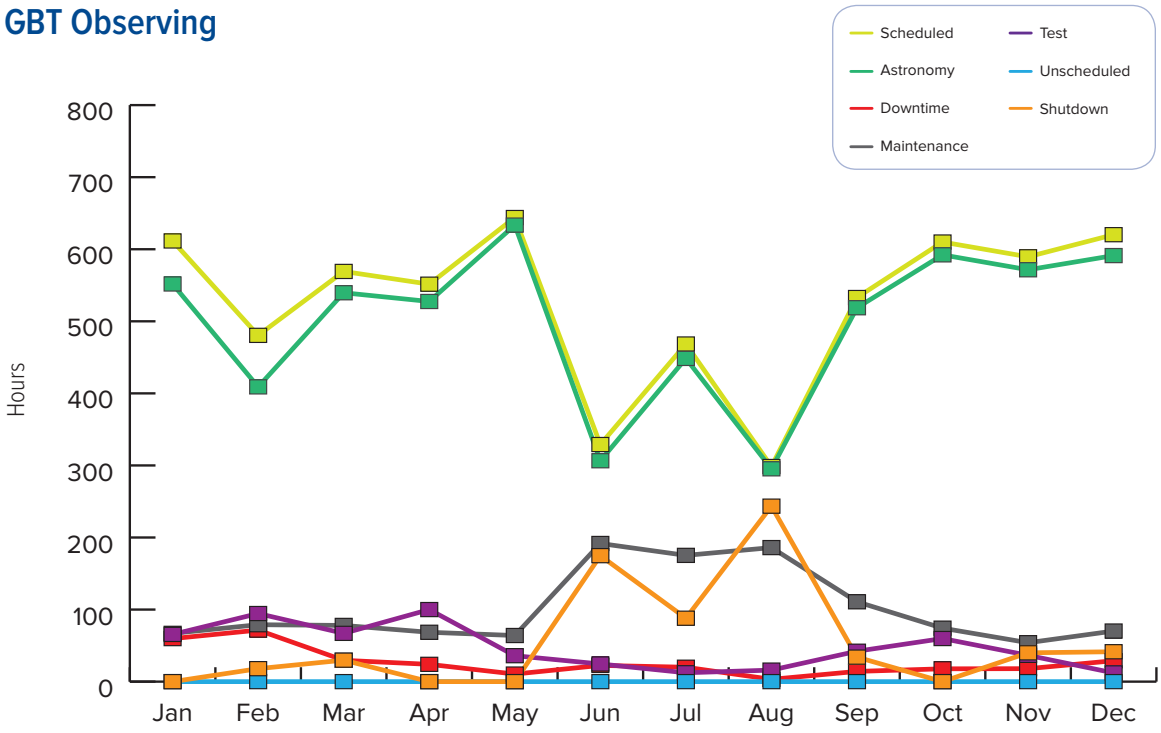
ALMA Observing



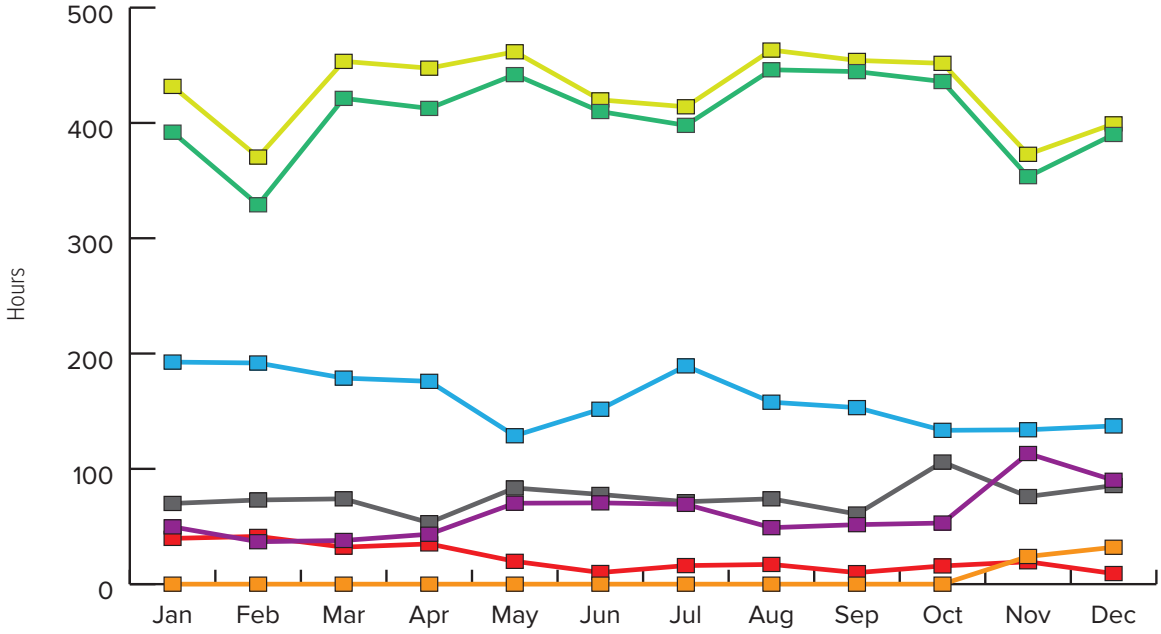
VLA Observing



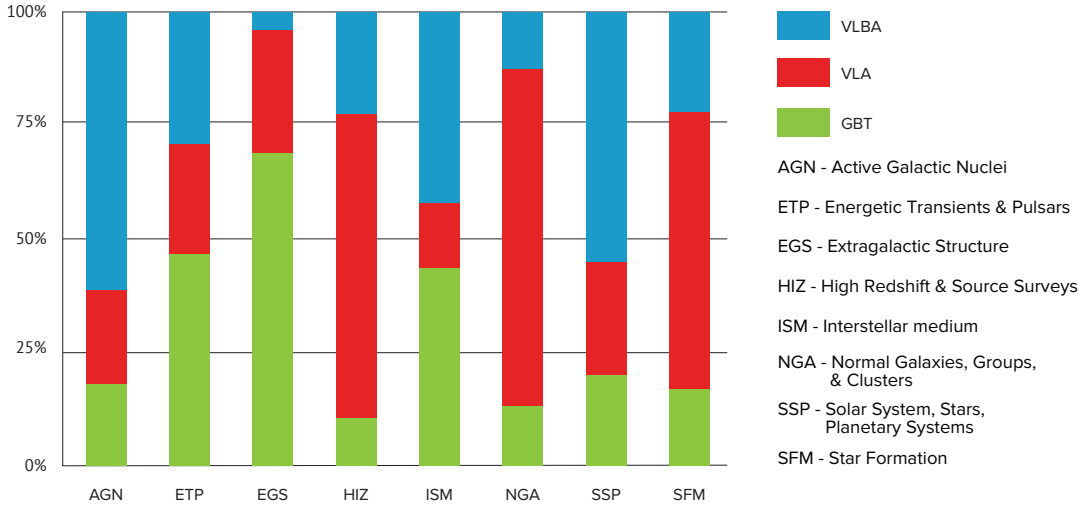
GBT Observing



VLBA Observing

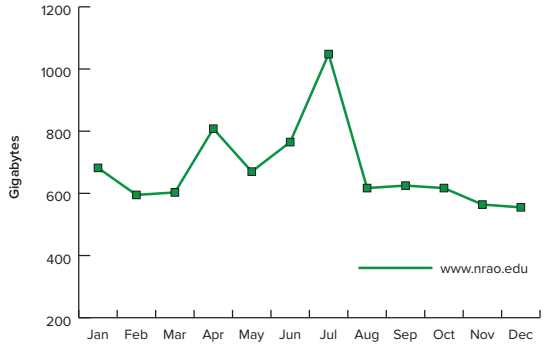


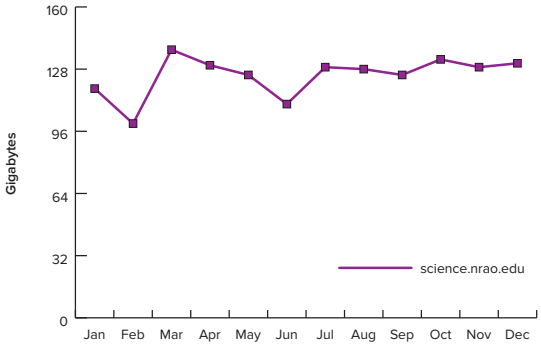
Observing Hours by Science Category

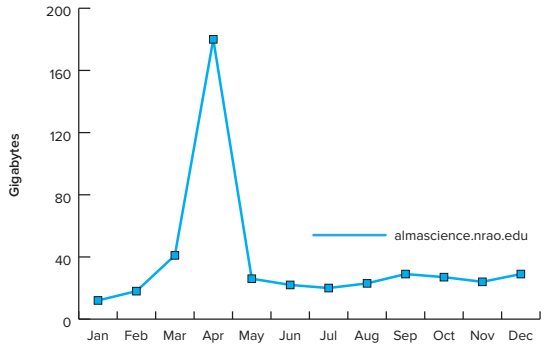


Observing hours for each of the GBT, VLA, and VLBA are tracked in the eight science categories that are included in the NRAO proposal evaluation and time allocation process:

NRAO Website Volume

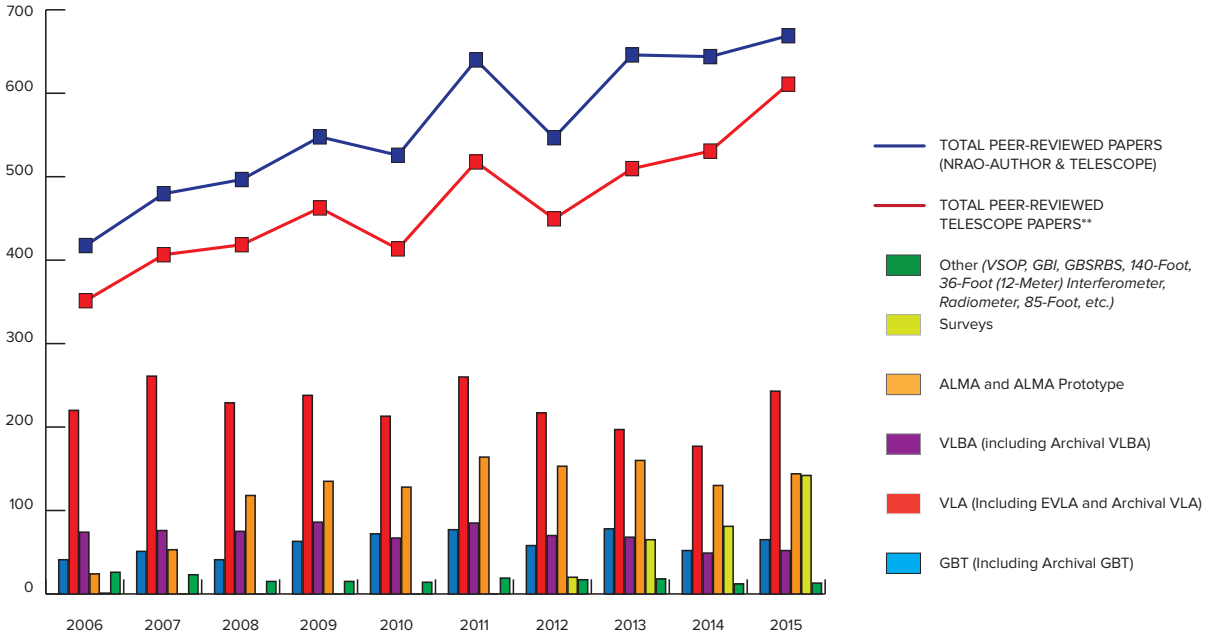






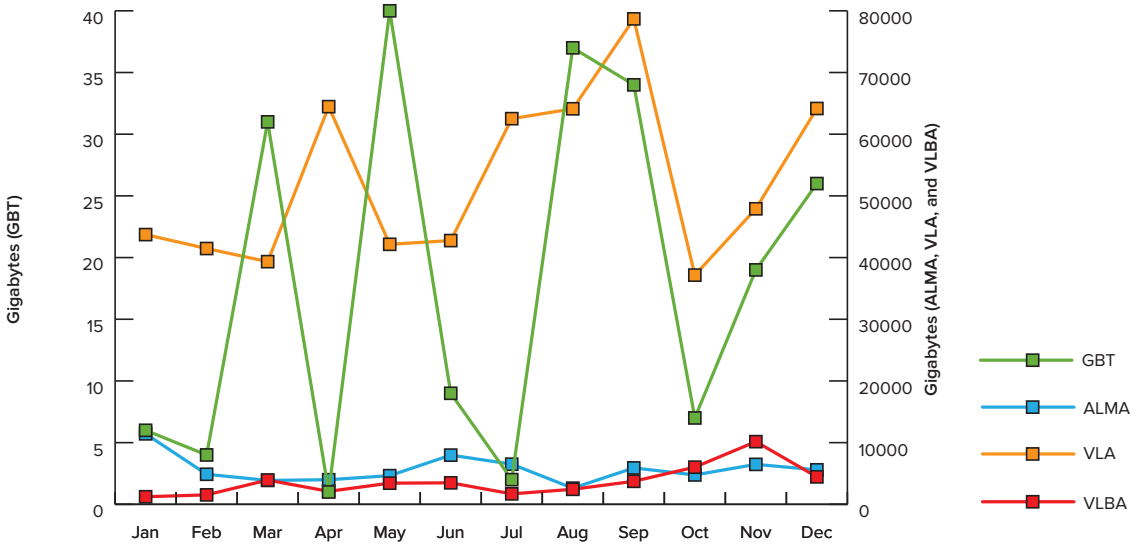
The almascience.nrao.edu website volume reflects activity by scientists interested in submitting observing proposals or seeking other professional astronomical information about ALMA. The science.nrao.edu website volume reflects activity by scientists interested in submitting observing proposals or seeking other professional astronomical information about GBT, VLA, and VLBA. The *www.nrao.edu* website volume reflects activity for press releases and other online public information.

Refereed Telescope and Author Papers



Total Peer-Reviewed NRAO-Author and Telescope Papers: Peer-reviewed publications that include NRAO telescope data, plus peer-reviewed publications by NRAO staff based on non-NRAO telescope data. **Total Peer-Reviewed Telescope Papers**: Peer-reviewed publications that include NRAO telescope data. **Other:** Peer-reviewed publications based on data from NRAO telescopes other than ALMA, VLA, VLBA, and GBT.

Science Data Archive Volume



The GBT science data archive was released to the community 1 October 2012. Most scientists, however, directly access their GBT data from the local disks in Green Bank rather than from the NRAO Science Archive.

APPENDIX A: PUBLICATIONS

2015 NRAO REFEREED PUBLICATIONS

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Ackermann, M.; Ajello, M.; Albert, A.; Atwood, W. B.; Baldini, L.; Ballet, J.; Barbiellini, G.; Bastieri, D.; Becerra Gonzalez, J.; Bellazzini, R.; Bissaldi, E.; Blandford, R. D.; Bloom, E. D.; Bonino, R.; Bottacini, E.; Bregeon, J.; Bruel, P.; Buehler, R.; Buson, S.; Caliandro, G. A.; Cameron, R. A.; Caputo, R.; Caragiulo, M.; Caraveo, P. A.; Cavazzuti, E.; Cecchi, C.; Chekhtman, A.; Chiang, J.; Chiaro, G.; Ciprini, S.; Cohen-Tanugi, J.; Conrad, J.; Cutini, S.; D'ammando, F.; De Angelis, A.; De Palma, F.; Desiante, R.; Di Venere, L.; Domí´Nguez, A.; Drell, P. S.; Favuzzi, C.; Fegan, S. J.; Ferrara, E. C.; Focke, W. B.; Fuhrmann, L.; Fukazawa, Y.; Fusco, P.; Gargano, F.; Gasparrini, D.; Giglietto, N.; Giommi, P.; Giordano, F.; Giroletti, M.; Godfrey, G.; Green, D.; Grenier, I. A.; Grove, J. E.; Guiriec, S.; Harding, A. K.; Hays, E.; Hewitt, J. W.; Hill, A. B.; Horan, D.; Jogler, T.; Jóhannesson, G.; Johnson, A. S.; Kamae, T.; Kuss, M.; Larsson, S.; Latronico, L.; Li, J.; Li, L.; Longo, F.; Loparco, F.; Lott, B.; Lovellette, M. N.; Lubrano, P.; Magill, J.; Maldera, S.; Manfreda, A.; Max-Moerbeck, W.; Mayer, M.; Mazziotta, M. N.; Mcenery, J. E.; Michelson, P. F.; Mizuno, T.; Monzani, M. E.; Morselli, A.; Moskalenko, I. V.; Murgia, S.; Nuss, E.; Ohno, M.; Ohsugi, T.; Ojha, R.; Omodei, N.; Orlando, E.; Ormes, J. F.; Paneque, D.; Pearson, T. J.; Perkins, J. S.; Perri, M.; Pesce-Rollins, M.; Petrosian, V.; Piron, F.; Pivato, G.; Porter, T. A.; Rainò, S.; Rando, R.; Razzano, M.; Readhead, A.; Reimer, A.; Reimer, O.; Schulz, A.; Sgrò, C.; Siskind, E. J.; Spada, F.; Spandre, G.; Spinelli, P.; Suson, D. J.; Takahashi, H.; Thayer, J. B.; Thompson, D. J.; Tibaldo, L.; Torres, D. F.; Tosti, G.; Troja, E.; Uchiyama, Y.; Vianello, G.; Wood, K. S.; Wood, M.; Zimmer, S.; Berdyugin, A.; Corbet, R. H. D.; Hovatta, T.; Lindfors, E.; Nilsson, K.; Reinthal, R.; Sillanpää, A.; Stamerra, A.; Takalo, L. O.; Valtonen, M. J. "Multiwavelength Evidence for Quasi-periodic Modulation in the Gamma-Ray Blazar PG 1553+113" ApJ 813: L41 (8 pp), 2015.

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ALMA photograph by Pablo Carrillo

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APPENDIX B: EVENTS & MILESTONES

2 January 2015
NRAO Semester 2015B
Call for Proposals open

4-8 January
223rd AAS meeting
Seattle, Washington
NRAO Town Hall
next generation VLA Workshop
ALMA invited plenary session
(Al Wootten)

NRAO Exhibit
Splinter Session – New Capabilities At the NRAO
Summer Student Presentations
Undergraduate Orientation Sponsor & Exhibitor
Local EPO Event Sponsor & Participant

2 February
NRAO Semester 2015B
Call for Proposals deadline

15 February
American Association for the Advancement of Science
Building Galaxies: Some Assembly Required
San Jose, CA

19-20 February
AUI Board of Trustees
Pasadena, CA

26-27 February
NRAO Community Day
Centro de Radioastronomía y Astrofísica
Universidad Nacional Autónoma de México (UNAM)
Campus Morelia, Mexico

9-10 March
NRAO Community Day
Florida Institute of Technology
Melbourne, Florida

24 March
ALMA Cycle 3 Call for Proposals published
Joint ALMA Observatory, Chile

27 March
NRAO Community Day
Star & Planet Formation in the Southwest
Oracle, AZ

31 March – 1 April
NRAO Community Day
University of California, San Diego
San Diego, CA

6-7 April
NRAO Postdoctoral Symposium
Socorro, New Mexico

9 April
AUI Executive Committee
Washington, D.C.

13 – 14 April
NRAO Community Day
Space Telescope Science Institute
Baltimore, Maryland

23 April
ALMA Cycle 3 Call for Proposals deadline
Joint ALMA Observatory, Chile

6 – 8 May
ALMA Data Reduction Party
Charlottesville, Virginia

20 May
ALMA North American Science Advisory Committee (ANASAC)
Green Bank, West Virginia

21-22 May
NRAO Users Committee
Green Bank, West Virginia

9-10 June
The Future of Planetary Radio Astronomy with Single-dish Telescopes
Green Bank, West Virginia

18-19 June
AUI Board of Trustees
Ithaca, New York

30 June
NRAO Semester 2016A
Call for Proposals open

5-10 July
Single Dish School
Green Bank, West Virginia

12-14 July
Interferometry School
Green Bank, West Virginia

19-24 July
North American Radio Science Meeting
Vancouver, British Columbia, Canada

3 August
NRAO Semester 2016A
Call for Proposals deadline

3-14 August
International Astronomical Union General Assembly
Honolulu, Hawaii
NRAO Exhibit
Undergraduate Orientation Sponsor
EPO Event Sponsor & Participant

17-21 August
ALMA Summer School
Penticton, British Columbia, Canada

2 September
AUI Executive Committee
Washington, D.C.

21-23 September
High Frequency Science Workshop
Green Bank, West Virginia

30 September
ALMA Cycle 2 science observations ended
Joint ALMA Observatory, Chile

9-10 October
Observational Evidence of Gas Accretion onto Galaxies? Workshop
Charlottesville, Virginia

14-16 October
4th China-U.S. Workshop on Radio Astronomy Science & Technology
Shanghai, China

22-23 October
AUI Board of Trustees
Arlington, Virginia

1 October
ALMA Cycle 3 science observations began
Joint ALMA Observatory, Chile

3 November
Jansky Lecture: Dr. Nick Scoville Star & Planet Formation Through Cosmic Time
Charlottesville, Virginia

6 November
Jansky Lecture: Dr. Nick Scoville Star & Planet Formation Through Cosmic Time
Socorro, New Mexico

6 November
31st New Mexico Symposium
Socorro, New Mexico

2 December
AUI Executive Committee
Washington, D.C.

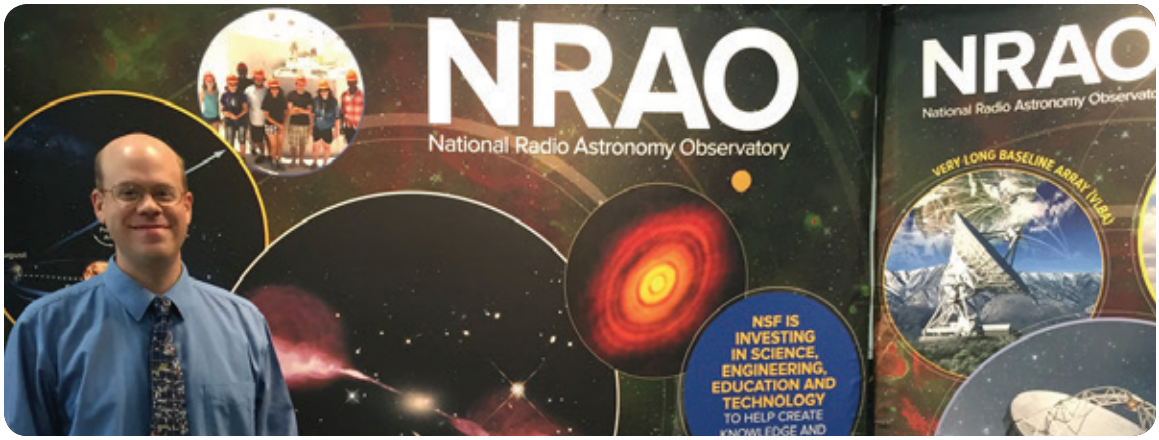
2-4 December
Science at Low Frequencies II Workshop
Albuquerque, New Mexico

8-9 December
Second ngVLA Technical Workshop
Socorro, New Mexico

11 December
NSF FY 2016 Program Review
Charlottesville, Virginia

14 December
ALMA Cycle 4 Pre-Announcement
Joint ALMA Observatory, Chile

15-17 December 2015
U.S. Radio – Millimeter – Submillimeter Futures Conference
Chicago, Illinois



APPENDIX C: ADVISORY COMMITTEES

Users Committee & ALMA North American Science Advisory Committee

The Users Committee is a scientific advisory group that provides input to NRAO on issues that affect the Observatory's scientific productivity and user relations and advises NRAO on matters of concern to those whose research is dependent on the Observatory's research facilities. The Committee also provides advice on scientific, technical, operational, and development issues relating to the astronomical community's current and future use of NRAO research facilities and makes recommendations that maximize the Observatory's scientific productivity and improve its effectiveness for the user community.

To perform these duties, the members of the Committee consult widely with current and potential NRAO users and communicate their requirements, recommendations, issues, and concerns to the Observatory.

The Committee delivers an annual report to the NRAO Director that summarizes the Committee's recommendations and concerns. In recent years, the Committee has become increasingly active in advising the Observatory between formal meetings. This is a valuable role that NRAO welcomes and encourages.

As ALMA began to focus more on science operations and construction was completed, NRAO integrated the ALMA North American Science Advisory Committee (ANASAC) as a subcommittee of the Users Committee. Established in February 2003, the ANASAC has four primary charges:

- Advise the NRAO Director on issues relating to the scientific use of ALMA, including scientific and technical requirements for ALMA, user support, preparatory programs with existing facilities, and/or providing access to new facilities in Chile, science with ALMA during the construction and commissioning stage, definition and preparation for the NAASC, priorities for ALMA Chilean operations and the ALMA development plans.

- Provide a conduit between the NRAO and the NA scientific community for dissemination of information pertaining to the status and progress of the ALMA construction project and operations.

- Provide input on charges given to the ALMA Science Advisory Committee (ASAC) by the ALMA Board.

- Carry out other tasks as may be requested by the NRAO Director.

The ANASAC includes the four North American representatives to the ASAC, a Taiwan representative, and any other Users Committee members interested in ALMA.

The 2015 Users Committee members, their home institution, and the last year of their term of service follow. Members who also serve on the ANASAC or the ASAC are indicated.

Loren D. Anderson
West Virginia University, 2018

Steven W. Ellingson
Virginia Tech, 2018

James Miller-Jones
Curtin University, 2015

Alberto Bolatto (ANASAC/ASAC)
University of Maryland, 2016

Rachel Friesen
University of Toronto, 2018

Karin Öberg (ANASAC)
Harvard-Smithsonian Center for Astrophysics, 2015

John Carpenter (ANASAC/ASAC)
Caltech, 2015

Gregg Hallinan
Caltech, 2015

Rachel Osten (ANASAC/ASAC)
Space Telescope Science Institute, 2018

Shami Chatterjee
Cornell University, 2016

Shih-Ping Lai (ANASAC)
National Tsing-Hua University, 2018

Dick Plambeck (ANASAC/ASAC)
University of California, Berkeley, 2015

Laura Chomiuk, Co-Chair
Michigan State University, 2016

Joseph Lazio, Chair
JPL/CIT, 2016

Dominik Riechers
Cornell University, 2016

Sheperd Doeleman (ANASAC)
MIT Haystack Observatory, 2015

Dan Marrone (ANASAC)
University of Arizona, 2015

Douglas Scott (ANASAC/ASAC)
University of British Columbia, 2017

Visiting Committee

The AUI Visiting Committee is appointed by the AUI Board of Trustees to review the management and research programs of the Observatory. The bi-annual Visiting Committee meetings are held at alternating NRAO sites. Edwin Bergin was the chair for the 2014 Visiting Committee. The Committee's most recent bi-annual face-to-face meeting was held at the NRAO Domenici Science Operations Center in Socorro, New Mexico 24 – 25 April 2014; the next will be held in spring 2016 in Charlottesville, Virginia. The Visiting Committee members, their home institution, and their last year of their term of service follow.

Edwin Bergin, Chair
University of Michigan, 2018

Katherine Blundell
Oxford University, 2018

Xiaoyu Hong
Shanghai Astronomical Observatory, 2016

Ryohei Kawabe
National Astronomical Observatory of Japan, 2016

Elizabeth A. Lada
University of Florida, 2014

Malcolm Longair
University of Cambridge, 2014

Maura McLaughlin
West Virginia University, 2016

Suzanne Staggs
Princeton University, 2016

Greg Taylor
University of New Mexico, 2018

Dan Werthimer
University of California – Berkeley, 2018

APPENDIX C: ADVISORY COMMITTEES

Time Allocation Committee

The scientists listed below served on the NRAO Time Allocation Committee (TAC) for Semesters 2015B and 2016A. The scientific purview of each TAC member is indicated.

Semester 2015B

Jeremy Darling
Extragalactic Structure (EGS)
University of Colorado

Robert Zavala
Solar System, Stars, and Planetary Systems (SSP)
U.S. Naval Observatory

Mattew Malkan
Active Galactic Nuclei (AGN)
University of California Los Angeles

Larry Rudnick
Normal Galaxies, Groups and Clusters (NGA)
University of Minnesota

David Sanders
High Redshift and Source Surveys (HIZ)
University of Hawaii

Roland Kothes
Interstellar Medium (ISM)
Dominion Radio Astrophysical Observatory

Luis Rodriguez
Star Formation (SFM)
Universidad Nacional Autonoma de Mexico

Joseph Lazio
Energetic Transient and Pulsars (EPT)
Jet Propulsion Laboratory

Semester 2016A

Jeremy Darling
Extragalactic Structure (EGS)
University of Colorado

Brenda Matthews
Solar System, Stars, and Planetary Systems (SSP)
U.S. Naval Observatory

Mattew Malkan
Active Galactic Nuclei (AGN)
University of California Los Angeles

Larry Rudnick
Normal Galaxies, Groups and Clusters (NGA)
University of Minnesota

Dominik Riecher
High Redshift and Source Surveys (HIZ)
Cornell University

Roland Kothes
Interstellar Medium (ISM)
Dominion Radio Astrophysical Observatory

Luis Rodriguez
Star Formation (SFM)
Universidad Nacional Autonoma de Mexico

Robert Fender
Energetic Transient and Pulsars (EPT)
University of Southampton

Photo by Pablo Carrillo

APPENDIX D: FISCAL YEAR 2015 FINANCIAL SUMMARY

(all figures are $k USD)

Functional Work Breakdown Structure Element	GBT	VLA	VLBA	ALMA	GB Ops	NM Ops	HQ & CV Ops	CDL & Other	Solar Radio Burst Spectrometer	ALMA-C	EVLA-C	External Grants	Total
Administrative Services	$135.99	$2,054.77	$536.07	$13,471.24	$2,843.97	$2,017.09	$3,929.01	–	–	–	–	–	$24,988.2
Development Programs	$363.82	–	–	$3,744.29	$526.37	–	$765.04	$2,490.29	–	–	–	–	$7,889.8
Director's Office	–	–	–	$5,208.31	$21.55	$2.42	$4,686.63	–	–	–	–	–	$9,918.9
Science Operations	$610.36	$31.23	$49.48	$6,337.43	$19.67	–	$6,784.34	–	–	–	–	–	$13,832.5
Telescope Operations	$5,190.11	$7,723.56	$3,813.15	$11,341.87	$221.47	$117.62	$1,293.03	–	–	–	–	–	$29,700.8
SPO-4 Solar Radio Burst Spectrometer	–	–	–	–	–	–	–	–	$2.37	–	–	–	$2.4
ALMA Construction	–	–	–	–	–	–	–	–	–	$2,293.06	–	–	$2,293.1
EVLA Construction	–	–	–	–	–	–	–	–	–	–	$0.77	–	$0.8
External Grants	–	–	–	–	–	–	–	–	–	–	–	$3,700.42	$3,700.4
Grand Total	$6,300.3	$9,809.6	$4,398.7	$40,103.1	$3,633.0	$2,137.1	$17,458.0	$2,490.3	$2.4	$2,293.1	$0.8	$3,700.4	$92,326.8

Fiscal Year 2015 = 1 October 2014 – 30 September 2015

Photo by Pablo Carrillo

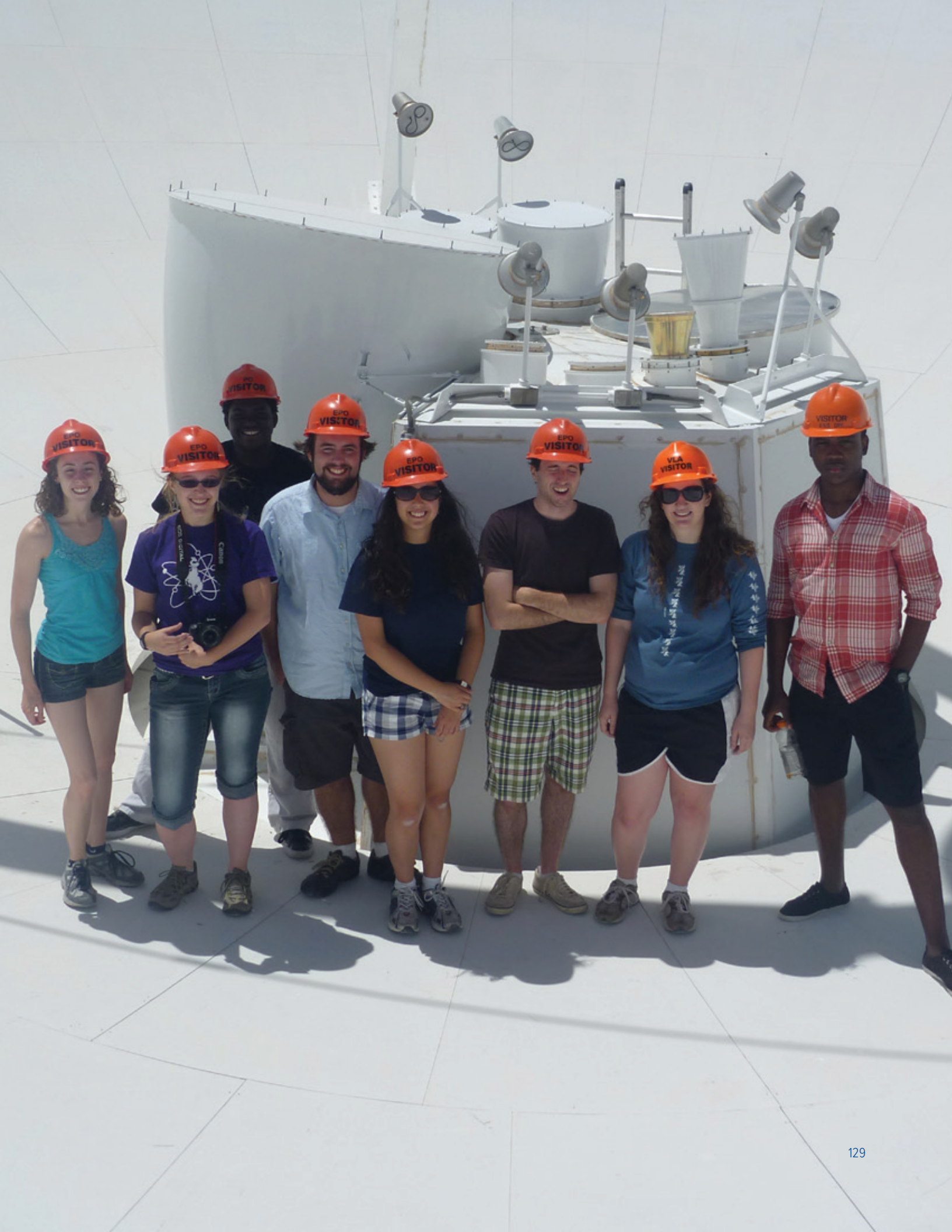
APPENDIX E: ACRONYMS

Acronym	Definition
AAAS	American Association for the Advancement of Science
AAS	American Astronomical Society
ADMIT	ALMA Data Mining Toolkit
AGN	Active Galactic Nuclei
ALMA	Atacama Large Millimeter/submillimeter Array
ANASAC	ALMA North American Science Advisory Committee
AOS	Array Operations Site
APEX	Atacama Pathfinder Experiment
API	Atmospheric Phase Interferometer
APP	ALMA Phasing Project
ARC	ALMA Regional Center
ASIAA	Academia Sinica Institute for Astronomy and Astrophysics
ASKAP	Australian Square Kilometer Array Pathfinder
AST	NSF Division of Astronomical Sciences
AU	Astronomical Unit
AUI	Associated Universities, Incorporated
AURA	Association of Universities for Research in Astronomy
BeSSeL	Bar and Spiral Structure Legacy Survey
CARMA	Combined Array for Research in Millimeter Astronomy
CARTA	Cube Analysis and Rendering Tool for Astronomy
CASA	Common Astronomy Software Applications
CASPER	Collaboration for Astronomy Signal Processing and Electronics Research
CDE	Community Day Event
CDL	Central Development Laboratory
CDR	Critical Design Review
CGM	Circum-galactic Medium
CfP	Call for Proposals
CIS	Computing Information Systems
CMOS	Complementary Metal Oxide Semiconductor
COM	Communications Office
COSMOS	Cosmic Evolution Survey
CSRH	Chinese Spectral Radioheliograph
DARE	Dark Ages Radio Explorer
DMSD	Data Management & Software Department
EGS	Extragalactic Structure
EPO	Education and Public Outreach
ESA	European Space Administration
ESO	European Organisation for Astronomical Research in the Southern Hemisphere
ETP	Energetic Transients and Pulsars
EVLA	Expanded Very Large Array
FAST	Five hundred meter Aperture Spherical Telescope
FCC	Federal Communications Commission
FIRST	Faint Images of the Radio Sky at Twenty centimeters
FPGA	Field Programmable Gate Array
FRB	Fast Radio Bursts
FWHM	Full Width at Half Maximum
GB	Green Bank, West Virginia
GBT	Green Bank Telescope
GHz	Gigahertz
GMVA	Global 3mm VLBI Array
GO	General Observing
HBT	Heterojunction Bipolar Transistors
HERA	Hydrogen Epoch of Reinonization Array
HIZ	High Redshift and Source Surveys
HPC	High Performance Computing
HR	Human Resources
HRIS	HR Information Systems
HSA	High Sensitivity Array
HST	Hubble Space Telescope
IAU	International Astronomical Union
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IfA	Institute for Astronomy
IGM	Intergalactic Medium
IPAC	Infrared Processing and Analysis Center
IPT	Integrated Product Team
ISM	Interstellar Medium

ITU-R . . . . . International Telecommunication Union – Radiocommunication
IUCAF . . . . . Inter-Union Committee on the Allocation of Frequencies
JAO . . . . . Joint ALMA Observatory
JPL. . . . . Jet Propulsion Laboratory
kHz . . . . . kiloHertz
KFPA . . . . . K-band Focal Plane Array
Kpc . . . . . kiloparsec
LBC . . . . . Long Baseline Campaign
LMT . . . . . Large Millimeter Telescope
LNA . . . . . Low Noise Amplifier
LO . . . . . Local Oscillator
LoFASM . . . . . Low Frequency All Sky Monitoring Array
LSST . . . . . Large Synoptic Survey Telescope
LWA . . . . . Long Wavelength Array
MEASURE . . . . . Magnetometers along the Eastern Atlantic Seaboard for Undergraduate Research and Education
MeerKAT . . . . . Karoo Array Telescope
MHz. . . . . Megahertz
MMIC. . . . . Monolithic Millimeter-wave Integrated Circuit
MPIfR. . . . . Max Planck Institut für Radioastronomie
MPIfA. . . . . Max Planck Institut für Astronomie
MREFC. . . . . Major Research Equipment and Facility Construction
MSIP . . . . . Mid-Scale Initiative Program
MWR . . . . . Murchison Widefield Array
Myr . . . . . Megayear
μJy. . . . . microJansky
MUSTANG . . . . . Multiplexed SQUID/TES Array at Ninety Gigahertz
NA . . . . . North American
NAASC . . . . . North American ALMA Science Center
NAC . . . . . National Astronomy Consortium
NAIC . . . . . National Astronomy and Ionosphere Center
NAOC. . . . . National Astronomical Observatories, Chinese Academy of Sciences
NAOJ . . . . . National Astronomical Observatory of Japan
NANOGrav. . . . . North American Nanohertz Observatory for Gravitational Waves
NASA . . . . . National Aeronautics and Space Administration
NEON. . . . . National Ecological Observatory Network
NGA . . . . . Normal Galaxies, Groups, and Clusters
NGST . . . . . Next Generation Space Telescope
ngVLA . . . . . Next Generation Very Large Array
NINS . . . . . National Institutes of Natural Sciences
NIO . . . . . New Initiatives Office
NIR. . . . . Near Infrared
NIST. . . . . National Institute of Standards and Technology
NM. . . . . New Mexico
NMT. . . . . New Mexico Institute of Mining and Technology
NRAO. . . . . National Radio Astronomy Observatory
NRC . . . . . National Research Council
NRL . . . . . Naval Research Laboratory
NRQZ. . . . . National Radio Quiet Zone
NSF . . . . . National Science Foundation
NSBP . . . . . National Society of Black Physicists
NSC . . . . . National Science Council Canada
NVSS . . . . . NRAO Very Large Array Sky Survey
NWNH . . . . . New Worlds, New Horizons
OC . . . . . Organizing Committee
OCA. . . . . Office of Chilean Affairs
ODI . . . . . Office of Diversity and Inclusion
OMT. . . . . OrthoMode Transducer
OPT . . . . . Observation Preparation Tool
OSF . . . . . Operations Support Facility
PAF . . . . . Phased Array Feed
PAPER . . . . . Precision Array for Probing the Epoch of Reionization
PHAMAS . . . . . Phased Array for Millimeter Astronomy
PHT . . . . . Proposal Handling Tool
PI . . . . . Principal Investigator
PING . . . . . Physicists Inspiring the Next Generation
PSC . . . . . Pittsburg Supercomputing Center
PST . . . . . Proposal Submission Tool
REU . . . . . Research Experiences for Undergraduates
RF . . . . . Radio Frequency

APPENDIX E: ACRONYMS

RFI . . . . . Radio-Frequency Interference
RMS . . . . . Radio-Millimeter-Submillimeter
RSRO . . . . . Resident Shared Risk Observing
SCO . . . . . Santiago Central Office
SFM . . . . . Star Formation
SHAO . . . . . Shanghai Astronomical Observatory
SIS . . . . . Superconductor–Insulator–Superconductor
SJS. . . . . Skynet Jr. Scholars
SKA . . . . . Square Kilometre Array
SOC . . . . . Scientific Organizing Committee
SOS . . . . . Student Observing Support
SRDP . . . . . Science Ready Data Products
SRO . . . . . Shared Risk Observing
SRP . . . . . Science Review Panel
SSP . . . . . Solar System, Stars & Planetary Systems
SSR . . . . . Science Support and Research
STEM . . . . . Science, Technology, Engineering, and Mathematics
STScI . . . . . Space Telescope Science Institute
SUS . . . . . Science User Support
SWG. . . . . Science Working Group
TAC . . . . . Time Allocation Committee
TES . . . . . Transition Edge Sensor
THz . . . . . TeraHertz
TTA . . . . . Telescope Time Allocation
UVML. . . . . University of Virginia Microfabrication Laboratory
VA . . . . . Virginia
VEGAS . . . . . Versatile Green Bank Astronomical Spectrometer
VLA . . . . . Very Large Array
VLASS . . . . . Very Large Array Sky Survey
VLBA . . . . . Very Long Baseline Array
VLBI . . . . . Very Long Baseline Interferometry
VLITE . . . . . VLA Ionospheric and Transient Experiment
WIDAR . . . . . Wideband Interferometric Digital Architecture Correlator
WMAP . . . . . Wilkinson Microwave Anisotropy Probe
WV . . . . . West Virginia
WV SPOT . . . . . West Virginia Space Public Outreach Team
XSEDE . . . . . Extreme Science and Engineering Discovery Environment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The National Radio Astronomy Observatory is a facility of the
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